Technical Note

Noninvasive Assessment of Portomesenteric Venous Thrombosis: Current Concepts and Imaging Strategies

Michelle S. Bradbury, Peter V. Kavanagh, Michael Y. Chen, Therese M. Weber, and Robert E. Bechtold

Abstract: Rapid, noninvasive imaging strategies, especially multidetector spiral CT and CT angiography (CTA) as well as gadolinium-enhanced MR angiography (MRA), have facilitated early diagnosis of splanchic venous thrombosis, a potentially lethal cause of intestinal ischemia. Single breath-hold volumetric acquisitions permit superior temporal and contrast resolution while eliminating motion artifact and suppressing respiratory misregistration. Increased spatial resolution is aided by thinner slice collimation. These cross-sectional imaging techniques are becoming a preferred noninvasive alternative to conventional selective mesenteric angiography with delayed imaging for venous evaluation and should be considered the primary diagnostic modalities for evaluating patients with high clinical suspicion of nonsurgical mesenteric ischemia. Index Terms: Portomesenteric venous thrombosis—Noninvasive imaging.

INTRODUCTION

Splanchnic venous occlusions comprise a relatively infrequent but important cause of mesenteric ischemia (1,2). The application of rapid, non- or minimally invasive imaging strategies has facilitated earlier recognition and detection of a disease process that has often presented with nonspecific clinicoradiologic findings. This has previously delayed diagnosis and resulted in higher morbidity and mortality rates. Earlier noninvasive imaging may improve the prognosis of this disease by permitting patients to be managed more effectively (i.e., transcatheter delivery of thrombolytic agents, surgical thrombectomy, or medical management). This article discusses the technical aspects and optimization methods used in the detection and evaluation of portomesenteric venous thrombosis, and their advantages and limitations, with particular emphasis on spiral CT/CT angiography (CTA) and MR angiography (MRA). Typical CTA and MR/MRA protocols for abdominal applications are presented.

IMAGING METHODS

A variety of methods, including conventional arteriography, Doppler ultrasound, spiral CT/CTA, and MRA, are currently used for evaluation of portomesenteric venous thrombosis. Development and implementation of multidetector CTA and MRA techniques have permitted high resolution, breath-hold imaging to be performed rapidly and less invasively. The clinical utility of these imaging strategies, specifically applied to evaluation of the main splanchic vessels, rivals that of conventional selective mesenteric angiography with delayed imaging for venous evaluation. These strategies additionally serve as problem-solving tools, in conjunction with transcatheter therapeutic techniques, in the management of symptomatic portal and mesenteric venous thrombosis (3–5). However, angiography, traditionally used only in cases where CT is equivocal or nondiagnostic for suspected venous thrombosis or where there is high clinical suspicion for acute arterial mesenteric ischemia, remains superior for demonstrating the small mesenteric branch vessels (6–8).

Helical CT/CTA

The introduction of rapid volumetric CT scanning using helical CT has revolutionized the acquisition of im-
aging data and has facilitated development of novel imaging strategies such as CTA. As detailed elsewhere (9–19), this has been the result of successive advances in helical CT technology over the last decade, including faster gantry rotation, more accurate interpolation algorithms (12,20), improved heat capacity characteristics of X-ray tubes, and, most importantly, multidetector CT scanners. These technical innovations have decreased susceptibility to respiratory and motion artifacts as a result of faster scan times, yielding higher quality images.

The evolution of multidetector CT scanners, which combine helical scanning with multislice acquisition, has been detailed previously (9,12). The latest development in CT scanner systems is currently capable of acquiring multiple, (e.g., 16 and soon 32) channels of helical data simultaneously. This has afforded substantially greater z-axis coverage and successive gains in scan speed compared with single detector row helical CT scanners, without compromising image quality (9). Additional advantages include significantly shorter acquisition times, retrospective thin or thick section reconstructions from the same raw data, and improved three-dimensional rendering with decreased helical artifact (9,11). These innovations have had a significant impact on the growth of CTA applications and the performance of CTA, with improvements in image quality arising from faster scanning capability. In addition, higher spatial resolution can be achieved in 3D reconstructions and potentially lower contrast agent doses can be administered.

CTA

CTA protocols combine single breath-hold, volumetric helical CT acquisitions, using thinner slice collimation, with intravenous bolus administration of iodinated contrast material. Single breath-hold scanning means that images can be acquired during the time of maximum circulating levels of contrast material, ensuring peak vascular opacification following peripheral intravenous administration. This has permitted successful imaging of entire vascular distributions, in addition to minimizing motion artifact, suppressing respiratory misregistration, facilitating bolus tracking methods, and increasing longitudinal spatial resolution (9).

Multidetector CT Scanners

The evolution of multidetector CT scanners, which combine helical scanning with multislice acquisition, has been detailed previously (9,12). The latest development in CT scanner systems is currently capable of acquiring multiple, (e.g., 16 and soon 32) channels of helical data simultaneously. This has afforded substantially greater z-axis coverage and successive gains in scan speed compared with single detector row helical CT scanners, without compromising image quality (9). Additional advantages include significantly shorter acquisition times, retrospective thin or thick section reconstructions from the same raw data, and improved three-dimensional rendering with decreased helical artifact (9,11). These innovations have had a significant impact on the growth of CTA applications and the performance of CTA, with improvements in image quality arising from faster scanning capability. In addition, higher spatial resolution can be achieved in 3D reconstructions and potentially lower contrast agent doses can be administered.

Technical Considerations

Optimization of scanning technique requires trade-offs between volume coverage and spatial resolution (along the z axis) in addition to accurate selection of bolus timing parameters. A number of variables, listed below, can be controlled.

Collimation. Spatial resolution and the signal-to-noise ratio are affected by collimation. The lowest collimation setting should be selected to maximize longitudinal resolution without introducing unacceptable pixel noise. Evaluation of portomesenteric branch vessels requires thin collimation settings in the 1 to 2 mm range. However, pixel noise can be considerable under these conditions, given current X-ray tube output constraints (6), especially in patients of large body habitus. In such cases, scanning may be performed using 2.5 to 5 mm collimation. Scan coverage considerations, however, may require further compromises to be made between collimation and pitch. Selecting thinner collimation settings for achieving volume coverage requirements mandates higher pitch settings [pitch (single detector CT) = table movement per rotation/slice collimation, and pitch (multidetector CT) = table movement per rotation/single slice collimation]. This in turn can be accomplished by increasing table speed.

Resolution. Submillimeter transaxial resolution is usually achieved for abdominal and pelvic spiral CT applications, while the longitudinal resolution is typically an order of magnitude greater (6,32). (Certain current multidetector CT scanners, however, offer 0.5-mm-thick sections and can produce isotropic data sets.) Maximizing longitudinal resolution is necessary for accurately delineating vascular structures on coronal or sagittal 2D or 3D reformations. This can be accomplished by minimizing the collimation, table feed, or reconstruction interval (6). Associated trade-offs, however, are increased pixel noise, limited volume coverage over the duration of the scan, and increased processing time and data storage requirements, respectively. In general, selecting thinner collimation and higher pitch settings will yield improved longitudinal resolution compared with slightly thicker collimation at lower pitch settings (6). These and other considerations have been documented extensively elsewhere (6,10,11).
**Timing Parameters.** The scan duration time for CTA is dependent on the breath-holding capability of the patient, scanner-related considerations for a given tube current, and bolus timing methods (rate and timing of injection) (6). The breath-hold capability of the patient should be initially assessed (some institutions administer oxygen to help prolong breath-hold). Twenty to 30 s breath-holds are usual, with prolonged breath-holds up to 40 s sometimes required. The contrast material injection parameters are then selected to coincide with the desired scan duration (6,10). High injection flow rates (4–5 ml/s) are generally used to achieve maximum vascular opacification. Establishing an injection duration equal to the scan duration (i.e., 30 s) makes the scanning delay time critical. The delay between the start of the injection and the commencement of the scan can be optimized for both arterial and/or venous phase imaging. Utilizing high bolus concentrations (300–350 mg of I/ml) maximizes subject contrast. The resultant 3D volume data set permits reformation of vascular structures in any projection.

**Venous Phase Imaging.** Optimal opacification of portomesenteric venous anatomy can be achieved with scanning delays of 55–70 s, following a large volume bolus injection (140–180 ml) at high flow rates (4–5 ml/s) through a peripheral vein (Fig. 1). Dynamic evaluation of the splanchnic veins, including the peripheral branches, may be performed prospectively with dedicated multidetector CTA using optimal bolus technique or retrospectively with postprocessing techniques applied to routine abdominal spiral CT data sets (6), although the former yields far superior results. These techniques have been successfully applied to imaging abdominal pathology, including detection of mesenteric ischemia, cirrhosis, and hepatic malignancy with venous extension (Figs. 2–4). Recommended ranges of parameter values typically used on the GE Lightspeed scanner for both single slice and multidetector protocols when evaluating the portomesenteric vasculature are detailed in Table 1. Parameters applicable to multidetector row CT units of other vendors are available elsewhere (13).

**Three-Dimensional Reformatting Techniques**

The combined use of 3D postprocessing techniques with multidetector CT imaging to create vascular maps, detailed previously (25,30), permits a more accurate assessment of vessel patency as well as facilitates detection of early vascular thrombosis or occlusion in the setting of malignancy or other disease process. Of the three main rendering algorithms available, namely, shaded surface display (SSD), maximum intensity projection (MIP), and volume rendering, volume rendering was found to be superior to SSD for displaying detailed images of the bowel wall in cases of mesenteric ischemia (33) and superior to both SSD and MIP for delineating peripancreatic vasculature (34). The superiority of volume rendering is related to its accurate depiction of both vascular structures and the surrounding extravascular anatomy while preserving spatial relationships. In addition, image quality is comparable with that of conventional angiography, with overall decreased costs and processing time.

**Advantages/Limitations.** Spiral CTA is a rapid and minimally invasive technique for evaluating the abdominal vasculature and nonvascular organ anatomy. Compared with conventional angiography, it is faster, less costly, and less invasive and provides less radiation exposure given the higher pitch of multidetector row scanners (10,25). Additionally, the data can be retrospectively edited using volume rendering, MIPs, and SSDs and redisplayed into any possible projection. Current limitations are related to optimization of bolus timing dynamics and cumulative radiation doses, although, in the latter case, utilizing a higher pitch, more efficient scanner detector system, and/or lower mAs can minimize total exposure (25).

**MRI/MRA**

Routine evaluation of the portomesenteric arteriovenous vasculature using conventional MRA techniques, such as spin echo or gradient echo imaging (35) and velocity-dependent inflow time-of-flight (TOF) or phase contrast (PC) methods, is well documented (36–41). The results of these noninvasive techniques have correlated well with those of conventional angiographic procedures (41) and are favored in the assessment of the splanchnic circulation. Beyond visualization of the normal anatomy, portal venous patency, flow direction, splanchnic throm-
bosis, and changes of portal hypertension have been successfully evaluated. The determination of flow characteristics in both portal and mesenteric vessels using functional MR techniques has complemented analysis of splanchnic venous morphology. Cardiac or peripherally gated PC methods (cine PC) have permitted accurate quantitation of vascular flow rates from acquired time-resolved velocity profiles (42–44). In its specific application to chronic mesenteric ischemia, PC MRI has been used to evaluate postprandial flow rates in both the SMA and the SMV of humans and animal models, with the ratio of flow rates in the SMV to SMA thought to be the most sensitive indicator of ischemia (45–48). Extension of these methods to MR oximetry studies has permitted assessment of the oxygenation status of the SMV in chronic mesenteric ischemia (49–51) and has offered the potential of monitoring these events in vivo.

These flow-sensitive methods are hampered by a number of limitations (detailed below) as well as a relative lack of direct anatomic information. These limitations have been successfully eliminated using rapid, contrast-enhanced, spoiled gradient echo (SPGR) MRA techniques during a single breath-hold. The application of these 3D contrast-enhanced techniques has been driven by advancements in gradient technology, implementation of single breath-hold protocols, improvements in image reconstruction algorithms, optimization of contrast agent administration techniques, and coil technology (8,52). Fat suppression and appropriate timing of data acquisition have permitted improvement in vessel conspicuity. With these techniques, detailed anatomic splanchnic venous anatomy has been displayed during the portal venous and equilibrium phases of abdominal arterial MRA. Image reformating in any plane has facilitated preprocedural planning and permitted improved analysis of portomesenteric venous abnormalities, including thrombosis and cavernous transformation (Figs. 5 and 6).

While spatial resolution limits the delineation of the small distal portomesenteric branch vessels, this is offset by advantages of greater speed, improved image quality, and minimal invasiveness. Likely, future implementation of a combined morphologic and functional imaging approach will permit more sensitive detection of acute or chronic mesenteric ischemia.
Conventional MRA

Traditional 2D or 3D MRA techniques have visualized the splanchnic circulation by exploiting the characteristics of flowing blood in the absence of intravenous contrast material. TOF or “inflow” approaches typically rely on flow-compensated gradient-refocused sequences to demonstrate differential saturation properties of inflowing blood (bright) from the surrounding stationary or fixed tissues (dark). In PC imaging, phase shifts generated by flowing blood in the presence of “flow-encoding” gradients are used to measure flow velocities and assess flow direction. PC angiographic methods, implemented as 2D or 3D gradient-refocused sequences, have been used for portal venous evaluation (41,53). Conventional MRA methods have been limited by longer image acquisition times, intravoxel signal losses in regions of turbulent flow (i.e., stenotic vessels or sites of occlusive disease) (54,55), and bulk motion or susceptibility artifacts. PC sequences demonstrate sensitivity only over specific velocity ranges (56). A major disadvantage of TOF methods is in-plane flow saturation effects within tortuous or slowly flowing vessels (57–59). In-plane flow saturation effects may be particularly problematic, sometimes limiting detection of distal arterial and venous branches (59).

The use of single breath-hold 3D non-gadolinium-infused techniques has circumvented these problems, but at the expense of contrast resolution between vessels and surrounding tissue (60). Additional limitations relating to the triphasic flow pattern and pulsatile motion of the SMA may decrease visibility, degrade signal-to-noise ratio, and require systolic gating (52,61). Nonetheless, PC flow maps have been used to accurately quantitate flow rates in the SMA and SMV (45–47).

Contrast-Enhanced MRA

The application of high resolution, breath-hold MRA techniques using intravascular gadolinium-based agents such as Gd-DTPA has eliminated saturation effects and flow- and respiratory-induced motion artifacts (18,52,55,60,62–64,67–71), permitting exquisite detail of the mesenteric vascular anatomy. Fast gradient echo sequences combined with high T1 relaxivity intravascular contrast agents have removed the contribution of blood inflow to the observed signal, thereby improving contrast resolution. In turn, this has permitted decreases in the overall number of slices needed to display a large field of view (FOV) and has shortened overall image acquisition times (8). Fat suppression and the appropriate timing of data acquisition have eliminated the presence of unwanted signal from background tissues as well as venous (or arterial) enhancement. Additional increases in signal-to-noise ratio have been achieved using a phased-
array body coil (60). Finally, the routine use of targeted MIP images from the 3D volume data allows depiction of the vascular anatomy during the arterial or venous phases of contrast enhancement, although routine inspection of source images is advocated to decrease the likelihood of a misinterpretation due to artifact caused by the 3D reconstruction process itself. Alternatively, selected applications may benefit from volume- or surface-rendering techniques as well as virtual endoscopy.

Although arterial applications were the primary focus of earlier MRA studies (55,63,65–67), including depiction of aortic aneurysms and identification of renal artery stenosis, recent extension to venous applications (72,73) has yielded high quality imaging of the portomesenteric veins comparable with that achieved using conventional angiographic methods. In combination with extravascular information, staging of abdominal neoplasms and

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**TABLE 1.** Recommended single slice and multidetector protocol imaging parameter values employed on single slice helical CT (SS-CT) and multidetector row CT (MD-CT) scanners for evaluation of portomesenteric vasculature.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SS-CT</th>
<th>MD-CT</th>
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<tr>
<td>Slice thickness (mm)</td>
<td>3–5</td>
<td>1.25–2.5</td>
</tr>
<tr>
<td>Data reconstruction interval (mm)</td>
<td>1–3</td>
<td>1.25–2.5</td>
</tr>
<tr>
<td>Pitch</td>
<td>1.5:1–2:1</td>
<td>3:1–6:1</td>
</tr>
<tr>
<td>Oral contrast agent</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Intravenous contrast agent volume (ml) and type</td>
<td>NICM 350 mg of I/ml × 140–180 ml</td>
<td>NICM 350 mg of I/ml × 140–180 ml</td>
</tr>
<tr>
<td>Injection rate (ml/s)</td>
<td>4–5</td>
<td>4–5</td>
</tr>
<tr>
<td>Scan delay (s)</td>
<td>25</td>
<td>25 (arterial)</td>
</tr>
<tr>
<td>kV</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>mA</td>
<td>320</td>
<td>320</td>
</tr>
</tbody>
</table>

NICM, nonionic contrast medium.
postsurgical transplant complications can be accurately assessed (74). Delayed imaging provides additional views of the urinary tract.

Multiple well known technical factors pertaining to optimal utilization of 3D contrast-enhanced MRA techniques have been previously discussed (8,74–76) and can be generally categorized in terms of bolus timing characteristics, image acquisition parameters, data collection strategies, contrast dose optimization, breath-hold protocols, postprocessing techniques, MR-compatible devices, and patient positioning. While a detailed discussion addressing each of these technical factors is beyond the scope of this article, considerations specifically pertaining to evaluation of the portomesenteric vasculature, namely, bolus timing issues, multiphased vascular imaging, scanning acquisition parameters, contrast agent dose requirements, breath-holding, optimal patient positioning, and data processing, will be briefly addressed.

Bolus Timing Parameters. Accurate timing of the contrast agent bolus is essential for optimal implementation of 3D contrast MRA. If image acquisition is delayed relative to initiating contrast agent infusion, there will be relative enhancement of venous as compared with arterial structures. While this may be intentional in certain situations, for example, in the evaluation of the portal venous system, it is obviously not desirable when arterial structures are mainly of interest. Severe “ringing” or “banding” artifacts may also be seen with early imaging relative to the start of bolus infusion. Premature commencement of the imaging sequences relative to the arrival of the contrast agent bolus can produce artifacts simulating dissections, termed “Maki artifacts” (8,77). The start of data collection must therefore coincide with the presence of contrast agent in the vascular territory of interest. This will depend both on the length of contrast agent infusion as well as on precisely coordinating the start of bolus infusion with the onset of data collection (8,63). In turn, these parameters can be defined in relation to the Fourier image data acquisition, or k-space data, which defines features of the image. To obtain an arterial phase image, it is critical that central k-space data (“low” spatial frequencies dominating image contrast) be acquired during maximal arterial gadolinium concentration, which can be achieved with a bolus lasting one-half to two-thirds of the scan duration (8). This will yield improved image quality as a result of higher signal-to-noise and contrast-to-noise ratio data, permitting reductions in contrast agent dose. Larger signal increases, secondary to pronounced T1 shortening, may be achieved with a tighter bolus injection. However, rapid, time-varying concentration gradients during collection of the critical central portion of k-space may result in significant artifact production.

Timing of the bolus to exactly coincide with central

![FIG. 5. A 46-year-old man with known renal cell carcinoma and a history of extensive portomesenteric venous thrombosis. A: Coronal 3D contrast MR angiography image demonstrates a long thrombus within the superior mesenteric vein (arrows) that extends into the portal vein (arrowhead). The superior portion of an enlarged, heterogeneous mass (M) is seen arising from the right kidney. B: A more anterior image from the same series reveals the proximal extent of the clot in the portal vein (arrow). C: Thrombus additionally extends from the right renal vein (not shown) into the inferior vena cava to the level of the cavoatrial junction (arrows). (From ref. 19).](image-url)
k-space data acquisition mandates knowledge of the contrast agent travel time or time required for the bolus to travel from the site of injection to the vascular territory being considered. Issues relating to timing considerations for both long and fast (breath-hold) scans have been extensively detailed elsewhere (8). For breath-hold scans, several approaches to determining the optimal bolus timing have been previously discussed (8,77). In short, the least successful and reliable approach is the “best-guess” technique, which requires an estimation of the contrast agent travel time for determination of the imaging delay. More precise techniques have used a test bolus or an automatic triggering sequence that monitors the arrival time of contrast agent in the aorta before initiating imaging [e.g., MR SmartPrep (GE) is an automatic triggering sequence that samples a region of interest placed within the aorta at 20 ms intervals. A trigger threshold of 20% signal increase will detect the leading edge of the contrast agent bolus. The scan is usually initiated 5–6 s later] (78,79). In the latter instance, a centric acquisition is triggered, whereby central k-space is acquired at the start, rather than the midpoint, of data collection (80,81). This change in phase-encoding order is less affected by incomplete breath-holds and is less

**FIG. 6.** Postcontrast conventional MRI and 3D MR angiography in a 44-year-old man with a history of cryptogenic portosystemic venous thrombosis, portal hypertension, and esophageal varices. A: Noncontrast, axial gradient echo imaging demonstrates a large thrombus within the superior mesenteric vein (arrowhead). Thrombus is additionally present within the inferior mesenteric vein (not shown). B: Proximal to this level, large left retroperitoneal collaterals (arrows) are identified just adjacent to the posterior margin of the spleen (SP). C: Coronal 3D MR angiography from the source image data set illustrates marked splenomegaly (S) with evidence of portosystemic venous thrombosis. Individual source images are frequently noisy but are still helpful in distinguishing true defects from artifacts on maximum intensity projection and other 3D reconstructed images. An enlarged splenic vein (SV) is seen at the level of, and distal to, the splenic hilum. A large thrombus is identified within the midportion of the splenic vein (filled arrow). Dilated, tortuous collaterals (PV, portal vein) are present in the region of the porta hepatis, consistent with cavernous transformation and suggestive of chronic portal venous thrombosis. Thrombus is additionally present within the superior mesenteric vein (open arrow). D: A more anterior image from the same series demonstrates complete occlusion of the main portal vein (arrowhead). The intrahepatic portal veins are additionally occluded (not shown).
dependent on bolus timing considerations (77,82). Direct real-time visualization of the approaching contrast agent bolus can also be used to initiate imaging (MR fluoroscopy) in conjunction with centric phase encoding (83,84).

A final approach, ultrafast 3D MR digital subtraction angiography, is based on the rapid, sequential collection of 3D image data over a number (typically three to four) of phases. Each phase is an independent breath-hold and lasts \( \approx 10 \) s (85). The patient is allowed to breathe between phases. The first phase is obtained prior to contrast agent administration, and subsequent phases are obtained during arterial, venous, and equilibrium phases. A knowledge of the exact contrast agent travel time is therefore not necessary. This technique is variably known as multiphased dynamic MRA or time-resolved MRA. An additional advantage of this strategy is the increased temporal resolution, which provides information on the relative enhancement rates of structures within the FOV, facilitating detection of pathologic lesions and hemodynamically significant stenoses. The preinfusion image data set may be subtracted from arterial phase images to improve the contrast-to-noise ratio of arterial structures. This also reduces background signal and aliasing. For venous structures, increased conspicuity will be achieved by subtraction of arterial phase from equilibrium phase images. In practice, variations in breath-holding can yield misregistration artifacts, with venous phase subtraction results tending to be more useful (74).

**Venous Phase Imaging.** Splanchnic venous morphology can be demonstrated during the portal venous and early equilibrium phases of the arterial 3D contrast mesenteric MRA study. As these phases of the study are longer than the arterial portion of the exam, timing considerations are not of critical concern. Therefore, at least one more set of image data can be acquired, without additional contrast agent administration, following breath-hold arterial phase imaging in the coronal plane. A 5 to 10 s delay between phases allows the patient to breathe and is followed by suspension of respiration at the start of each imaging acquisition. A large imaging volume, extended sufficiently anteriorly, should be used to encompass the entire portal and mesenteric circulation. As the MRA study is acquired in the coronal plane, the patient’s arms should be extended out of the imaging plane or over the head for small FOV imaging without aliasing (63). Dedicated imaging of the splanchnic vasculature is typically performed using 40 ml of contrast agent (0.2–0.3 mmol/kg). Additional dosing considerations relate to progressive dilution and redistribution of contrast agent within the extracellular compartment during its passage through the capillary bed, with concomitant increases in the intravascular T1. Rather than increase the initial contrast agent dose to offset signal losses, decreased flip angles (i.e., 30° rather than 45°) have been used in some instances, although this not only tends to delay initiation of venous phase imaging but may produce some loss of image contrast.

**Scanning Acquisition Parameters.** Shortening of the image acquisition time can be achieved in several ways (8). The TR or scan resolution can be decreased. A wider receiver bandwidth may be used, with a commensurate reduction in signal-to-noise ratio. Reductions in matrix size, in either the phase-encode or the slice-select directions, can be made at the expense of resolution. To decrease scan time without a loss of resolution, an asymmetric (rectangular) FOV is sometimes used at the expense of a decreased FOV (8,77). Partial Fourier techniques (fractional number of excitations), which allow reconstruction of a 3D volume of image data without having a complete set of Fourier image data, do not affect TR or decrease resolution but permit reductions in acquisition time at the cost of decreased signal-to-noise ratio. Decreased image acquisition time as well as improvements in reconstructed spatial resolution can also be achieved with a zero-filling interpolation scheme. Such a strategy expands the periphery of k-space with zeros prior to Fourier transformation, leaving only central k-space to be filled. As previously mentioned, it is the contrast information in central k-space that is critical.

In general, a short TR and TE should be selected that will not effect large increases in the bandwidth, as this will significantly reduce the signal-to-noise ratio. To maintain a narrow bandwidth, TEs on the order of 2–2.5 ms are optimal (at 1.5 T). This will reduce dephasing and susceptibility artifact as well as contribute additional fat suppression. A short TR will reduce the overall examination time at the expense of signal-to-noise ratio, although this may be offset by rapidly injecting a higher contrast agent bolus (77). Finally, trade-offs in volume coverage, resolution, and breath-holding time require the number of slices and phase-encode steps to be balanced (77). As noted in the preceding discussion, reductions in imaging times using partial Fourier imaging can additionally be implemented to further optimize volume coverage.

**Extravascular Imaging.** Conventional fast spin echo or gradient echo imaging will usually be performed prior to contrast agent injection for evaluation of suspected extravascular pathology. In addition to identifying and characterizing potential masses, these sequences serve to define the extent of the abnormality for inclusion in the 3D contrast MRA study.

**Advantages/Limitations.** While 3D contrast-enhanced MRA is similar to contrast-enhanced helical CTA, there are several advantages of the former, which have been detailed previously (8,19). These include 1) the use of paramagnetic agents, which are not nephrotoxic and are associated with a decreased frequency of allergic reactions compared with iodinated contrast agents (64); 2) the multiplanar capability of MR, allowing the imaging plane of acquisition to be tailored to the vascular territory under consideration; 3) simpler 3D reconstruction of projection images from the 3D MRA data set (8), and 4) absence of ionizing radiation. However, as MRA indirectly relies on detection of vascular signal, degradation of signal related to turbulence can be observed. Spatial
resolution is lower compared with CTA. Additional limitations are applicable mainly to arterial imaging, namely, decreased sensitivity for detecting calcification and reduced ability to visualize stented vessels.

**MRI/MRA Protocols.** Indications for utilizing a portomesenteric MRA protocol include abdominal pain (particularly postprandial pain), pre-/postoperative liver transplantation workups, preoperative mesenteric vascular mapping and postsurgical vascular bypass evaluation, and weight loss. As detailed below, typical protocols routinely use 3D contrast-enhanced MRA and 2D TOF sequences and may use T1- and T2-weighted spin echo or gradient echo sequences for depiction of extravascular anatomy or pathology (Fig. 6). Recommended ranges of parameter values typically used in 2D TOF and 3D contrast-enhanced MRA protocols for evaluating the portomesenteric vasculature are shown in Table 2.

A sagittal localizer is initially obtained. On echo planar magnets, a single shot fast spin echo sequence eliminates the breath-holding requirement and provides optimal views of the hepatobiliary system. Alternatively, a fast multplanar spoiled gradient echo or spin echo black blood sequence may be used. A fat-suppressed axial T1-weighted sequence may then be acquired to identify or characterize liver masses, inflammatory processes, and portal venous abnormalities. Performance of an axial T1-weighted sequence may be useful for evaluating retroperitoneal pathology or features of cirrhosis. Coronal 3D gadolinium-enhanced MRA can then be obtained using 0.3 mm/kg Gd-DTPA. Following arterial phase imaging, the patient is instructed to take three to four breaths prior to initiation of venous phase imaging. An equilibrium phase set of images can also be acquired after a short breath-holding interval. This can be followed by non-breath-hold 2D TOF postgadolinium imaging with respiratory compensation, which provides additional images of the portosystemic venous vasculature and potential extravascular pathology. Total imaging time, typically 30–45 min, is considerably longer than with CTA. However, this protocol can be tailored appropriately for a specific clinical application. In cases of suspected mesenteric ischemia, these can be supplemented with cardiac or peripherally gated 3D PC MRA for evaluation of blood flow within the SMA and SMV. Typical cine PC sequence parameters are listed in Table 3.

### Other Imaging

Radiographic findings of bowel ischemia or infarction using plain films or barium are usually nonspecific and are of limited utility in diagnostic evaluation. Doppler ultrasonography allows direct evaluation of the mesenteric and portal veins, provides semiquantitative flow information, and permits Doppler waveform analysis of the visceral vessels but is limited by its operator dependency, insensitivity to slow flow, and absence of a suitable acoustic window if overlying bowel gas is present. At the present time, this modality is less sensitive than CT or MR for detection of splanchnic vein thrombosis, particularly for evaluation of the splenic and superior mesenteric veins. In the future, substantial improvement in the sonographic evaluation of portal or mesenteric venous thrombosis might be achieved with ultrasound-compatible intravascular contrast agents and gray scale harmonic imaging. Angiographic procedures, including transhepatic portal venography, direct splenoportography, and late phase superior mesenteric angiography, are invasive, may be limited by flow dynamics, and require the use of potentially nephrotoxic iodinated contrast material and ionizing radiation. These techniques are usually reserved for inconclusive findings on noninvasive imaging and may be used, in select cases, in conjunction with transcatheter therapeutic techniques for management of symptomatic portomesenteric venous thrombosis.

### TABLE 2. MR venography technique for portomesenteric venous evaluation using 2D TOF and 3D contrast-enhanced MR angiography

<table>
<thead>
<tr>
<th>Options</th>
<th>2D TOF (SPGR)</th>
<th>3D contrast-enhanced (SPGR)</th>
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<tbody>
<tr>
<td>Scan timing</td>
<td></td>
<td></td>
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<tr>
<td>TR (ms)</td>
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<td>FOV (cm)</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>Phases</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Breath-hold</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

### TABLE 3. MR venography technique for portomesenteric venous evaluation using 3D PC MR angiography

<table>
<thead>
<tr>
<th>Options</th>
<th>3D PC (SPGR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td></td>
</tr>
<tr>
<td>TR (ms)</td>
<td>25</td>
</tr>
<tr>
<td>TE (ms)</td>
<td>10</td>
</tr>
<tr>
<td>Flip angle (°)</td>
<td>30</td>
</tr>
<tr>
<td>Slice thickness (mm)</td>
<td>5</td>
</tr>
<tr>
<td>Contrast agent</td>
<td>None</td>
</tr>
<tr>
<td>Plane of acquisition</td>
<td>Axial</td>
</tr>
<tr>
<td>Coil</td>
<td>Surface/phased array</td>
</tr>
<tr>
<td>Matrix size</td>
<td>100</td>
</tr>
<tr>
<td>NEX</td>
<td>10</td>
</tr>
<tr>
<td>FOV (cm)</td>
<td>24</td>
</tr>
<tr>
<td>Phases/cardiac cycle</td>
<td>16</td>
</tr>
<tr>
<td>Flow encoding (venc)</td>
<td>Through-plane (cm/s)</td>
</tr>
<tr>
<td>Postprandial</td>
<td>150</td>
</tr>
</tbody>
</table>

Resp comp, respiratory compensation; venc, velocity encoded value.
SUMMARY AND FUTURE DIRECTIONS

Traditionally, conventional angiography has been the gold standard for assessment of the splanchnic vasculature. Noninvasive diagnosis using Doppler sonography is limited principally by the inability to visualize vascular anatomy in the presence of overlying bowel gas, fat, or vessel wall calcification. More recently, the development of multidetector CTA and 3D contrast-enhanced MRA protocols has permitted volumetric acquisitions in a single breath-hold, providing superior temporal and contrast resolution of the portomesenteric circulation. In addition, the ability to obtain both morphologic and functional information in a single examination is cost-effective compared with arteriographic assessment. The clinical utility and diagnostic accuracy of CTA and MRA techniques have become competitive with those of arteriographic procedures in the evaluation of the main splanchnic vasculature and should be the initial diagnostic methods used in cases of suspected nonsurgical mesenteric ischemia. A minor limitation is the slightly inferior spatial resolution of these cross-sectional techniques compared with selective angiographic methods when evaluating the distal mesenteric branch vessels. However, continuing improvements in temporal and spatial resolution are expected using newer multidetector CT scanners with increased detector number (8–24), acquisition speeds, and thinner slice collimation (0.5 mm) (25). In addition, increased detector efficiency and pitch, coupled with decreased milliampere-seconds, will minimize cumulative radiation exposure. Paralleling advances in CTA technology is the current development of MRA strategies to increase acquisition speeds. These include manipulation of k-space (i.e., keyhole imaging and time-resolved imaging of contrast kinetics, or TRICKS), utilization of alternative imaging methods (echo planar imaging), and reduction of phase-encoding steps using the spatial information derived from phased-array coil elements (74).

REFERENCES

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