Chapter 5
Duplex Ultrasound of the Mesenteric Vessels

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Angiography has been considered the gold standard technique for the diagnosis of chronic mesenteric ischemia. Due to its invasive nature and improvements in noninvasive diagnostic studies, angiography is currently reserved for patients with classic signs and symptoms of chronic mesenteric ischemia who have planned endovascular or open reconstruction. Among patients with atypical symptoms, it is not unusual to have significant delay in diagnosis [1]. Since the first published evaluation of the splanchnic human vasculature by duplex scanning in 1984 [2], the technique brought up intense interest in the medical community, mainly due to its noninvasive characteristic but also because it provides hemodynamic and anatomic information. In the last decades, duplex ultrasound has proved to be an accurate method to detect stenosis and is typically the first imaging study obtained in the evaluation of patients with suspected mesenteric artery occlusive disease.

Technique

Evaluation of the splanchnic circulation can be technically challenging. In experienced hands, the average time for exam completion is around 15–20 min. Besides experience and knowledge of vascular anatomy, some factors can potentially

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contribute to increased difficulty. Obesity, previous abdominal surgery, dressings, anatomic variants, respiratory motion, and excessive bowel gas are the main factors contributing to a suboptimal examination. Modern and efficient equipment, an experienced sonographer, and appropriate patient selection are keys to a successful imaging.

The examination is performed in fasting state (at least 6 h) to minimize bowel gas and also because the established criteria used to diagnose mesenteric artery disease have been based on fasting velocities. Studies showed little or no improvement in accuracy when food challenges were used to detect stenosis. Furthermore, it is important to recognize that much of these patients are classically afraid of eating, due to intense pain [3, 4]. The postprandial state is induced by an 8-oz protein calorie supplement, and the exam is performed after 30 min [5].

The examination is typically performed with the patient in supine position. When bowel gas prevents adequate visualization of the vessels, patients may be turned to a lateral oblique decubitus position, which may provide a better window. Patient cooperation with breath hold is critical to record adequate Doppler spectral samples [6].

At the Mayo Clinic, we most commonly use the 1–5 MHz curved array or 9 MHz linear array transducers. Caution should be taken to keep the Doppler angle of insonation, ideally <60°. The variations of peak systolic velocity measurement as a function of angle of insonation is well documented [7]. This should be kept in mind especially in follow-up comparison examinations where similar technique should be used. Initially, the abdominal aorta is identified in transverse and sagittal planes, paying attention to diameter and atherosclerotic involvement. Spectral Doppler waveform is obtained with peak systolic velocity (PSV) and end-diastolic velocity (EDV) measurements in the area of mesenteric vessels origin. Color Doppler is used to identify the arteries and to guide sample volume placement for spectral Doppler analysis (Fig. 5.1). The superior mesenteric artery (SMA) and the celiac axis (CA) are best identified in the sagittal plane, arising from the anterior aspect of the aorta. The CA branches (hepatic and splenic) are best viewed in transverse orientation. Velocity measurements are obtained at the origin of the vessel and a few centimeters within the celiac artery during tidal breathing; specifically, measurements are obtained in deep inspiration and expiration for evaluation of median arcuate ligament compression syndrome (Fig. 5.2). Spectral Doppler sampling with PSV and EDV measurements are obtained at the origin and at the proximal, mid and distal SMA. Shortly after the origin, the SMA will curve inferiorly and course almost parallel to the aorta for several centimeters where it may be difficult to obtain a Doppler angle of <60°. Whenever possible, the inferior mesenteric artery (IMA) should be also evaluated. It is best identified using the transverse plane, arising from the anterolateral aspect of the aorta, generally a few centimeters above the aortic bifurcation. Measurements of PSV and EDV are obtained at the origin and distally as far as visible. Generally, only a short segment of the IMA near the origin is visualized, and because of its inferior trajectory nearly parallel to the aorta, optimal angle of insonation may not be obtained.

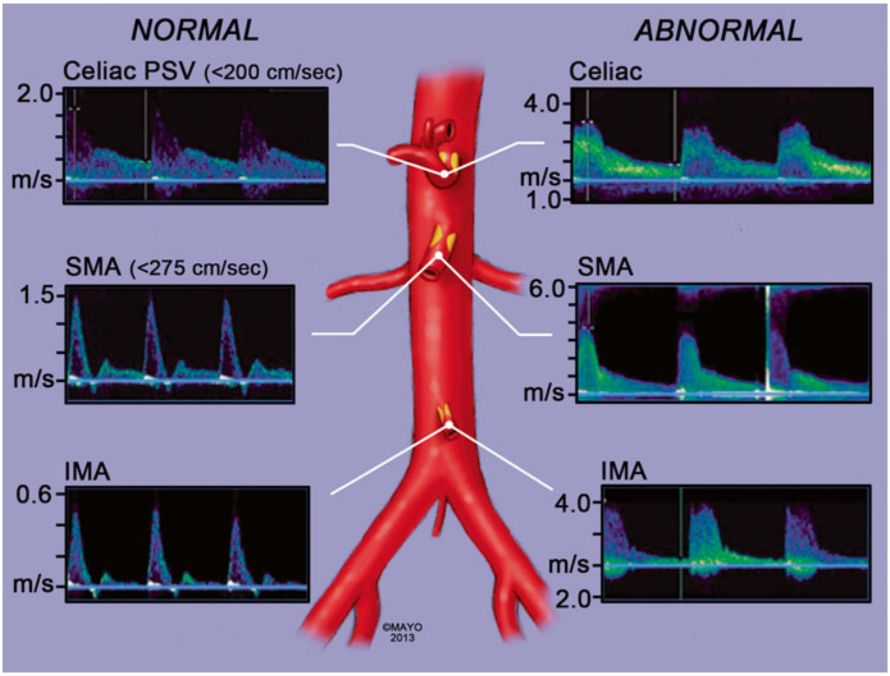

Fig. 5.1 Normal and abnormal mesenteric arteries' waveforms: The normal celiac artery has a low-resistance waveform. A peak systolic velocity of 2.5 m/s or greater is indicative of a significant stenosis. The normal superior mesenteric artery has a high-resistance waveform in the postprandial state and a peak systolic velocity of <2.75 m/s. The inferior mesenteric artery has a waveform similar to the superior mesenteric artery with high resistance. A peak systolic velocity of 2.75 m/s or greater is suggestive of a significant stenosis

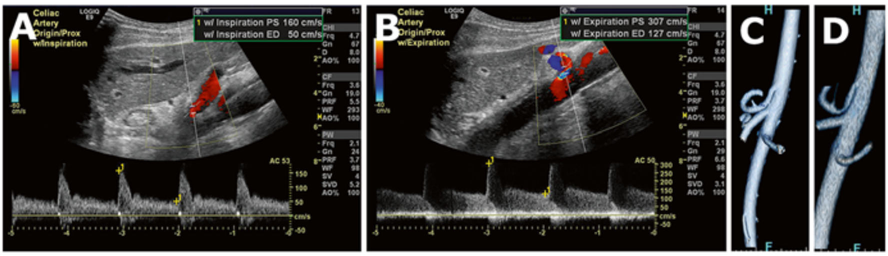

Fig. 5.2 Doppler ultrasound of the celiac artery in inspiration (**a**) reveals normal peak systolic velocity. During inspiration, the celiac artery moves caudally, and the median arcuate ligament moves anteriorly. With expiration, the opposite occurs, resulting in compression of the artery and elevated velocities (**b**). Volume rendered computed tomography images in inspiration (**c**) and expiration (**d**) are also elucidative.

In published series, the mesenteric arteries have been successfully identified in 85–100 % of patients. There are a few studies reporting duplex evaluation of the IMA but no one with more than 14 % of inappropriate evaluation of the vessel [7–10].

Normal Waveforms

The normal celiac artery and SMA have distinct waveforms reflecting the different end-organ blood supply requirements (Fig. 5.1). The major branches of the celiac artery supply the liver and spleen. These organs are low-resistance arterial beds, resulting in a biphasic celiac artery waveform composed of a peak systolic component and higher end-diastolic flow. The SMA supplies the small bowel and proximal colon. In the fasting state, the Doppler waveform is triphasic, composed of a systolic peak, an early diastolic reversal of flow, and low end-diastolic flow approaching zero. In the postprandial state, due to the normal hyperemic response described in Chap. 2, the end-organ resistance is decreased, and blood flow is increased for adequate food absorption, resulting in changes in the arterial waveform. PSV increases, early diastolic flow reversal disappears, and end-diastolic flow increases. Approximately 45 min after a meal, these changes reach their apex, and the diameter of the SMA also increases by a mean of 112 %. On the other hand, the CA waveform remains similar to the fasting state, basically because of the unchanged demands of the liver and spleen [11]. The Doppler arterial waveform is also affected by food composition, with mixed calorie meals resulting in the most pronounced change [12]. A low-resistance waveform can also be a normal finding if there is a replaced or accessory hepatic artery originating from the SMA. Although IMA examination can be difficult because of small size and posterior location, this vessel can be identified in up to 89 % of patients by skilled sonographers [8]. The IMA supplies the distal colon and upper rectum and therefore has a high-resistance waveform, similar to the triphasic SMA waveform.

Anatomic variations in the origin of the hepatic arteries, which occur in approximately 20 % of the population, can result in changes in the SMA waveform in the fasting state. The most common variation described above is a replaced right hepatic artery originating from the SMA, which occurs in up to 17 % of individuals. In these cases, the typical waveform has a lower-resistance pattern in the SMA, resembling the waveform of a CA. A normal PSV and the finding of a non-turbulent waveform with a clear systolic window favor the diagnosis of an anatomic anomaly as opposed to a stenotic lesion [1].

There is a paucity of data on duplex evaluation of the IMA; consequently its normal and pathological characteristics are not well described. Typically the IMA waveform shows a high-resistance pattern, similar to what is observed for the SMA during fasting state but with a higher resistance index [10]. The IMA is usually not affected by meals unless this vessel provides important compensatory collateral flow to the SMA [5].

Detection of Stenosis

In 1991, Moneta and colleagues reported the first retrospective study evaluating the role of duplex scanning of splanchnic arteries to identify SMA and CA stenosis (Fig. 5.3) in patients undergoing abdominal aortography [13]. In that study, a PSV of >275 cm/s for the SMA and >200 cm/s for the CA accurately detected stenosis >70 %. It also suggested that PSV was a better predictor than EDV and that an aorto-mesenteric ratio had no significant improvement in the ability to diagnose a significant stenosis. A few years later, the same group validated their findings in a prospective study of 100 patients who underwent duplex ultrasound and abdominal aortography, including 13 patients who had investigation for chronic mesenteric ischemia. Duplex ultrasound was able to adequately visualize the SMA in 92 % and the CA in 83 % of cases. Using the previously described PSV criteria, these authors found a sensitivity of 92 %, specificity of 96 %, positive predictive value (PPV) of 80 %, negative predictive value (NPV) of 99 %, and accuracy of 96 % to diagnose 70 % or greater stenosis. For the CA, the same parameters were 87, 80, 63, 94, and 82 %, respectively [14]. At the Mayo Clinic, we use the same criteria for the SMA but have adjusted the celiac artery criteria to 250 cm/s to improve diagnostic accuracy.

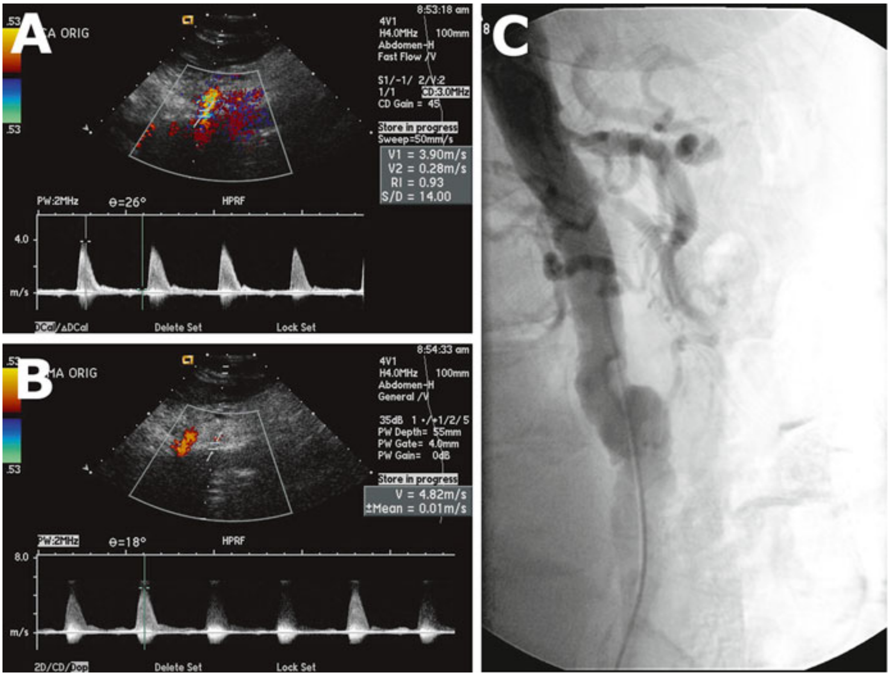

Fig. 5.3 Doppler ultrasound shows elevated peak systolic velocity at the origin of the celiac artery (**a**) and superior mesenteric artery (**b**) indicative of a significant stenosis. Angiogram correlation confirms significant stenosis of the celiac and superior mesenteric arteries (**c**)

Other velocity criterion has been proposed in the literature. In 1991, Bowersox and colleagues reported a retrospective study which identified EDV > 45 cm/s as the most accurate predictor of a >50 % SMA stenosis. [15]. Later, the same group published a prospective study validating these findings. An EDV of >45 cm/s had a sensitivity of 90 %, specificity of 91 %, PPV of 90 %, NPV of 91 %, and accuracy of 91 %. The same parameters for a >50 % stenosis in CA are, respectively, 93, 100, 100, 89, and 95 %.

More recently, AbuRahma and colleagues published results of a retrospective study of 153 patients who underwent angiography to evaluate for chronic mesenteric ischemia. In that study, the best PSV criteria to diagnose >50 and >70 % SMA stenosis were 295 cm/s (accuracy of 88 %) and 400 cm/s (accuracy of 85 %), respectively. The best PSV threshold to identify >50 and >70 % celiac stenosis were 240 cm/s (accuracy of 86 %) and 320 cm/s (accuracy of 85 %), respectively. Differences in velocity criteria in these studies need to be interpreted carefully given distinct methodology, equipment, and patient demographics [16].

Only a few studies have validated the criteria for IMA stenosis. The first one was published by Pellerito and colleagues in 2009, where he proposed the most accurate criteria was a PSV higher than 200 cm/s (specificity of 90 %, specificity of 97 %, PPV of 90 %, and NPV of 97 %) to diagnose >50 % stenosis [9].

AbuRahma and colleagues reported duplex evaluation of 85 patients with suspected chronic mesenteric ischemia. In that report, an IMA PSV of 250 cm/s predicted >50 % stenosis with 95 % of accuracy or 270 cm/s could predict a >70 % stenosis with accuracy of 92 %. In an ROC analysis, none of the criterion proved better than the others to diagnose >50 % stenosis [17]. Others have advocated the use of a test meal in cases where higher velocities are believed to occur for reasons other than stenosis, such as stented vessels. It is expected that, if a stenosis exists, a pressure gradient across the stenosis should develop, and consequent damping of the waveform will be detected. The CA and the IMA must be minimal or not affected by food challenge [5] The data concerning previous studies and the established criteria for SMA, CA, and IMA stenosis are summarized in Tables 5.1, 5.2, and 5.3.

Table 5.1 Most accurate cutoff points to diagnose stenosis of the superior mesenteric artery in different studies

Studies	Design	Stenosis grade	Cutoff (cm/s)	Sb (%)	St (%)	PPV (%)	NPV (%)	Ac (%)
Moneta (1993) [14]	Prospective	≥70 %	PSV ≥ 275	92	96	80	99	96
Zwolak (1998) [1]	Prospective	≥50 %	PSV ≥ 300	60	100	100	73	81
AbuRahma (2012) [16]	Retrospective	≥70 %	PSV ≥ 400	72	93	84	85	85
			PSV ≥ 410	68	95	88	84	85
			EDV ≥ 70	65	95	89	82	84
		≥50 %	PSV ≥ 295	87	89	91	84	88
			EDV ≥ 45	79	79	84	72	79

Sb sensitivity, *St* specificity, *PPV* positive predictive value, *NPV* negative predictive value, *Ac* accuracy, *PSV* peak systolic velocity, *EDV* end-diastolic velocity

Table 5.2 Most accurate cutoff points to diagnose stenosis of the celiac artery in different studies

Studies	Design	Stenosis grade	Cutoff (cm/s)	Sb (%)	St (%)	PPV (%)	NPV (%)	Ac (%)
Moneta (1993) [14]	Prospective	≥70 %	PSV ≥ 200	87	80	63	94	82
Zwolak (1998) [1]	Prospective	≥50 %	PSV ≥ 200	93	94	96	88	93
			EDV ≥ 55	93	100	100	89	95
AbuRahma (2012) [16]	Retrospective	≥70 %	PSV ≥ 320	80	89	84	86	85
			EDV ≥ 100	58	91	83	74	77
			EDV ≥ 110	56	92	85	74	77
			EDV ≥ 120	53	95	89	73	77
		≥50 %	PSV ≥ 240	87	83	93	72	86
			EDV ≥ 40	84	48	80	54	73
			EDV ≥ 45	80	58	82	53	73

Sb sensitivity, *St* specificity, *PPV* positive predictive value, *NPV* negative predictive value, *Ac* accuracy, *PSV* peak systolic velocity, *EDV* end-diastolic velocity

Table 5.3 Most accurate cutoff points to diagnose stenosis of the inferior mesenteric artery in different studies

Studies	Design	Stenosis grade	Cutoff[a]	Sb (%)	St (%)	PPV (%)	NPV (%)	Ac (%)
Pellerito (2009) [9]	Retrospective	≥ 50 %	PSV ≥ 200	90	97	90	97	95
			EDV ≥ 25	40	91	57	83	79
			MAR ≥ 2.5	80	88	67	93	86
AbuRahma (2012) [17]	Retrospective	≥ 50 %	PSV ≥ 250	90	96	90	96	95
			PSV ≥ 260	85	98	94	95	95
			EDV ≥ 80	60	100	100	83	96
			EDV ≥ 80	60	100	100	83	96
			MAR ≥ 4	75	100	100	92	93
			MAR ≥ 4.5	75	100	100	92	93

Sb sensitivity, *St* specificity, *PPV* positive predictive value, *NPV* negative predictive value, *Ac* accuracy, *PSV* peak systolic velocity, *EDV* end-diastolic velocity, *MAR* mesenteric/aortic velocity ratio
[a]PSV and EDV in cm/s; MAR is a ratio

Intraoperative Imaging

The main cause of early failure of arterial reconstructions is technical imperfection. Acute thrombosis of the mesenteric vessels is usually a life-threatening event, resulting in bowel infarction and its drastic consequences. Intraoperative duplex scanning emerges as a suitable option, providing anatomic and hemodynamic information with high accuracy. One of the first attempts to demonstrate the utility of the technique was published in 1987, by Okuhn and colleagues [18], and since then it has gained considerable interest.

In our institution, after the completion of the revascularization, a staff radiologist performs the intraoperative duplex ultrasound with assistance of an ultrasound technician. A 8–18 MHz linear probe is placed in a sterile plastic sheath previously filled with sterile acoustic gel. Sterile gel or saline solution is used for acoustic coupling between the probe and the vessel. Grayscale and color Doppler images are obtained in the native vessels proximal and distal to the revascularization, in the anastomosis, and in the conduct.

A normal exam is one where no technical defects are identified, waveforms have a normal expected appearance, and velocities are within normal range. Abnormal findings are divided into minor and major defects. Minor defects include residual plaque, small intimal flap, and graft kinks, which do not result in significant hemodynamic changes and are not necessarily repaired. Major defects (Fig. 5.4) require immediate revision and include residual stenosis, thrombus, larger intimal flap, dissection, and bypass graft kinks, which result in significant hemodynamic changes and are frequently corrected [19, 20].

Oderich and colleagues retrospectively reported their experience with this routine in 2003 [19]. The incidence of minor defects was 6.6 % and major defects 8.4 %. Major defects included severe residual stenosis [4], thrombus [2], kink [2], bidirectional flow [1], and intimal flap [1] and were promptly revised. One dissection was detected after revision and was treated again. Patients with persistent abnormal ultrasounds had increased risk of graft-related complications (45.5 % vs. 10.5 %; $p = 0.01$), early graft thrombosis (11.7 % vs. 0.97 %; $p = 0.04$), graft-related death (27.3 % vs. 3.5 %; $p = 0.02$), and reintervention (17.6 % vs. 3.9 %).

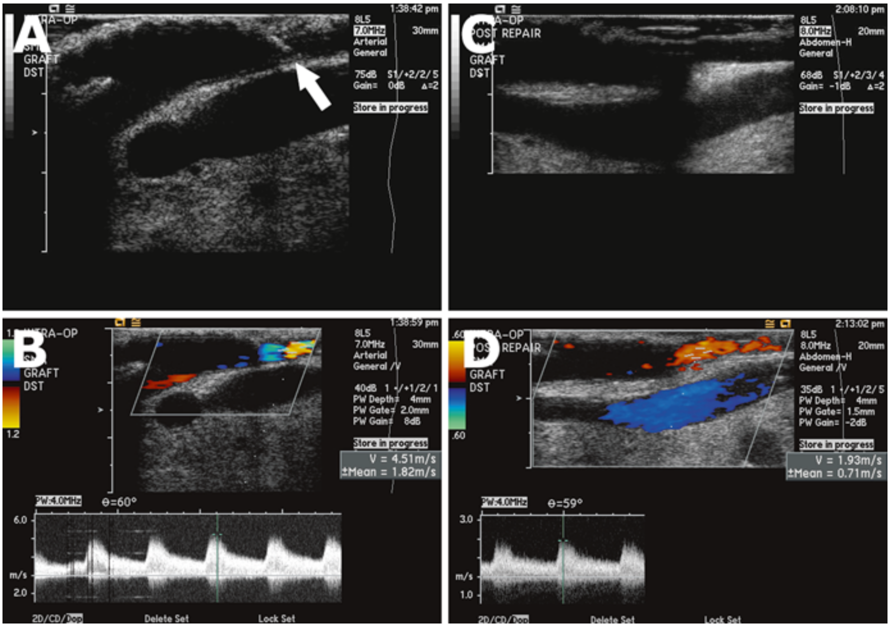

Fig. 5.4 Intraoperative ultrasound of a supraceliac bifurcated aorta to celiac and superior mesenteric artery bypass graft: Grayscale longitudinal image at the distal anastomosis reveals a linear filling defect (**a**, *arrow*). Spectral Doppler waveform confirms hemodynamic disturbance with elevated velocity >4 m/s (**b**). Post revision image reveals resolution of intimal flap and normalization of velocity (**c** and **d**)

Post-intervention Imaging

It is well known that clinical follow-up by itself has a sensitivity of as low as 33 % to predict graft occlusion [21]. This finding obviates the usefulness of a complementary imaging examination, which can detect a threat to the revascularization and prompt intervention to promote maintenance of primary-assisted patency. Unfortunately, there is no consensus on Duplex criteria to define significant recurrent stenosis that needs reintervention.

Prior to the examination, review of surgical notes or procedure report to clarify the type of intervention performed is critical for adequate imaging. Evaluation should include inflow and outflow arteries, anastomosis, and graft or stent.

There is no established criterion to diagnose recurrent stenosis in mesenteric bypass grafts. In our practice, we typically use the same threshold that is applied for native vessels (Fig. 5.5). Liem and colleagues showed their results in duplex scanning follow-up of visceral bypass procedures where ultrasound surveillance led to one reintervention due to stenosis at proximal anastomosis but failed to predict two graft occlusions [22]. An important observation was the finding that the mean PSV generally remains stable over time.

There is some evidence that the established duplex criterion that is used to diagnose stenosis in native arteries may overestimate stenosis rates in stented vessels [23, 24]. This has been more extensively studied in the carotid arteries. One of the possible explanations is that the stent may reduce vessel wall compliance, resulting in higher velocities, even when no narrowing is detected [5]. A retrospective study by Mitchell and colleagues compared mean PSV before and after stenting of the SMA and found post-stenting PSVs higher than 275 cm/s, despite reduction in

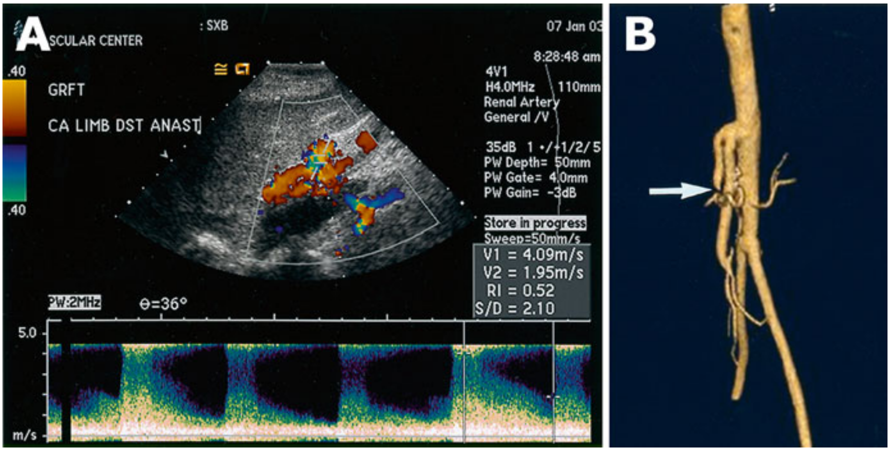

Fig. 5.5 Surveillance Doppler ultrasound of a supraceliac bifurcated aorta to celiac and superior mesenteric artery bypass graft: Longitudinal view of the distal celiac limb anastomosis reveals elevated peak systolic velocity with turbulent flow indicative of significant stenosis (**a**). Computed tomography angiography with volume-rendered 3D reconstructed image confirmed a severe stenosis at the distal anastomosis (**b**)

pressure gradients and satisfactory arteriographic image [25]. Similar findings were published by Baker et al. [23].

In our experience, we have found optimal criteria to identify 50 % or greater stenosis in stented superior mesenteric artery to be PSV of 350 cm/s (100 % sensitivity, 76 % specificity and 79 % accuracy) and in the celiac artery 270 cm/s (100 % sensitivity, 77 % specificity and 80 % accuracy). This is similar to the findings reported by AbuRahma and colleagues, who proposed a PSV over 325 cm/s to detect > 50 % stenosis in stented SMA (89 % of sensitivity, 100 % of specificity, 91 % of accuracy) and 274 cm/s in the celiac artery (96 % of sensitivity, 86 % of specificity, 93 % of accuracy) [24]. Interestingly, in our experience, the majority of patients without significant (<50 %) in-stent stenosis had velocities in the normal range, with a mean stented superior mesenteric artery PSV of 260 cm/s.

An important aspect to consider when evaluating post-stent examinations is stability over time. An exam shortly after the procedure is helpful to establish a baseline, which serves for comparison with future follow-up studies. Although it has been suggested a potential role for meal tests to help differentiate elevated velocities related to stenosis or not in stented mesenteric arteries [5], to this date there is no convincing literature that it is helpful. Given the limitations of available studies and controversy regarding optimal criteria to identify in-stent restenosis, it is prudent to use caution interpreting elevated velocities on duplex ultrasound examinations (Fig. 5.6).

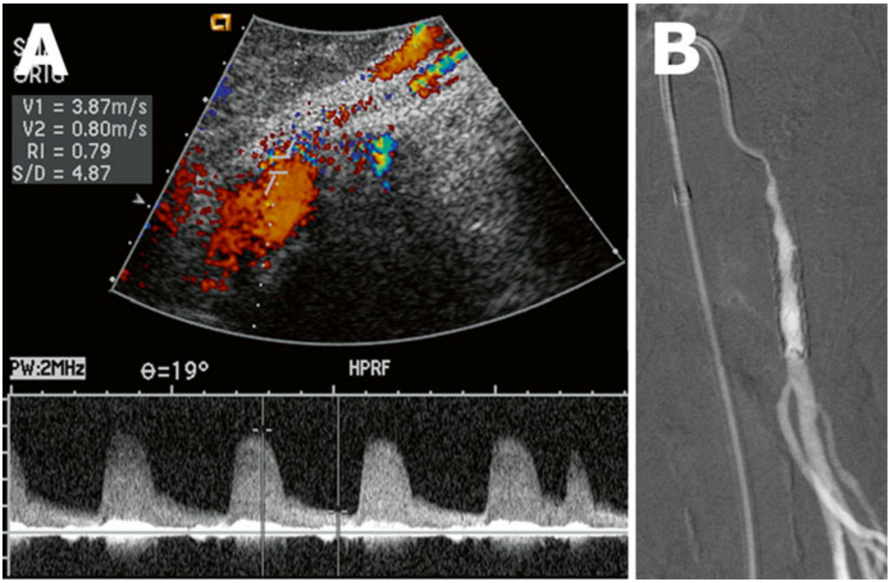

Fig. 5.6 Surveillance Doppler ultrasound of a stented superior mesenteric artery: Longitudinal view of the origin of the superior mesenteric artery reveals elevated peak systolic velocity with turbulent flow indicative of significant stenosis (**a**). Selective angiogram confirmed a severe in-stent stenosis (**b**)

Other Applications

Median Arcuate Ligament Syndrome

Median arcuate ligament compression syndrome (Fig. 5.2) remains a controversial entity. These patients often present with abdominal pain, which is believed to be related to compression of the celiac artery by the median arcuate ligament of the diaphragm. During inspiration, the celiac artery moves caudally, and the median arcuate ligament moves ventrally, which minimizes compression. During expiration, the opposite happens which results in maximal vessel compression. The questionable clinical significance of this entity is largely supported by the fact that a significant number of individuals in the general population have asymptomatic celiac axis compression [26]. Furthermore, although immediate relief has been widely reported with surgical decompression, the long-term success is poor with recurrence rates in the range of 50–83 %. There is a great deal of debate on the pathophysiology of this syndrome with respect to ischemia, steal phenomena, or ganglionic compression of the arterial adventitia causing pain.

Irrespective of these controversies, duplex ultrasound has been widely applied to screen patients with suspected median arcuate ligament syndrome. The variations in celiac artery compression related to respiration seen in celiac compression syndrome can be well documented with duplex ultrasound. Findings include a significant change in PSV between inspiration and expiration, associated with elevated PSV on expiration (Fig. 5.2). At times, the velocity during inspiration remains above the threshold for significant stenosis indicating a degree of fixed stenosis, which can develop over time. Commonly, another imaging modality such as computed tomography angiography (CTA) or magnetic resonance angiography (MRA) is used to anatomically delineate and confirm the diagnosis (see Chap. 7). Careful interpretation of the ultrasound findings seems prudent; it must be understood that respiratory changes in PSV are seen in patients with celiac compression syndrome but can also be seen in normal individuals. Clinical presentation and thorough evaluation are necessary to establish this diagnosis.

Acute Mesenteric Ischemia

Although duplex ultrasound has been obtained in patients with suspected acute intestinal ischemia, its applicability is limited, and it cannot be recommended as a test of choice in this setting [27, 28]. The last updated ACCF/AHA guideline for patients with peripheral arterial disease, published in 2013, considers duplex ultrasound as not an appropriate diagnostic tool for acute mesenteric ischemia, strongly not recommending its use [29].

Inflammatory Bowel Disease

Recent reports have raised interest in flow patterns at the splanchnic vessels to identify activity of Crohn's disease. These studies have shown that patients with active Crohn's often have hyperdynamic mesenteric circulation, which can be demonstrated by evaluating PSV, resistance index, and flow estimates in the SMA, as well as flow patterns at the aorta and distal small bowel vasculature. Even though it could be a useful tool in the future, the ability to detect disease activity still shows conflicting results [30].

Mesenteric Artery Dissection and Aneurysms

Ultrasound is frequently obtained in patients with abdominal pain. Isolated mesenteric artery dissections (Fig. 5.7) and aneurysms can be incidentally diagnosed or found to be a cause of the patient's symptoms. Among patients with aneurysms, ultrasound is often used for the assessment of size diameter during follow-up, prior or after an intervention.

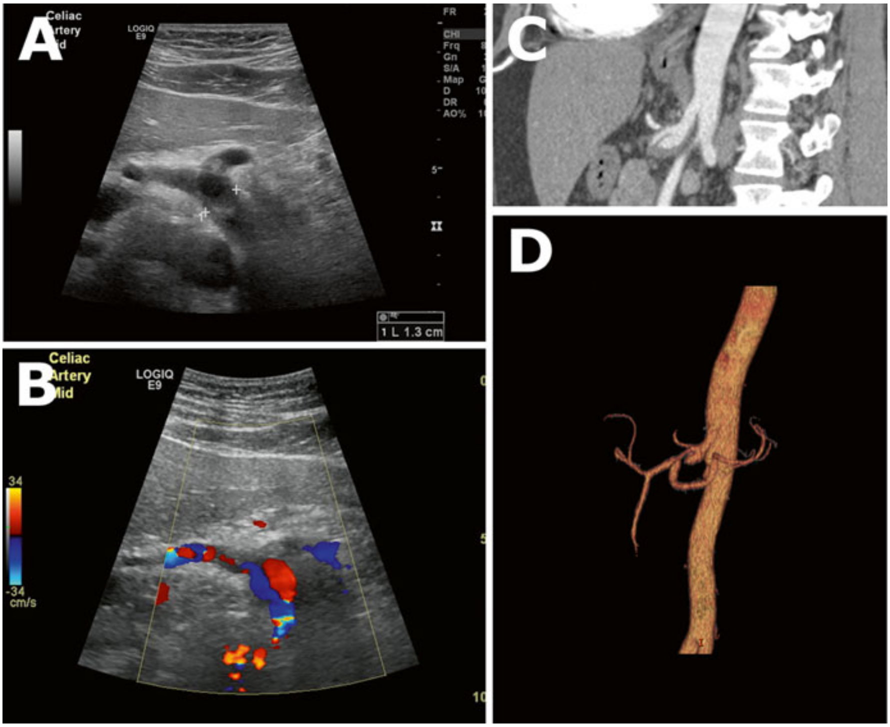

Fig. 5.7 Ultrasound performed during investigation of abdominal pain suggested celiac artery dissection (**a** and **b**). Computed tomography angiography confirms the diagnosis (**c** and **d**)

Conclusion

Duplex examination is widely used in the diagnosis and follow-up of mesenteric artery disease. It is well accepted as the first screening study in patients with symptoms of chronic mesenteric ischemia and suspected mesenteric artery occlusive disease. It is safe, noninvasive, low cost without ionizing radiation, and readily accessible. While well-established criteria are available for native vessel disease, caution should be used with elevated velocities in the stented arteries.

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