Three-dimensional MDCT angiography of splanchnic arteries: Pearls and pitfalls

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Abstract  Fast scanning along with high resolution of multidetector computed tomography (MDCT) have expanded the role of non-invasive imaging of splanchnic arteries. Advancements in both MDCT scanner technology and three-dimensional (3D) imaging software provide a unique opportunity for non-invasive investigation of splanchnic arteries. Although standard axial computed tomography (CT) images allow identification of splanchnic arteries, visualization of small or distal branches is often limited. Similarly, a comprehensive assessment of the complex anatomy of splanchnic arteries is often beyond the reach of axial images. However, the submillimeter collimation that can be achieved with MDCT scanners now allows the acquisition of true isotropic data so that a high spatial resolution is now maintained in any imaging plane and in 3D mode. This ability to visualize the complex network of splanchnic arteries using 3D rendering and multiplanar reconstruction is of major importance for an optimal analysis in many situations. The purpose of this review is to discuss and illustrate the role of 3D MDCT angiography in the detection and assessment of abnormalities of splanchnic arteries as well as the limitations of the different reconstruction techniques.

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Splanchnic arteries form a complex network that can be involved by a number of abnormalities [1–3]. The proximal portions of the celiac trunk, superior and inferior mesenteric arteries are usually evaluated using multidetector row computed tomography (MDCT) images obtained in the axial and sagittal planes. However, a comprehensive evaluation of these vessels that include visualization of their distal portions along with the hepatic and splenic arteries is needed and is at the best obtained using three-dimensional (3D) imaging software [1].

MDCT has been subjected to considerable refinements during recent years [4]. MDCT now allows submillimeter imaging and the creation of isotropic data sets [5]. The acquisition of isotropic and submillimeter voxels with MDCT, along with major progress in 3D imaging software, now makes it possible to obtain high-resolution images of
splanchnic arteries; including celiac trunk, splenic, superior and inferior mesenteric arteries obviating the need for angiography in patients with suspected abnormalities of these vessels [5,6]. Consequently, MDCT angiography along with 3D imaging has become the primary imaging technique for the investigation of splanchnic arteries. This is because multiplanar reconstructions (MPR), curved plane reconstruction, maximum intensity projection (MIP), and 3D volume rendering are now available on virtually all workstations [7–10]. Another reason is that it is now well established that 3D MDCT images help detect arterial abnormalities not seen on axial MDCT images alone in up to 66% of patients [11].

The purpose of this review was to discuss and illustrate the role of MPR and MIP reformations and 3D MDCT angiography using submillimeter and isotropic voxels as an adjunct to axial MDCT images in the detection and assessment of abnormalities of splanchnic arteries as well as the limitations of these techniques.

3D MDCT angiography technique

Thin collimation (i.e. < 1 mm) for acquisition of MDCT raw data is essential for reconstructing high-resolution images in all planes and to further obtain high definition 3D images. Because of the complexity of the splanchnic vasculature, MPR, curved reconstructions and volume rendered 3D images are needed to fully visualize all the arterial branches. 3D images can be obtained with three different rendering algorithms that include shaded-surface display, maximum intensity projection (MIP) and volume rendering [12,13]. The various 3D modes have specific properties, including advantages and limitations, so that the use of a combination of the various 3D modes is recommended for a comprehensive evaluation.

Shaded-surface display uses voxels that are selected based on their Hounsfield values. Shaded-surface rendering is a basic algorithm but is of limited value for evaluating the abdominal vasculature. Shaded-surface rendering only allows visualization of the surface of the vessels so that no information about luminal content are available [7,12,13].

MIP is a projection algorithm that displays the brightest voxel along a ray. The thickness of the reconstructed volume of interest may be adapted to the region being studied. Thin MIP with a thickness of 2 to 10 mm is used to visualize the origin of a given vessel and the anatomy of vascular bifurcation and particularly helpful before an interventional vascular procedure to choose the most appropriate catheter. Thick whole volume MIP is useful to reproduce an angiographic view of the whole vascular network within the volume of interest. The algorithm uses all the data in a volume of interest to generate a single bi-dimensional image [7,12,13].

Strictly speaking, MIP images are bi-dimensional but they are considered as 3D images in clinical practice. For each x, y coordinate, only the pixel with the highest Hounsfield number along the z-axis is represented so that in a single MIP image all hyper-attenuating structures in a given volume are visible. MIP is often used because it helps better understand the complete course of a tortuous vessel. It can be used to enhance visualization of small and distal vascular branches, and more frequently to best analyze distal branches of the superior mesenteric artery [14,15].

Volume rendering allows the brightness, opacity, window width, and level to be adjusted in real time to favour visualization of arterial wall, intraluminal content, or adjacent soft tissues [13,16]. Volume rendering is the best 3D technique for an accurate evaluation of artery stenosis [11,12,13].

Curved plane reconstruction is a reconstruction that displays all voxels in a selected curved surface as a single bi-dimensional image. Curved plane reformations are helpful in the lengthwise displaying of the entire course of a tortuous artery. This allows following structures with curved course in their entirety along their path in a single image. This technique is particularly useful to investigate splenic artery and identify arterial stenosis, dilatation or aneurysm [9].

The protocol for MDCT data acquisition must be tailored to the specific situation and the most likely diagnosis. For patients with suspected splanchnic artery aneurysm, a dedicated examination of the abdominal aorta and its branches should be performed. Approximately 120–140 mL of non-ionic contrast material at a concentration of 370–400 mg of iodine/100 mL are injected at a rate of 3–5 mL/s, using a power injector through an 18 G peripheral catheter. Arterial phase MDCT images are obtained approximately 30 s after the start of the injection. Venous phase MDCT images may also be helpful in selected cases and can be acquired approximately 60 s after the start of the injection. This dual-phase MDCT acquisition allows excellent visualization of the splanchnic arteries and veins. For patients referred for active bleeding, a first MDCT imaging set is obtained before contrast injection (non-contrast phase), to detect pre-existing hyper-attenuating material in the bowel lumen, such as tablets, contrast, material metallic clips or foreign bodies, which may result in false-positive finding [5,17–19].

Then, a second data set (arterial phase) and a third data set (venous phase) are obtained 20–30 s and 70 s, respectively, after the start of contrast material administration. The second data set is obtained with bolus tracking and automated triggering with a threshold value of 120 HU. When no active bleeding is visible during the previous three phases, a delayed phase is obtained 3–5 min after the start of the injection.

The axial data are reconstructed using a soft tissue reconstruction kernel. Multiplanar reconstructions (3–5 mm thickness), MIP views (10–15 mm thickness), shaded-surface display images and volume rendered images are created interactively with a large range of dedicated workstations or most often with the 3D program of a PACS workstation. MIP and 3D views are analyzed along with axial, MPR and curved images. In this regard, it is crucial to understand that 3D images should not replace careful analysis of the axial images because interpretation of 3D images alone may result in false-positive or false-negative findings [5].

Results

Anatomical variations

3D MDCT angiography is useful to understand the complex anatomy of splanchnic vessels and distribution of collateral vessels. In addition, variations in vessel anatomy are
common and may have an impact on a range of treatments including surgical and interventional ones [20,21]. In this regard, it is important to keep in mind that only half of the patients have a classical arterial anatomy without variations [22].

There are multiple variations of celiac trunk anatomy, which consist of accessory or replaced individual hepatic arteries [2,22,23]. Variations in distribution of the celiac trunk are observed in up to 51% of abdominal MDCT examinations [2,3,22]. Classically, the celiac trunk originates from the abdominal aorta and gives origin to the left gastric artery, the splenic artery, and the common hepatic artery. The common hepatic artery extends anteriorly and bifurcates into the gastroduodenal artery and the proper hepatic artery. The proper hepatic artery extends cephalad and runs to the left side of the common hepatic duct to bifurcate into the right and left hepatic arteries. The common hepatic artery originated from the superior mesenteric artery in 2% [22].

The superior mesenteric artery gives branches to jejunum and ileum, as well as providing blood flow to the proximal portions of the colon via the ileocolic, right colic, and middle colic arteries. In approximately 10—15% of patients, a right replaced hepatic artery originates from the superior mesenteric artery and gives blood flow to the right hepatic lobe with a course posterior to the portal vein through the portacaval space in the majority of patients [22] although a course anterior to the portal vein has been reported [24].

In 8—10% of patients, a replaced left hepatic artery originating from the left gastric artery is present providing blood flow to the left lateral segment of the hepatic lobe [22,25].

The inferior mesenteric artery provides circulation to the colon, starting at the level of the splenic flexure and extending through the rectum, via the left colic, sigmoid, and superior hemorrhoidal arteries. Communication between superior and inferior mesenteric arteries exists either along the mesenteric margin of the colon (i.e., the marginal artery of Drummond) or through a more centrally located anastomosis (i.e., the arcade of Riolan or paracolic arcade) [1,21].

Depiction of anatomical variants is of major importance before orthotopic liver transplantation, before abdominal surgery to facilitate surgical dissection, avoid inadvertent vessel injury or ligation, and also before transcatheter arterial treatment to avoid non-targeted embolization in unwanted locations [20,26]. 3D MDCT angiography has an accuracy of virtually 100% for detecting arterial variants [27].

Arcuate ligament

Median arcuate ligament syndrome, which is also called celiac trunk compression syndrome or Dunbar syndrome, is due to compression of the celiac trunk by a fibrous arch that originates from the diaphragmatic crura on either side of the aortic hiatus and passes anterior to the origin of the celiac trunk [28]. Compression of the celiac trunk, may cause abdominal pain or even chronic ischemia in the more severe forms and may render its catheterization difficult [29].

Clinical presentation of median arcuate ligament syndrome includes chronic postprandial abdominal pain typically during full expiration, nausea or vomiting, weight loss and audible epigastric bruit. Although open surgical release of the median arcuate ligament has been used for the treatment of this syndrome, laparoscopic release has been reported recently [30]. Laparoscopic release of the median arcuate ligament is a safe, feasible, and effective means of managing median arcuate ligament syndrome with symptomatic relief obtained in the majority of patients treated this way [28,30]. Conversely, percutaneous transluminal angioplasty is usually ineffective [31]. Similarly, current data do not support the use of balloon expandable stents [28,31]. This is probably due to the extraluminal compression of the artery by the arcuate ligament. By contrast, after recurrence of symptom after surgical decompression, angioplasty may be beneficial [31].

The diagnosis of median arcuate ligament syndrome is based on clinical symptoms and further confirmed by the depiction of focal narrowing, with a suggestive hooded appearance, of the origin of the celiac trunk on MDCT angiography [32]. Arcuate ligament is best seen on MDCT images in the sagittal plane obtained during the arterial phase (Fig. 1) [29]. Although stenosis of the celiac trunk due to median arcuate ligament is often discovered during a failed or difficult catheterization, it is important to be aware of such abnormality before planning intra-arterial treatment in order to avoid long and potentially ineffective interventional procedure, minimize the risk of celiac axis dissection, reduce the radiation dose and select the most appropriate catheters [29].

Superior mesenteric artery syndrome

Superior mesenteric artery syndrome is due to the compression of the third portion of the duodenum between the aorta and the superior mesenteric artery [33]. Clinically, the diagnosis of superior mesenteric artery syndrome is suspected by a combination of postprandial abdominal pain, nausea and vomiting that often lead to chronic anorexia and weight loss. It is assumed that compression of the duodenum is due to a loss of intra-abdominal fat located between the superior mesenteric artery and the aorta. The treatment consists of making a side-to-side gastro-jejunostomy when conservative measures have failed [33].

The diagnosis is suspected clinically and further confirmed by 3D MDCT angiography. In patients with this condition, 3D MDCT angiography shows an abnormal aortomesenteric angle < 22° and a shortened aortomesenteric distance < 8 mm by comparison with more than 28° and greater than 10 mm, respectively as observed in control subjects [34,35]. Associated findings include duodenal compression, gastric dilatation and left gonadal vein dilatation [35].

Aneurysms

Splanchnic artery aneurysms are relatively uncommon conditions that are predominantly detected incidentally. These aneurysms should be diagnosed accurately because they carry a high morbidity and mortality, even in asymptomatic patients because of a high risk of rupture. Most frequent locations include splenic, hepatic and gastroduodenal arteries, but other locations, such as superior (Fig. 2) or inferior mesenteric artery are possible [6].
Splenic artery aneurysm

Splenic artery aneurysms account for 60% of all splanchnic artery aneurysms [36]. The prevalence varies from 0.2 to 10.4% [6,36]. Splenic artery aneurysm is associated with a variety of conditions, including arterial hypertension, portal hypertension, liver cirrhosis, liver transplantation and pregnancy [37]. Less frequent associations include arterial fibrodysplasia, arteritis, collagen vascular disease, α1-antitrypsin deficiency, inflammatory and infectious diseases and hereditary hemorrhagic telangiectasia [37].

Clinically, splenic artery aneurysms are asymptomatic in 97.5% of patients [38]. Splenic artery aneurysms are more common in women but rupture is more frequent in men. The risk of rupture ranges between 2 and 3% [37]. The majority of splenic artery aneurysms are true aneurysms, containing the three normal layers of the arterial wall [37].

Most asymptomatic patients with aneurysms <2 cm do not need intervention [38]. Symptomatic aneurysms usually present with acutely with pain, bleeding, and hypotension. Symptomatic splenic artery aneurysms are treated with either surgical repair or transcatheter embolization [39–41]. In addition, data from the literature support the treatment of asymptomatic splenic artery aneurysms >2 cm in patient with acceptable operative risks and in patient whose life expectancy is >2 years [38].

Indications for intervention include the presence of symptoms, pregnancy, or willingness to become pregnant. Other indications include increasing size of the aneurysm or diameter >2 cm. Elective removal or resection are extremely low-risk treatments and have minimal morbidity. In most cases, the spleen can be preserved. Splenectomy is only necessary for aneurysms located in the hilum of the spleen or during emergency situations. Endovascular techniques are preferred as minimally and definitive treatments [42]. Endovascular treatment, when possible, consists of covered stent placement at the site of the aneurysm, mostly when the splenic artery is not too tortuous.
3D MDCT angiography is particularly helpful in determining the best therapeutic option [36]. Curved reformations are needed to best evaluate the relationship of aneurysm to the splenic artery, the size of the neck and determine the size of the aneurysms (Fig. 3). Splenic artery aneurysm is usually homogeneous after intravenous administration of iohexiton contrast material, although partial or complete spontaneous thrombosis can be observed. In a few cases, aneurysm may mimic hypertensive neuroendocrine pancreatic tumor (Fig. 4) [43]. 3D MDCT images are helpful in distinguishing between these two entities. Similarly, 3D MDCT helps differentiate tortuous vessel from actual aneurysm [37].

Pancreaticoduodenal artery aneurysms
Pancreaticoduodenal artery aneurysms account for approximately 2% of all visceral artery aneurysms with a male predominance [44]. The actual incidence is difficult to determine because of the confusion in terminology found in the literature between true pancreatic duodenal artery aneurysms and pseudoaneurysms.

Patients can present with non-specific abdominal pain or a palpable mass in case of large aneurysm. Up to 62% of patients with pancreaticoduodenal aneurysms have a ruptured pseudoaneurysm at presentation, so that this condition is associated with a 21% mortality rate [44]. Because the risk of rupture does not depend on the size, a definitive treatment is needed as soon as the diagnosis is made.

Patients with pancreaticoduodenal artery aneurysms often have associated occlusive disease involving the celiac trunk [6,44]. It is assumed that reduced flow in celiac trunk may result in increased flow in peripancreatic arteries, so that these arteries play the role of collateral routes from the superior mesenteric artery to maintain visceral organ perfusion. Increased flow may participate in the development of aneurysms. However, pancreaticoduodenal artery aneurysms may occur in patients without stenosis of the celiac trunk.

Treatment is needed in patients presenting with ruptured aneurysm. Percutaneous arterial embolization is the preferred option and metallic coils are often used as occluding embolic material.

3D MDCT angiography is the best imaging modality for the evaluation of pancreaticoduodenal artery aneurysms. 3D MDCT angiography is particularly helpful in determining the best therapeutic option [6]. Curved reformations are helpful to best evaluate the relationship of aneurysm to the artery, the size of the neck and determine the size of the aneurysms. In patients presenting with ruptured aneurysm, 3D MDCT shows direct extravasation of contrast material and retroperitoneal hemorrhage.

Pseudoaneurysms
Pseudoaneurysms (or false aneurysms) are histologically different from true aneurysms and usually result from pancreatitis, trauma, surgery, or peptic ulcer disease [45–47]. By contrast with true aneurysms, pseudoaneurysms do not have the three layers of the vascular wall and are therefore more fragile. Pseudoaneurysms contain a single loose connective tissue layer and have a tendency to enlarge progressively and rupture. Most are a complication of pancreatitis and are thought to result from destruction of the vessel wall by pancreatic enzymes but they may be secondary to intraoperative injury. Embolization is the first-line treatment for pseudoaneurysms and is generally based on the so-called "sandwich technique", which consists of occluding the parent artery of the pseudoaneurysm upstream and downstream to exclude it from arterial flow and avoid reperfusion [47]. At 3D MDCT angiography, pseudoaneurysm appears as a focal collection of iodinated contrast material that communicates with the parent artery lumen usually through a narrow neck.

Splenic artery pseudoaneurysm
Splenic artery pseudoaneurysm is extremely rare and less common than true splenic artery aneurysm [47]. The main
Figure 3. A 38-year-old woman with type IV collagen mutation with suspected visceral aneurysm. a: MDCT image in the axial plane suggests aneurysm (arrow) of left gastric artery at the level of the lesser gastric curvature; b: MIP image in the oblique plane confirms arterial aneurysm (arrow) although the exact origin is still unclear; c: 3D surface-rendered image demonstrates a tortuous splenic artery (arrowheads) and definitely confirms that the aneurysm (arrow) originates from the splenic artery.

Figure 4. A 47-year-old woman with suspected pancreatic mass. a: MDCT image in the axial plane shows hyperenhancing lesion in the pancreatic tail (arrow) compatible with hypervascular pancreatic tumor; b: 3D surface-rendered image demonstrates two aneurysms (arrows) originating from splenic artery and definitely excludes pancreatic tumor.
causes are acute pancreatitis, long-standing pseudocyst and intraoperative arterial injury [37]. Splenic artery pseudoaneurysm presents with a variable size, ranging from 3 mm to 17 cm [47].

Splenic artery pseudoaneurysms are symptomatic in 97.5% and present with abdominal pain, hematochezia, melena, wirsungorrhagia or hematemesis [47]. The risk of rupture is high and not related to size [47]. Due to the high risk of rupture of splenic pseudoaneurysms, prompt intervention is essential. Endovascular coils and covered metallic stents are now the favored treatment option [37].

3D MDCT angiography is useful to best diagnose ruptured pseudoaneurysm and plan the therapeutic approach. Depending on the size and location with respect to the feeding artery, coils, detachable balloon or gelatin sponge can be used [42].

Gastroduodenal artery pseudoaneurysm

Gastroduodenal artery pseudoaneurysms account for less than 2% of all splanchnic artery aneurysms [6]. They mostly occur as a complication of acute pancreatitis although in a few cases, they can be secondary to intraoperative injury (Fig. 5). They can be depicted either incidentally in patients with pancreatitis or during a rupture and bleeding episode. They are secondary to adjacent inflammation. If gastroduodenal artery aneurysm is found incidentally, treatment is required because of the high risk of rupture [41,48].

3D MDCT angiography confirms the diagnosis of gastroduodenal artery pseudoaneurysm and provides information with respect to the size, location and morphology of the aneurysm. This helps plan endovascular treatment [6]. 3D MDCT angiography shows direct extravasation of contrast material in case of ruptured pseudoaneurysm (Fig. 5).

Active lower gastrointestinal bleeding

Acute gastrointestinal bleeding is a severe condition, with a mortality rate of up to 40% when associated with hemodynamic instability. The diagnosis of acute intestinal bleeding is often challenging but recent reports suggest that MDCT angiography is the most appropriate technique [49]. In this regard, MDCT angiography allows depicting active extravasation of iodinated contrast material in up to 81% of the cases during the arterial phase, as high attenuating foci with attenuation values ranging from 137 to 330 Hounsfield units (HU) [17,19]. Moreover, MDCT is helpful to guide endovascular treatment, localize the bleeding and helps make alternate diagnosis. MDCT is now largely available and acquisitions are so fast that it should always be performed before an interventional procedure. A multiphasic acquisition is necessary to maximize the probability to depict an active bleeding [49].

3D MDCT angiography requires no bowel preparation, can be performed rapidly during active bleeding and is undoubtedly less invasive than angiography. Whereas gastrointestinal bleeding has to be caught in the act with other imaging techniques, a major advantage of MDCT is that it may suggest a potential cause in the absence of active bleeding [17,19].

Until recently, colonoscopy has been considered as the first-line procedure for the diagnosis and treatment in patients presenting with acute lower gastrointestinal bleeding. In favorable situations, when the bleeding source is visualized, adrenaline injection or thermal coagulation may be applied [50]. However, limitations to the use of colonoscopy in an emergency setting include poor visualization in an unprepared colon, particularly in cases of massive bleeding, and the potential risks of sedation in hemodynamically unstable patient. If colonoscopy fails to control the bleeding, surgical operation with bowel resection may be the next invasive option. However, this also carries substantial morbidity and mortality. Thus, with refinements in interventional radiological procedures, arterial embolization has become a more attractive therapeutic option [51]. In this regard, superselective embolization is a safe and effective modality for the treatment of lower gastrointestinal bleeding, stopping bleeding in up to 97% of cases with a rate of colonic ischemia as low as 3% [52].

MPR and MIP reformations are commonly used as an adjunct to axial MDCT images in patients with acute lower gastrointestinal bleeding. Reformatted images enhance the depiction of subtle vascular abnormalities and improve diagnostic capabilities [5,53,54]. Although we are aware that reformatted images should not replace careful analysis of the axial images in patients with acute gastrointestinal bleeding, reformatted images clarify the cause of the bleeding, add confidence to image analysis and help interventional radiologists or surgeons improving planning approach [5].

Small bowel

Acute small bowel bleeding is a challenging situation, because of the difficulties for accurately localizing the bleeding site with endoscopy in emergency and also because surgery carries a high morbidity and mortality rate [55].

Figure 5. A 61-year-old woman with intraperitoneal hemorrhage and hemodynamic instability after abdominal surgery. 3D MDCT angiography using surface rendering shows extravasation from ruptured pseudoaneurysm (curved arrow) of inferior gastroduodenal arcade (arrow) originating from superior mesenteric artery (arrowhead). Subsequent superselective embolization was successful in stopping the bleeding.
Small bowel hemorrhage is suspected when both upper and lower endoscopic examinations performed for hematochezia are negative. Acute small bowel hemorrhage is most frequently due to ulcer, submucosal or ulcerated tumor, Crohn disease, angiodysplasia, and other vascular malformations [56]. Gastrointestinal stromal tumor and carcinoid tumors are the most frequent causes of acute small bowel hemorrhage due to tumor. Mucosal ulcerations of small bowel wall, due to Crohn disease or other inflammatory conditions, represent the second cause of acute small bowel bleeding.

MDCT and 3D MDCT angiography can show a tumor with abnormalities of the mesentery should it be the cause of bleeding, but in most cases, 3D MDCT angiographic findings are non-specific when bleeding is due to vascular abnormalities, so that the diagnosis relies on direct depiction of extravasation of iodinated contrast material [5,57].

Colon and rectum

Colon and rectum are the two main origins of lower acute gastrointestinal bleeding. MDCT and 3D MDCT angiography have now a pivotal role in the evaluation of patients with this condition because it is well acknowledged that colonoscopy is often inconclusive due to lack of colonic preparation or large amount of blood obscuring the bleeding site [5]. The two most frequent causes of colonic acute bleeding are angiodysplasia and hemorrhagic colonic diverticulosis. Other causes of lower acute gastrointestinal bleeding from colonic origin are tumors (polyps or cancers), ischemic colitis, ulcers, inflammatory bowel diseases and variceal bleeding.

Colonic angiodysplasia is more and more recognized as one of the main causes of lower hemorrhage. Diagnosis is usually made by colonoscopy, which is also a therapeutic modality. However, in acute bleeding, superselective angiography can be used as a diagnostic and therapeutic tool [55]. Hemorrhagic colonic diverticulum is the second most frequent cause of acute lower gastrointestinal hemorrhage, after colonic angiodysplasia. It frequently involves the ascending colon. Diagnosis of hemorrhagic colonic diverticulosis needs precise identification of the bleeding diverticulum. Presence of isolated diverticulosis with no evidence of active bleeding is not sufficient to ascribe the bleeding to diverticulosis. The potential role of MDCT angiography for the evaluation of acute lower gastrointestinal hemorrhage from a colorectal origin has been recently highlighted [17,19,58]. MDCT angiography helps suggest angiodysplasia by showing signs similar to those previously described during angiographic studies, such as early filling of an enlarged vein originating from the angiodysplastic site, increased vascularity in the colonic wall and adjacent enlarged arterial branch (Fig. 6). Such findings result in a sensitivity of 70 and 100% specificity for the diagnosis of colonic angiodysplasia, with a number of cases in which MDCT angiography is diagnostic whereas colonoscopy is inconclusive. In case of active bleeding, endoluminal extravasation of iodinated contrast material provides accurate localization of the bleeding site, eases colonoscopic or angiographic treatment and can minimize emergency colonic resection. The same degrees of efficacy can be reasonably anticipated for 3D MDCT angiography in the diagnosis of hemorrhagic right colonic diverticulosis [58].

Figure 6. A 47-year-old woman with severe acute hematochezia and hemodynamic instability. 3D MDCT angiography shows active bleeding (curved arrow) in cecum in association with enlarged ileocecal artery (arrowhead) and early filling of ileocolic vein (arrow). These findings are typical of colonic angiodysplasia that was confirmed during colonoscopy and treated endoscopically.

Tumor involvement

A number of abdominal tumors can grow to involve splanchic arteries. Of these, pancreatic cancers and carcinoid tumors are most frequently associated with vessel involvement [59–61]. Vascular involvement can be defined as either occlusion or narrowing of a vessel, usually with an associated soft tissue mass surrounding the area of involvement [61]. Collateral vessels may be present and are a useful secondary sign of vascular involvement [60].

Pancreatic tumor

A critical goal of MDCT in patients with pancreatic cancer is the evaluation of adjacent vascular structures [59,62]. Involvement of any of the major arterial structures (i.e., celiac trunk and superior mesenteric artery) or venous structures (i.e., portal vein, splenic vein, superior mesenteric vein) will make resection impossible for most surgeons. Invasion of the superior mesenteric artery is one of the major contraindications for surgery in pancreatic cancer.

Native axial images are crucial to evaluate quantitatively the encasement of celiac trunk, hepatic and superior mesenteric arteries [63]. Best depiction of an encasement or involvement greater than 180° of these vessels is obtained with native axial images [62,63]. Conversely, 3D MDCT allows better visualization of arterial branching, thereby improving detection of involvement of the more distal portions of the peripancreatic arteries although their involvement do not always have impact on the therapeutic options [63]. Visualization of the vasculature is greatly improved with 3D volume rendering, which can display a given vessel in the best orientation.

Using 3D MDCT angiography, the rate of visualization for arteries around the pancreas is 86.6% for anterior superior pancreaticoduodenal artery, 85.0% for posterior superior pancreaticoduodenal artery, 76.6% for anterior inferior pancreaticoduodenal artery, 71.6% for posterior
in the axial plane shows defect (arrow) at the ostium of superior mesenteric artery; b: MIP image in the sagittal plane shows occlusion of proximal portion of superior mesenteric artery (arrow) and focal calcified plaque (arrowhead) at the ostium; c: 3D surface-rendered image angiography is limited at showing filling defect (arrow) but better identifies recruitment of collateral vessels (arrowheads) secondary to superior mesenteric artery occlusion.

Carcinoid tumor
Carcinoid tumors represent 20–30% of all primary neoplasms of the small bowel [60]. They originate from enterochromaffin cells and are predominantly located in the distal ileum [60]. Carcinoid tumors of the small bowel usually induce a desmoplastic reaction within the mesentery and are often associated with mesenteric masses and tethering of adjacent small bowel loops.

With recent progress in medical imaging, carcinoid tumors are frequently detected at an early stage [60,65]. However, in a number of patients, carcinoid tumor is still discovered at a late stage during which the tumor can cause vascular involvement defined as either occlusion or narrowing of an arterial branch originating from the superior mesenteric artery [60,66].

Collateral vessels are identified with MIP and 3D reconstructed images. Post-processing techniques are useful for the evaluation of vascular involvement in patients with carcinoid tumors and large mesenteric masses [67]. 3D MDCT angiography is very useful in depicting the full extent of associated mesenteric mass and its relationships to arterial vessels, which are both important factors for accurately determining the surgical approach [67].

Bowel ischemia
The diagnosis of mesenteric ischemia can be difficult, because most patients have non-specific symptoms of abdominal pain [68]. Abdominal pain, out of proportion to the findings on physical examination and persisting beyond 2 to 3 h, is the classic presentation. At least the 65% of cases of intestinal ischemia are due to arterial embolism or thrombosis with blood flow impairment in the superior mesenteric artery distribution affecting all or portions of the small bowel and right colon [69]. Most embolic events are thromboembolic in nature and have a cardiac origin. Thromboembolic events are due to atrial tachyarrhythmia, congestive heart failure, cardiomyopathy, recent myocardial ischemia or infarction, and ventricular aneurysms [59,68,70,71].

Bowel ischemia is due to acute occlusion of superior mesenteric artery although it can be related to a venous cause less frequently [59,72]. Arterial occlusion results in a slower progression of the disease than venous ischemia [69].

MDCT angiography is now the diagnostic test of choice and
the gold standard due to its ability to directly investigate and show secondary signs of mesenteric ischemia of arterial origin, such as bowel wall thinning, poor enhancement and free fluid effusion, with sensitivity ranging from 82 to 96% and specificity of 94% [69,73].

The diagnosis of superior mesenteric artery occlusion is best made using MPR or MIP images and preferably in sagittal projection whereas the use of surface-rendered images can be useful to identify spontaneous collateral arterial branches (Fig. 7). 3D MDCT angiography is often limited in this diagnosis because the lumen is usually occluded and a few amount of contrast material fills the superior mesenteric artery [72]. In the early phase, the presence of intraluminal filling defect indicative for emboli or thrombi can be observed. Their identification can be difficult if they are small and peripherally located. MIP images may be helpful to enhance visualization of distal branches when ischemia is due to occlusion of small distal vessels.

Dissection

Most isolated celiac and superior mesenteric artery dissections are asymptomatic and often discovered incidentally, supporting further imaging tests for surveillance with intervention limited to situations in which vascular compromise is present or anticipated [74]. Most patients with dissection can be successfully managed with conservative treatment including either observation or anticoagulation [74]. Surgical treatment or percutaneous intervention should be reserved for patients with severe mesenteric ischemia and those with failure of the initial conservative treatment [74,75].

MPR reconstructions and 3D MDCT images improve diagnostic capabilities. In this regard, up to 33% of the dissections diagnosed with MPR, MIP and 3D MDCT images can be missed when using standard MDCT images obtained in the axial plane [76]. MPR and MIP reconstructed images are the most effective for the detection of dissection whereas surface shaded 3D images may overlook dissection (Fig. 8).

Inflammatory bowel diseases

Patients with inflammatory bowel disease have changes in mesenteric blood flow that can be observed on MDCT angiography. MDCT features of hypervascularity involving the arteries of small bowel segments affected by Crohn disease include dilatation and tortuosity of distal branches of
superior mesenteric artery, and conspicuous prominence and wide spacing of the vasa recta. This latter finding is the so-called "comb sign" [14,77,78].

It is admitted that patients with active inflammatory bowel disease have increased blow flow. Increased vascularity is observed on MDCT and 3D MDCT angiography results from increased arterial flow. Accompanying fibrofatty proliferation in the mesentery and serosa of the affected small bowel segments enhances the conspicuity of dilated vessels [77]. MPR and MIP reconstructions add confidence in establishing the diagnosis of active Crohn disease and help in the differential diagnosis from other conditions [15].

**Hereditary hemorrhagic telangiectasia**

Hereditary hemorrhagic telangiectasia is an autosomal dominant disorder, which is characterized by repeated episodes of hemorrhage and by the presence of angiodysplastic lesions that may affect various organs [79]. The prevalence of hereditary hemorrhagic telangiectasia ranges from 1/5000 to 1/8000 in the general population and that of hepatic involvement ranges from 8 to 31% [79]. Liver involvement in hereditary hemorrhagic telangiectasia includes suggestive and non-specific abnormalities. Suggestive hepatic abnormalities include enlarged hepatic arteries, hepatic artery aneurysms, and telangiectasia and arteriovenous fistulas [78–82]. Non-specific lesions include indirect signs of portal hypertension, perfusion disorders, cirrhosis, fibrosis, bile duct dilatation and focal nodular parenchymal lesions. Similarly, pancreatic arteries can be involved in up to 31% of patients with hereditary hemorrhagic telangiectasia [81,82].

Intrapancreatic telangiectasia and intrapancreatic arteriovenous malformations are present in 40% and 16–31% of patients with hereditary hemorrhagic telangiectasia, respectively [81,82]. In patients with hereditary hemorrhagic telangiectasia, common hepatic artery diameter is significantly larger than that in control subjects. Using a cut-off value of 6.5 mm, common hepatic enlargement is 79% sensitive and 84% specific for the diagnosis of hereditary hemorrhagic telangiectasia in case-control studies [82]. But other cut-off values ranging between 4 mm and 6 mm have been reported [80]. Similarly, patients with hereditary hemorrhagic telangiectasia have greater splenic artery diameter by comparison with control subjects [81,82].

3D MDCT angiography can be used in patients with hereditary hemorrhagic telangiectasia to better identify hepatic and extrahepatic arterial lesions and to characterize the associated vascular shunts (Fig. 9). MIP images are particularly helpful in the depiction of small intrahepatic vascular lesions [83].

**Conclusion**

3D MDCT angiography is helpful in virtually all conditions that affect the splanchnic arteries. MIP images are useful and superior to the other reconstruction techniques for the evaluation of small and distal arteries and detection of internal occlusion. MPR is the modality of choice for the evaluation of ostial, proximal and mid portion of splanchnic arteries and is the favoured reconstruction technique when arcuate ligament or superior mesenteric artery syndrome are suspected. Volume rendered and surface shaded images are the modalities of choice when a comprehensive 3D evaluation is needed, such as detection of anatomical variants or to provide a better understanding of collaterality.

**Disclosure of interest**

The authors declare that they have no conflicts of interest concerning this article.
References


