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CLINICAL IMAGING

The Role of Noninvasive Vascular Imaging in Splanchnic and Mesenteric Pathology

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Traditionally, catheter angiography (CA) has been the mainstay of diagnosis for mesenteric arterial diseases. However, CA is invasive and is associated with complications that result from the procedure itself, depending on the experience of the operators, site of vascular access, ionized radiation that could be significant when combined with interventional procedures, and administered contrast material. During the past 2 decades, technical improvements in computed tomography (CT) and magnetic resonance hardware and methods have contributed new, noninvasive tools, specifically CT angiography (CTA) and 3-dimensional gadolinium-enhanced magnetic resonance angiography (3D Gd-MRA). This article outlines the current applications, strengths, and weaknesses of CTA and 3D Gd-MRA in imaging of the mesenteric vessels.

Techniques

For accurate grading of a luminal narrowing and depiction of small arteries, the volumetric data must be acquired with submillimeter isotropic or near isotropic voxel size. In-plane resolution of a computed tomography (CT) image is typically 0.5–0.7 mm. The longitudinal resolution is determined by the collimation. Thinner collimation provides higher spatial resolution in the longitudinal axis. Breath-hold imaging of a large anatomic region with submillimeter longitudinal resolution requires a CT scanner with fast gantry rotation. High-speed multi-detector CT (MDCT) systems allow simultaneous acquisition of 4 or more slices during a single gantry rotation of less than 0.5 seconds. As a result, today it is possible to obtain high spatial resolution mesenteric CT angiography (CTA) with submillimeter isotropic voxels that allow the depiction of the mesenteric arteries down to second-order branches and accurate grading of occlusive diseases during a single breath hold.

Meanwhile, 3-dimensional gadolinium-enhanced magnetic resonance angiography (3D Gd-MRA) has also evolved into standard of care in many diseases of the aorta and visceral branches. Some of the earliest studies have demonstrated a sensitivity and specificity of greater than 95% with 3D Gd-MRA in the evaluation of the proximal segments of the mesenteric arteries.[1–12] However, most authors have concluded that the spatial resolution of 3D Gd-MRA was too low for a reliable delineation and assessment of the small distal branches and inferior mesenteric artery. New MR scanners equipped with stronger gradients and parallel imaging techniques allow at least twice as fast imaging acquisitions, which partially overcomes this problem. Today, near isotropic 3D imaging with submillimeter voxel size of certain vascular territories is possible within a single breath hold.[13]

Catheter angiography (CA) is still superior to CTA and 3D Gd-MRA because of its excellent in-plane spatial resolution of 0.3×0.3 mm^2.[14]

The volumetric imaging capability of CT and MR has also led to the development of postprocessing techniques such as multiplanar reformation, maximum intensity projection (MIP), curved planar reconstruction, and volume rendering (VR). These techniques allow the production of images similar in appearance to CA. Compared with the limited number of imaging projections obtained with CA, isotropic CTA or 3D Gd-MRA datasets can be reformatted in any imaging plane. Specifically, MIP or MPR images perpendicular to the course of the artery allow precise assessment of the vessel lumen area at the site of stenosis. When combined with multiplanar reconstructions, CTA and 3D Gd-MRA might actually be more accurate than CA in the evaluation of the eccentric or irregular plaques and thrombosed dissection lumen, which can be underestimated or missed completely with CA.[13] The 3D MIP and VR reconstructions are useful to remove venous superimposition, and particularly preferable for demonstrating the collateral mesenteric circulation and the 3D relationship between the vessels and the abdominal organs and to demonstrate collateral mesenteric circulation.

Precontrast CT imaging might be required for detecting acute portal/mesenteric venous thrombosis (Figure 1) and fresh blood within the bowel lumen in patients with suspected gastrointestinal bleeding. Comprehensive CTA and 3D Gd-MRA protocols should include postcontrast portal and delayed venous phase imaging in addition to the arterial phase. Delayed phase images are required for the evaluation of portomesenteric and systemic veins as well as the dissections and aneurysms. Slow flow within a pseudoaneurysm or the false lumen of a

Abbreviations used in this paper: **AMI, acute mesenteric ischemia; APF, arterioportal fistula; CA, catheter angiography; CMI, chronic mesenteric ischemia; CT, computed tomography; CTA, computed tomographic angiography; MDCT, multi-detector computed tomography; MIP, maximum intensity projection; SMA, superior mesenteric artery; SMV, superior mesenteric vein; 3D Gd-MRA, three-dimensional gadolinium-enhanced magnetic resonance angiography; US, ultrasonography; VAA, visceral artery aneurysm; VR, volume rendering.**

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dissection can only be appreciated on delayed phases. Postcontrast equilibrium phase imaging is helpful for demonstrating organ perfusion patterns, vascular and nonvascular masses, arteriovenous malformations and fistulas, and perivascular inflammation associated with vasculitic syndromes.

Clinical Applications of Mesenteric Catheter Angiography and Magnetic Resonance Angiography

Variant Anatomy of the Splanchnic and Mesenteric Arteries and Veins

The conventional textbook description of a celiac trunk having 3 branches (hepatic, left gastric, and splenic) occurs in only 55% of the population.[15] Anatomic variations might alter the surgical approach in hepatobiliary and pancreaticoduodenal surgeries, liver transplantations, laparoscopic procedures, retroperitoneal mass resection, surgical shunting, and hepatic arterial infusion chemotherapy of advanced liver malignancies.[16–19] CTA is an excellent imaging technique in the assessment of the hepatic arteries up to their second-order branches (Figure 2) and the portal and hepatic venous anatomy.[20–23]

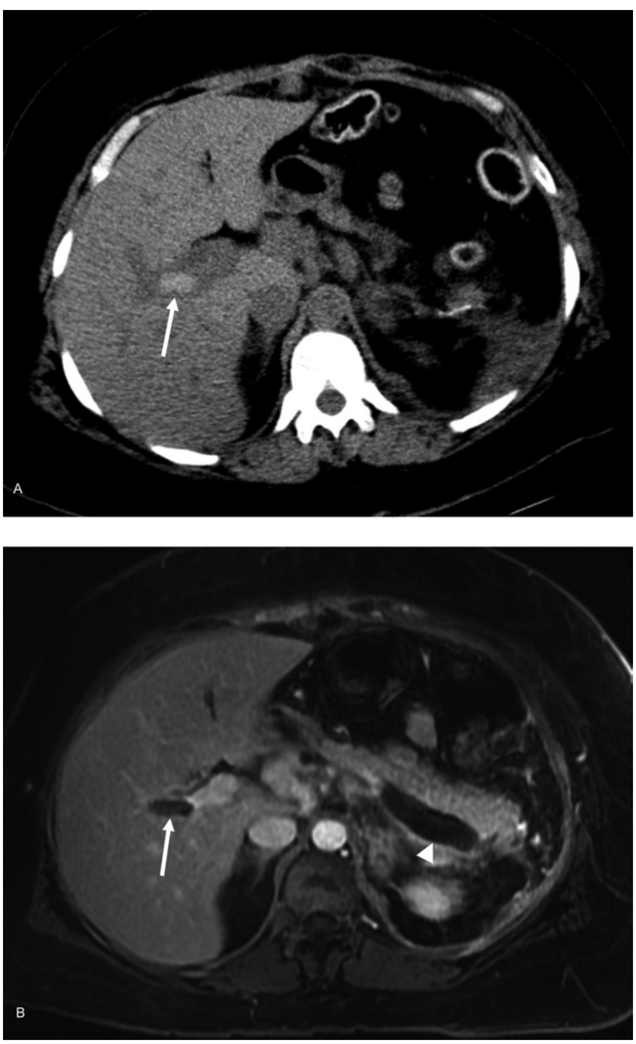

Figure 1. A 44-year-old woman with history of lymphoma and splenectomy presented with abdominal pain. (*A*) Precontrast CT study demonstrates hyperdensity within the right portal vein suggestive of acute thrombosis (*arrow*). (*B*) Axial post-contrast T1-weighted and fat-suppressed equilibrium phase MR image confirms the filling defect within the portal vein (*arrow*) as well as the splenic vein (*arrowhead*).

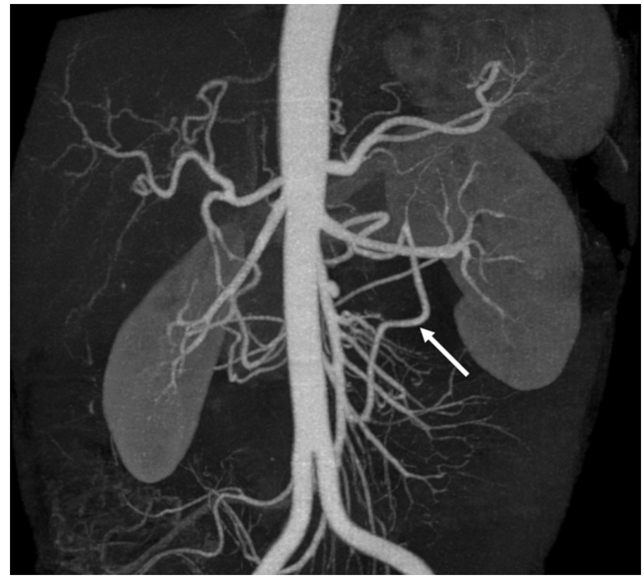

Figure 2. A 46-year-old woman, preoperative CTA study for potential liver donor. Scans were acquired with 64-slice MDCT at 100 kV and 120 mA. Coronal 3D MIP reconstruction demonstrates normal anatomic pattern of the splanchnic and mesenteric arteries. The arch of Riolan connecting the inferior mesenteric artery and middle colic branch of the SMA is also visualized (*arrow*).

Figure 3. A 66-year-old woman with arteriolosclerosis and end-stage renal failure on dialysis. A CTA study was obtained to determine the patency of the pelvic vessels for kidney transplantation. Axial CT images were acquired during breath hold in inspiration. Sagittal MIP reconstruction demonstrates the diaphragmatic crura causing wedge-shape indentation (*white arrow*) to the cranial aspect of the celiac trunk (median arcuate ligament syndrome) and associated moderate (50%–70%) diameter stenosis of the celiac trunk, compared with the normal proximal vessel segment. SMA is widely patent (*open black arrow*).

Figure 4. CTA of an 84-year-old woman with a history of atrial fibrillation presented to the emergency department with severe abdominal pain and vomiting. Sagittal MIP image shows near complete thrombosis of the celiac trunk and the proximal segment of the SMA (*arrows*).

Three-dimensional Gd-MRA is also highly accurate in depicting the anatomic variations of the celiac trunk and hepatic arteries as well as variant venous anatomy.[24,25]

Postoperative Surveillance of Liver Transplant

Vascular complications are seen in approximately 9% of liver transplant recipients.[26] The most common vascular complication is hepatic artery thrombosis, accounting for approximately 60% of all cases.[27] The hepatic artery is the sole vessel that supplies the biliary system. Therefore, acute hepatic artery thrombosis can lead to ischemic biliary complications such as liver failure, hepatic necrosis, ischemic cholangiopathy, cholangitis, and septic shock. Doppler ultrasonography (US) is the first-line screening method for vascular complications after liver transplantation. False-positive diagnosis of hepatic artery thrombosis with US might occur with markedly diminished hepatic artery flow caused by severe hepatic edema, systemic hypotension, or high-grade hepatic artery stenosis or with suboptimal US examinations. Microbubble contrast-enhanced US has been suggested as an alternative imaging technique and has been shown to improve flow visualization in hepatic arteries.[28] When Doppler US or contrast-enhanced US findings are inconclusive, CTA and 3D Gd-MRA are extremely helpful noninvasive imaging tools.

Chronic Mesenteric Ischemia

Chronic mesenteric ischemia (CMI) is most commonly associated with atherosclerosis involving the proximal segments of visceral arteries, but it can also be a manifestation of nonatherosclerotic disorders, such as median arcuate ligament syndrome (Figure 3), aortic dissection, isolated dissection of the visceral arteries, vasculitic syndromes, and connective tissue disorders.

Most patients with ischemic symptoms have compromised blood flow in at least 2 of 3 mesenteric arteries.[29] Both CTA and 3D Gd-MRA can accurately detect and grade a stenosis within the mesenteric arteries up to their second-order branches and successfully demonstrate prominent arterial connections. However, the relationship between the vascular obstruction and the decline in intestinal perfusion may not be appreciated just on the basis of angiographic stenoses. Qualitative and quantitative flow measurements with cine phase-contrast MR from superior mesenteric artery (SMA) and superior mesenteric vein (SMV) can provide a more confident diagnosis of the CMI. A reciprocal correlation between the degree of stenosis in the SMA and the flow augmentation after a caloric stimulation has been reported.[30] Additional cine imaging of the SMV can provide a more accurate assessment of global mesenteric blood flow, because mesenteric venous drainage occurs predominantly through

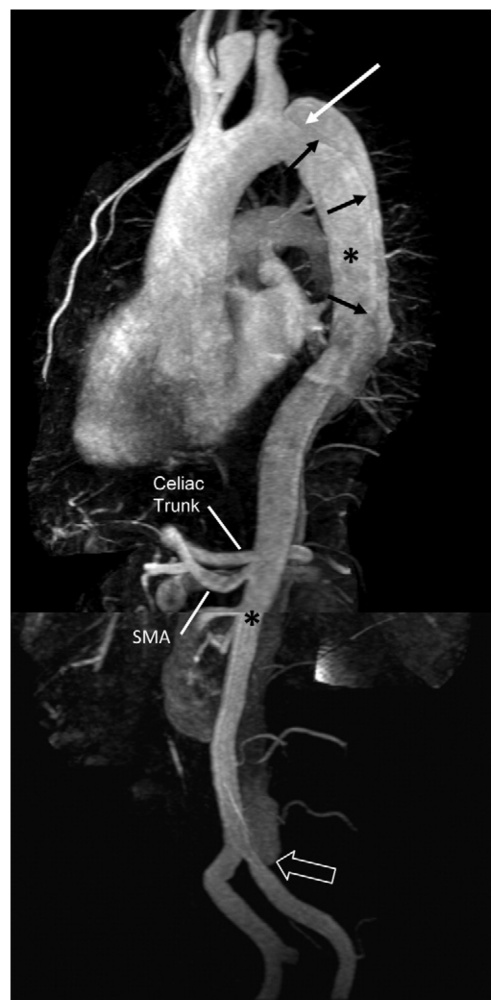

Figure 5. A 67-year-old man with long history of hypertension. Two-station 3D Gd-MRA of the thoracic and abdominal aorta shows a type B aortic dissection. Entry site is just below the orifice of the left subclavian artery (*white arrow*). Reentry site is the left common iliac artery origin (*open arrow*). Dissection flap (*black arrows*) separates true and false lumens. True lumen (*) is identified on the basis of its continuation with the aortic arch, higher intensity on arterial phase images, and the absence of thrombus. Both the celiac trunk and the SMA originate from the true lumen.

the SMV (unless there is a concomitant venous occlusion). Thus, the blood flow within the SMV reflects blood supply via a stenotic SMA and arterial collaterals.[31]

Acute Mesenteric Ischemia

Acute mesenteric ischemia (AMI) presents with abrupt onset of severe abdominal pain. Irreversible bowel damage might occur within 6–8 hours after the vascular insult. Four major causes of AMI are SMA emboli (30%–50%), SMA thrombosis (15%–30%), acute mesenteric vein thrombosis (5%–10%), and nonocclusive mesenteric vasoconstriction (20%–30%).[29] Emboli usually originate from left atrial or ventricular mural thrombus. Acute mesenteric artery thrombosis is typically associated with a preexisting atherosclerotic lesion and demonstrates a more silent clinical scenario compared with an embolic event, owing to the development of collateral circulation[32–34] (Figure 4). Acute thromboembolic occlusion of the celiac trunk or the inferior mesenteric artery usually does not cause bowel ischemia.[29] Nonocclusive mesenteric ischemia usually develops as a result of vasoconstriction of the mesenteric arteries during an episode of cardiogenic shock or a state of hypoperfusion.[35] In the case of suspected AMI, particularly in nonocclusive ischemia, CA is the first-line imaging modality because it permits accurate diagnosis and therapeutic interventions. CT is fast and readily available; therefore, it can be used in emergency settings. Indirect findings of AMI can be signs of other abdominal pathologies. The sensitivity of CT alone in the diagnosis of small bowel ischemia is only 14.8%–33.3%.[36] CTA significantly improves the confidence in the diagnosis of AMI.[37–39] MRA is not a feasible imaging tool in hemodynamically instable patients and currently does not offer sufficient resolution to demonstrate nonocclusive low-flow states or distal emboli.

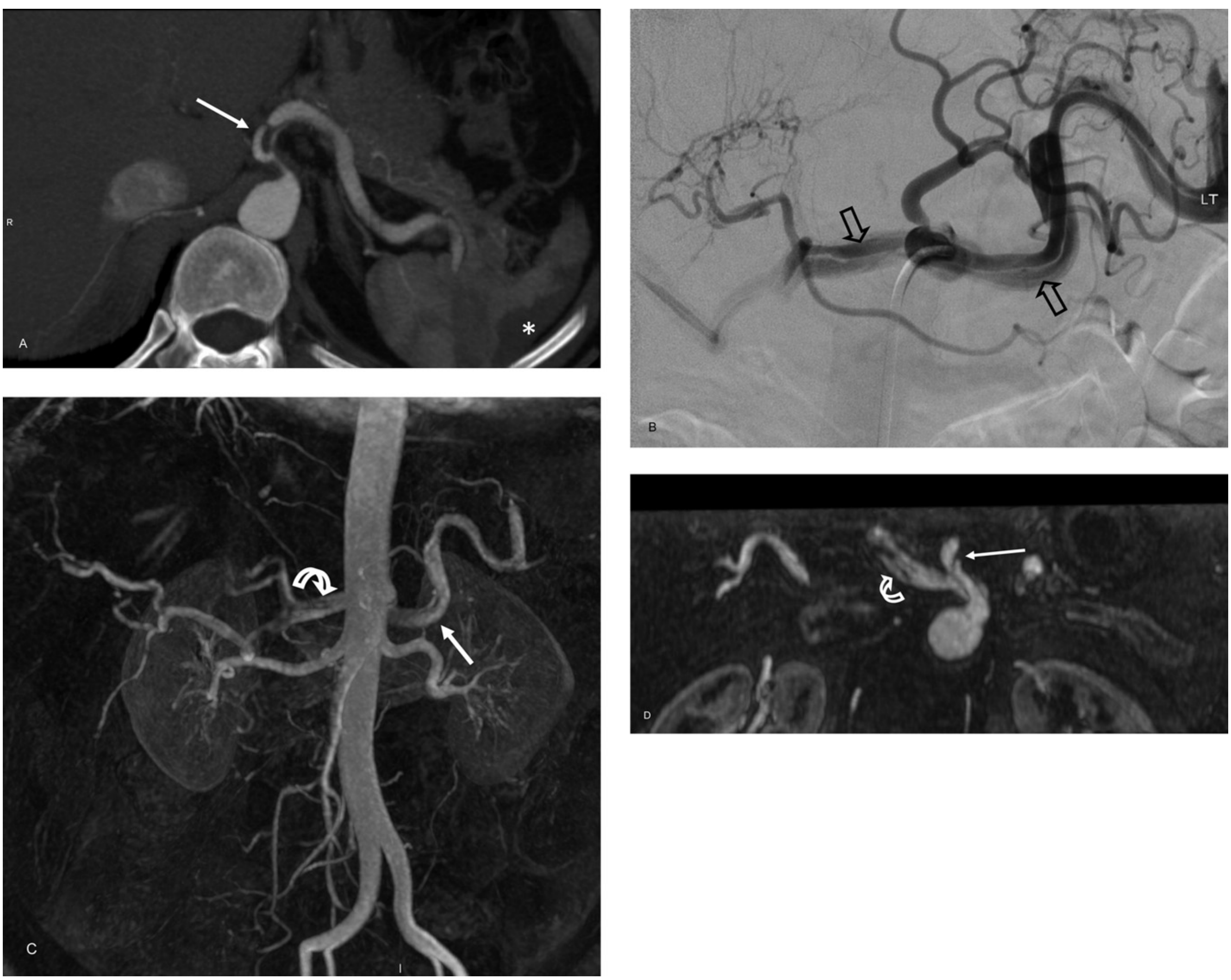

Figure 6. A 44-year-old man with a diagnosis of Ehlers-Danlos syndrome presented to emergency department with chest pain radiating down to the abdomen. (*A*) CTA shows dissection of the celiac trunk and partial thrombus within the false lumen (*arrow*). Note the wedge-shaped perfusion defect in the spleen (*). (*B*) Elective CA for peripheral vascular evaluation confirms the evidence of celiac trunk dissection as well as splenic and common hepatic artery involvement seen as a lucent line in the contrast within the artery (*open arrows*). (*C*) Coronal and (*D*) axial MIP images obtained from the follow-up 3D Gd-MRA also successfully demonstrate the extension of the dissection into common hepatic (*curved arrow*) and splenic arteries (*straight arrow*).

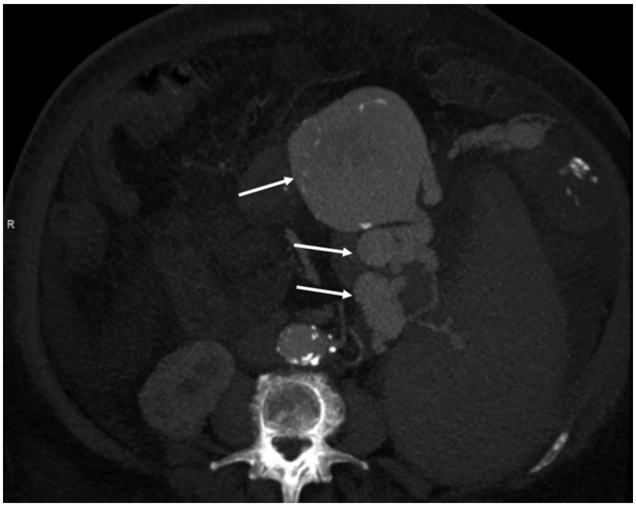

Figure 7. An 83-year-old woman with a long history of portal hypertension and splenomegaly. Axial MIP image of CTA shows multiple aneurysms of the splenic artery with focal wall calcifications.

Surveillance of Grafts and Stents for Acute Mesenteric Ischemia and Chronic Mesenteric Ischemia

Both surgical and endovascular treatments are subject to early or late failure and thus require close clinical and imaging follow-up. Early graft thrombosis and intestinal infarction occur in approximately 5% of patients.[40,41] Routine mesenteric CA after intervention for mesenteric ischemia and before recommencing oral intake is recommended to confirm patency of the graft and provide early intervention where necessary.[42] Stenosis usually develops within the first 3–6 months after surgery. Advanced stages of intimal hyperplasia can ultimately lead to graft thrombosis. In approximately 20% of the patients treated with percutaneous transluminal angioplasty and stent placement or open surgery, a secondary intervention is required.[43] CTA and 3D Gd-MRA are the most suitable noninvasive techniques for long-term follow-up of the graft and stent patency.[44–46]

Figure 9. An 82-year-old woman with a history of hypertension and carotid artery stenosis was admitted to the hospital for work-up of recurrent transient ischemic attack-like symptoms, abdominal pain, and elevated blood lactate levels. Carotid MRA is diagnostic as well. The 3D MIP image of 3D Gd-MRA demonstrates characteristic string-of-beads appearance of fibromuscular dysplasia in the right renal artery (*) and SMA branches (*arrows*).

Figure 8. A 57-year-old man with a history of alcohol abuse and chronic pancreatitis presented with acute abdominal pain and fever. (*A*) Axial arterial phase CTA image demonstrates a pseudoaneurysm of gastroduodenal artery (*arrow*). Note the slow filling of the partially thrombosed portion of the pseudoaneurysm (*). (*B*) CA shows the saccular pseudoaneurysm with a narrow neck (*open arrow*).

Aortic Dissection

Both CMI and AMI can be a manifestation of aortic dissection. When the visceral artery originates from the false lumen, slow flow or thrombosis of the false lumen can lead to visceral organ ischemia. Both CTA and 3D Gd-MRA are excellent noninvasive imaging tools for complete and dynamic display of aortic dissection and branch vessel involvement. Most recent published data on MDCT show it to have sensitivity and specificity of 99% and 100%, respectively, for detection of aortic dissection.[47] The reported sensitivity and specificity of 3D Gd-MRA are higher than 95%[48] (Figure 5).

Isolated Dissections of the Visceral Arteries

Isolated dissection of the visceral arteries is very rare. The SMA is the most frequent site of isolated dissection. Pathogenesis of SMA dissection is unknown in most cases. Some authors reported a relationship with atherosclerosis, hypertension, compensatory flow increase in SMA caused by the severe stenosis of the celiac trunk, cystic medial necrosis, fibromuscular dysplasia, systemic sclerosis, and segmental mediolytic arteriopathy. CTA has been proved to be as accurate as CA in evaluating the location and extent of dissection.[49,50] In fact, CA might fail to show a dissection if the false lumen is completely

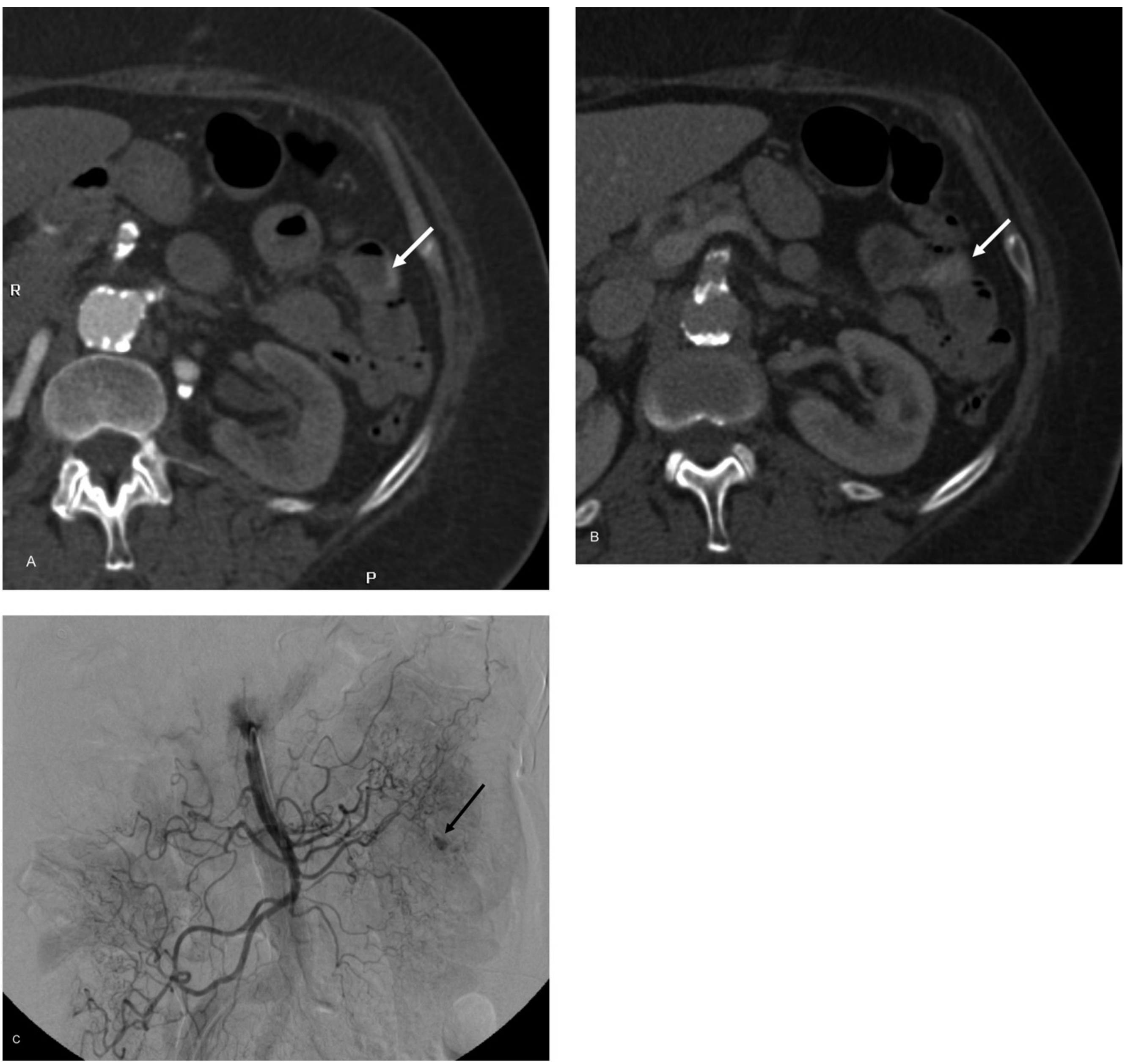

Figure 10. A 70-year-old woman with atrial fibrillation on Coumadin therapy admitted to the emergency department. Physical examination revealed red blood per rectum. Mesenteric CTA was obtained. (*A*) Arterial phase image shows hyperdense material (*white arrow*) within the jejunum lumen. (*B*) Late venous phase axial CT image demonstrates increased amount of hyperdense material, which was predictive of active contrast extravasation into the jejunum lumen. (*C*) Selective SMA catheterization confirms the evidence of active gastrointestinal hemorrhage in the proximal jejunum (*black arrow*).

Figure 11. Simultaneous demonstration of hepatic, portal, splenic, and mesenteric veins with MR venogram on a 66-year-old man.

thrombosed.[50] MRA can also successfully demonstrate a mesenteric artery dissection (Figure 6). On the other hand, CA is superior to both CTA and MRA in evaluating the collateral flow and the relationship of the dissection to distal branches, owing to its better spatial resolution.

Visceral Artery Aneurysms

The most common location of visceral artery aneurysms (VAAs) is the splenic artery, accounting for 60%–80% of the cases. Splenic artery aneurysms are commonly associated with medial dysplasia, multiple pregnancies, portal hypertension, and liver transplantation. They are more frequent in women (Figure 7). The second most common location of VAA is the hepatic artery, constituting about 20% of cases. Hepatic artery aneurysms are usually extrahepatic and are more frequent in men. Intrahepatic aneurysms usually develop as a result of trauma or percutaneous interventions. SMA aneurysms account for 5.5% of cases and are frequently associated with endocarditis. It can also develop as a result of atherosclerosis or pancreatitis. Aneurysms of the pancreatic and gastroduodenal arteries (10% of the cases) are rare and are usually a complication of pancreatitis (Figure 8). VAAs involve the celiac artery in 4%, the jejunal and ileocolic arteries in 3%, and the inferior mesenteric artery in less than 1%.[51–53] Fibromuscular dysplasia can cause multiple small aneurysms in the mesenteric arteries. Both CTA[52] and 3D Gd-MRA[53] are powerful tools for diagnosis and treatment planning in patients with VAA as well as the postprocedural follow-up (Figure 9).

Active Gastrointestinal Bleeding

CTA can depict an active gastrointestinal bleeding with a rate of 0.3 mL/min.[54] Yoon et al[55] reported an accuracy of approximately 98% with CTA in determining the location of the hemorrhage. Scheffel et al[56] have reported that the sensitivity of dual phase CT in the identification of bleeding sources was 83% in patients with severe and moderate gastrointestinal hemorrhage, and dual phase CT detected the underlying pathology in 78% of the patients[56] (Figure 10).

Intrahepatic and Extrahepatic Arterioportal Fistula

Arterioportal fistula (APF) is a vascular communication between the systemic arteries (in most cases, mesenteric arteries) and the portal vein. APF is usually associated with decreased arterial blood flow to the tissue beyond the fistula and increased venous pressure distal to the fistula. Approximately 50% of patients with splanchnic APF develop portal hypertension.[57] The prevalence of portal hypertension with peripheral APFs involving the splenic and mesenteric arteries is 30%.[58] APFs rarely cause arterial steal phenomenon between the celiac axis and the SMA, particularly when there is portal hypertension, and induce mesenteric ischemia.[57,59] Time resolved 3D Gd-MRA can demonstrate contrast passage from the artery to the portal venous system.[60]

Computed Tomographic Angiography and Three-Dimensional Gadolinium-Enhanced Magnetic Resonance Angiography in Venous Pathologies

The role of CA in venous imaging of the mesentery is limited. In comparison with CTA and 3D Gd-MRA, CA does not provide sufficient contrast enhancement of the portal system via arterial catheterization and thus cannot display the portal system and collateral vessels simultaneously (Figure 11). Multiphase CTA and 3D Gd-MRA have supplanted CA in the diagnosis and surgical planning of many venous pathologies. Both can readily determine a variety of venous disorders such as mesenteric, splenic, and portal vein thromboses, cavernous transformation of the portal veins, portosystemic shunts (Figure 12), hepatic vein and inferior vena cava obstructions,

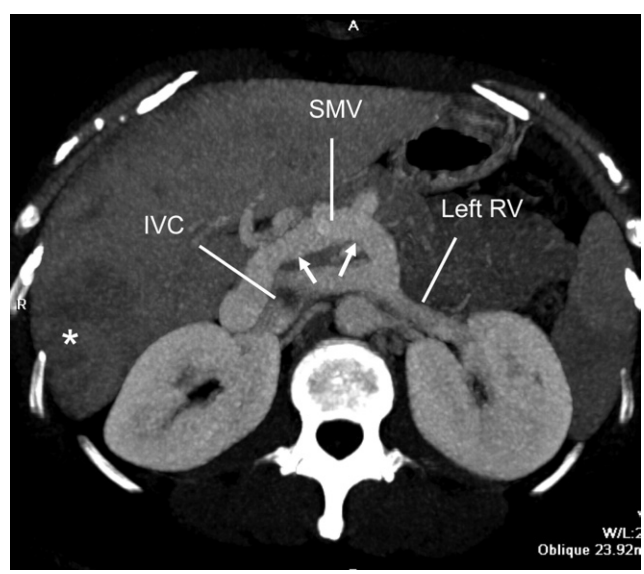

Figure 12. A 38-year-old woman with history of multiple aortic surgeries and cardiac arrhythmia underwent follow-up CTA study for splenic artery aneurysm and chronic occlusion of the splenic and portal veins. Axial MIP image of portal venous phase shows large venous shunts (*arrows*) between the SMV and the inferior vena cava (*IVC*) and SMV and the left renal vein (*RV*). Note the inhomogenous and delayed parenchymal enhancement of the liver (*) on the arteriovenous phase.

portal/mesenteric thrombophlebitis, and Budd-Chiari syndrome.

Portal vein thrombosis is usually associated with cirrhosis or primary and secondary hepatobiliary malignancy, but it can be a result of major abdominal infectious or inflammatory diseases or myeloproliferative disorders. Liver transplantation has become an emerging etiologic factor for portal vein thrombosis.

Clinical manifestations and treatment options of portal vein thrombosis are strongly associated with the involvement of the mesenteric veins or the peripheral segments of the portal vein.[61] In 50% of cases, cavernous transformation of the portal vein is already present at diagnosis.[62] Acute mesenteric venous thrombosis can lead to AMI.[63,64] Preoperative assessment of the patency and 3D display of the portal system including collateral vessels, mesenteric veins, renal veins, and inferior vena cava are extremely important for treatment planning. Acute portal thrombosis without involvement of too many branches can be treated by interventional thrombolysis via the SMV. If there is no involvement of the distal intrahepatic branches, surgical portosystemic shunt placement is used. Patent splenic veins or a SMV with long trunk and few branches can be used for portosystemic shunt operations.

CTA and 3D Gd-MRA accurately determine the extension of thrombosis, portosystemic shunts, and cavernous transformation of the portal vein. The 3D MIP or VR displays of angiograms are useful for depicting the anatomic relation between the portal venous bifurcation and the right hepatic vein to guide the portal vein puncture for transjugular intrahepatic portal shunt placement. Both CTA and 3D Gd-MRA can be used for monitoring the patency of surgical or percutaneous portosystemic shunts, the effects of sclerotherapy, and venous complications after liver transplantation.[65,66]

Conclusion

CTA and 3D Gd-MRA are reproducible, highly sensitive, and specific noninvasive imaging tools in the diagnosis and pretreatment evaluation of large and medium-size splanchnic/mesenteric arteries and portal/mesenteric veins.

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Conflicts of interest

The author discloses no conflicts.