Duplex Ultrasound for Evaluation and Surveillance of Fenestrated, Branched, and Parallel Stent-Grafts

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Thanila A. Macedo and Gustavo S. Oderich

Introduction

Fenestrated and branched stent-grafts have been increasingly utilized to treat complex aortic aneurysms offering a less invasive option. However lifelong surveillance is required to monitor for complications that can threat stent durability. Computed tomography angiography (CTA) is the most widely used modality to follow-up patients after endovascular procedure; however, it is associated with risks from iodinated contrast injection, radiation, and higher costs. Ultrasound is an attractive imaging alternative due to its low cost, wide availability, lack of ionizing radiation, or use of iodinated contrast. It is limited by inferior sensitivity and specificity to identify endoleaks [1], although recent literature has demonstrated that the use of ultrasound contrast can overcome this limitation. Ultrasound still suffers from operator dependency and its inability to reliably detect morphologic complications such as stent fracture or migration. Nonetheless, this modality can promptly diagnose branch vessel occlusion, stenosis, and endoleaks, which can adversely affect patient outcomes.

Our protocol typically includes a baseline study prior to stent-graft implantation, followed by target vessel ultrasound at 6–8 weeks, 6 months, and yearly after the operation. This chapter focuses on technical aspects of duplex ultrasound of renal-mesenteric arteries, diagnostic interpretation criteria, and examples of normal and abnormal findings in patients with fenestrated and/or branched endografts.

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Technique

The same basic principles applied for standard evaluation of the renal and mesenteric arteries are used to evaluate patients with fenestrated and branched stent-grafts. Duplex ultrasound evaluation of the renal and mesenteric circulation can be technically challenging. In experienced hands, the time for examination completion range between 40 and 60 min depending on patient's characteristics and on the number of vessels to be interrogated. Besides experience and knowledge of the vascular anatomy and the specific stent-graft design used in the patient, some factors can potentially 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, experienced sonographer, and appropriate patient selection are keys to success.

Patients are asked to fast for 8–12 h prior to the examination with a low-fiber dinner the night before the examination to minimize bowel gas. Furthermore, the established criteria currently used to diagnose mesenteric artery disease are based on fasting velocities.

Prior to the examination, review of surgical or procedure notes and correlation with CTA studies is helpful to define stent-graft designs and which specific vessels were target by fenestrations or branches, as well as bridging stent length and configuration.

The examination is typically performed with the patient in supine position and transducer at the midline or coronal window through the liver (Fig. 12.1). When bowel gas prevents adequate visualization of the vessels, patients may be turned to a lateral oblique or lateral decubitus, which may provide a better window. Patient cooperation with breath hold is critical to record adequate Doppler spectral samples. We most commonly use the C1-5 curved transducer with starting frequency of 4.5 MHz and on patients with challenging body habitus we use the

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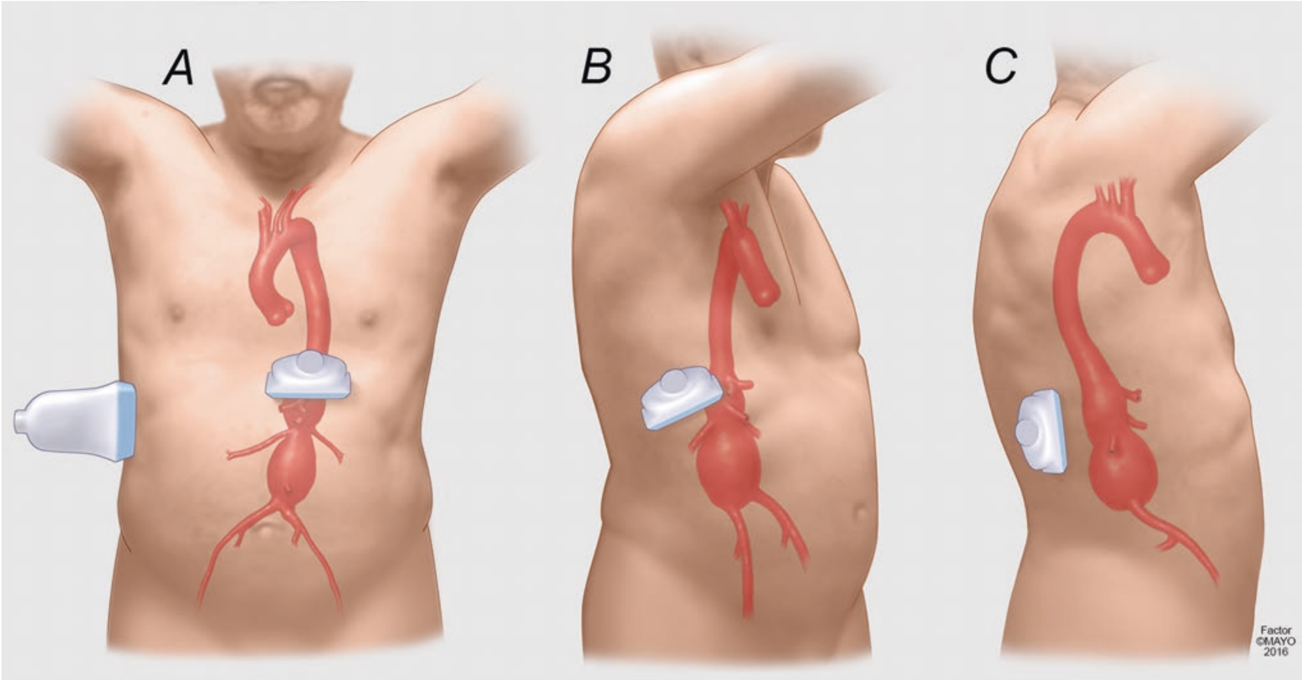


Fig. 12.1 Patient positioning for duplex ultrasound. Patient typically lies supine and transducer is located in the midline or lateral upper abdomen (**a**). Oblique (**b**) and lateral (**c**) decubitus are frequently used if better visualization is needed. Occasionally, the liver is used for window to obtain coronal images of the mesenteric and renal arteries (**c**). By permission of Mayo Foundation for Medical Education and Research.

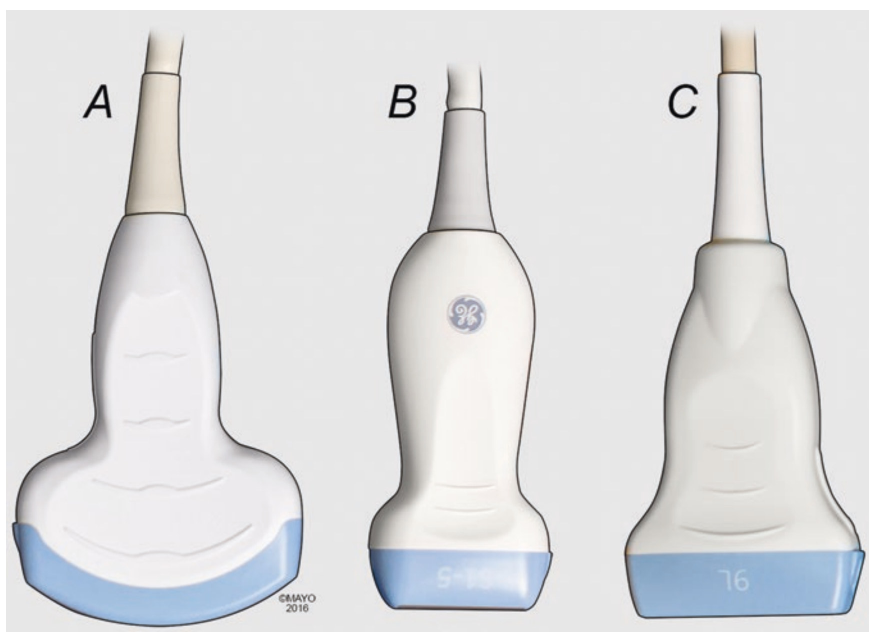
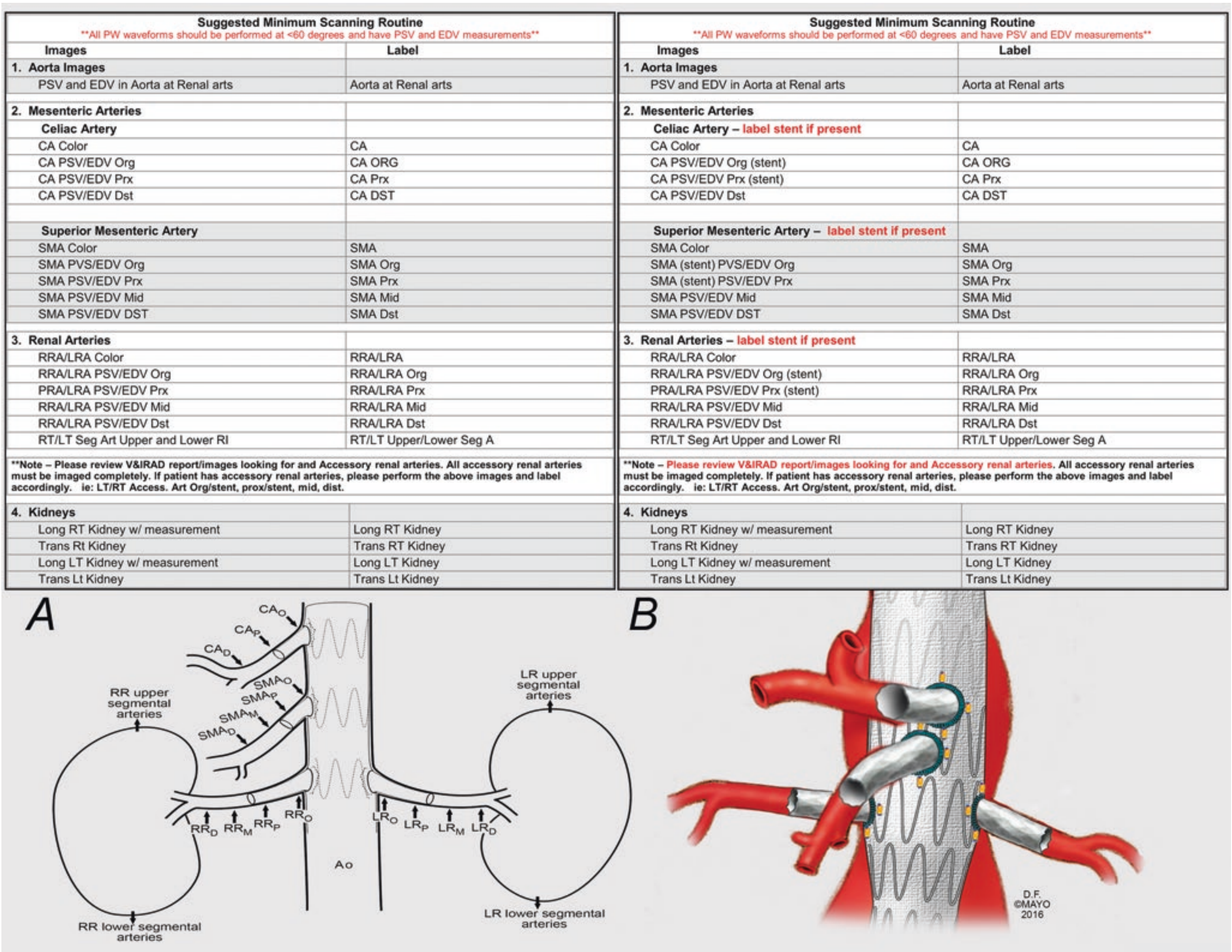


Fig. 12.2 Transducers used for duplex evaluation of renal and mesenteric arteries prior to fenestrated and branched endovascular procedure. Most commonly used is the C1-5 MHz (**a**). In patients with large body habitus, the S1-5 vector transducer (**b**) is often used. Occasionally, the 9L linear transducer (**c**) is an excellent choice for patients with slim body habitus. By permission of Mayo Foundation for Medical Education and Research.

S1-5 MHz vector transducer with lower frequency of 2 MHz. Occasionally, in small patients we are able to use the 9 MHz linear transducer with high frequencies up to 9 MHz (Fig. 12.2). Sonographers are instructed to use the smallest possible Doppler angle of insonation, which should always be less than 60°. It has been well documented the variations of peak systolic velocity measurement as a function of angle of insonation [2]. This should be kept in mind especially in follow-up comparison examinations where similar Doppler angle should be used to minimize velocity variations that may be incorrectly attributed to disease progression.



Suggested Minimum Scanning Routine **All PW waveforms should be performed at <60 degrees and have PSV and EDV measurements**	
Images	Label
1. Aorta Images	
PSV and EDV in Aorta at Renal arts	Aorta at Renal arts
2. Mesenteric Arteries	
Celiac Artery	
CA Color	CA
CA PSV/EDV Org	CA ORG
CA PSV/EDV Prx	CA Prx
CA PSV/EDV Dst	CA DST
Superior Mesenteric Artery	
SMA Color	SMA
SMA PVS/EDV Org	SMA Org
SMA PSV/EDV Prx	SMA Prx
SMA PSV/EDV Mid	SMA Mid
SMA PSV/EDV DST	SMA Dst
3. Renal Arteries	
RRA/LRA Color	RRA/LRA
RRA/LRA PSV/EDV Org	RRA/LRA Org
PRA/LRA PSV/EDV Prx	RRA/LRA Prx
RRA/LRA PSV/EDV Mid	RRA/LRA Mid
RRA/LRA PSV/EDV Dst	RRA/LRA Dst
RT/LT Seg Art Upper and Lower RI	RT/LT Upper/Lower Seg A
**Note – Please review V&IRAD report/images looking for and Accessory renal arteries. All accessory renal arteries must be imaged completely. If patient has accessory renal arteries, please perform the above images and label accordingly. ie: LT/RT Access. Art Org/stent, prox/stent, mid, dist.	
4. Kidneys	
Long RT Kidney w/ measurement	Long RT Kidney
Trans Rt Kidney	Trans RT Kidney
Long LT Kidney w/ measurement	Long LT Kidney
Trans Lt Kidney	Trans Lt Kidney

Suggested Minimum Scanning Routine **All PW waveforms should be performed at <60 degrees and have PSV and EDV measurements**	
Images	Label
1. Aorta Images	
PSV and EDV in Aorta at Renal arts	Aorta at Renal arts
2. Mesenteric Arteries	
Celiac Artery – label stent if present	
CA Color	CA
CA PSV/EDV Org (stent)	CA ORG
CA PSV/EDV Prx (stent)	CA Prx
CA PSV/EDV Dst	CA DST
Superior Mesenteric Artery – label stent if present	
SMA Color	SMA
SMA (stent) PVS/EDV Org	SMA Org
SMA (stent) PSV/EDV Prx	SMA Prx
SMA PSV/EDV Mid	SMA Mid
SMA PSV/EDV DST	SMA Dst
3. Renal Arteries – label stent if present	
RRA/LRA Color	RRA/LRA
RRA/LRA PSV/EDV Org (stent)	RRA/LRA Org
PRA/LRA PSV/EDV Prx (stent)	RRA/LRA Prx
RRA/LRA PSV/EDV Mid	RRA/LRA Mid
RRA/LRA PSV/EDV Dst	RRA/LRA Dst
RT/LT Seg Art Upper and Lower RI	RT/LT Upper/Lower Seg A
**Note – Please review V&IRAD report/images looking for and Accessory renal arteries. All accessory renal arteries must be imaged completely. If patient has accessory renal arteries, please perform the above images and label accordingly. ie: LT/RT Access. Art Org/stent, prox/stent, mid, dist.	
4. Kidneys	
Long RT Kidney w/ measurement	Long RT Kidney
Trans Rt Kidney	Trans RT Kidney
Long LT Kidney w/ measurement	Long LT Kidney
Trans Lt Kidney	Trans Lt Kidney

Fig. 12.3 Protocol for duplex ultrasound scanning of the renal and mesenteric arteries prior (**a**) and post procedure (**b**). By permission of Mayo Foundation for Medical Education and Research. All rights reserved

Images are acquired following a standard protocol (Fig. 12.3). 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. Next, attention is turned to mesenteric and renal arteries. Color Doppler is used to identify the arteries and to guide sample volume placement for spectral Doppler analysis. The stents are occasionally discretely identified, mostly in patients with favorable body habitus (Fig. 12.4). 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 (Fig. 12.5). The CA branches (hepatic and splenic) are best viewed in transverse orientation. The celiac artery is a short vessel and velocities are obtained at the origin, proximal, and distal segment during tidal breathing. In specific cases, measurements can be obtained in deep inspiration and expiration for evaluation of median arcuate ligament compression 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°. The inferior mesenteric artery (IMA) is not routinely evaluated, but can be evaluated when specifically requested. It is best identified using the transverse plane, arising from the anterior or slightly 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 can be challenging. Vessel identification is typically not an issue except in recent postoperative stage when there is abundant bowel gas and lack of patient cooperation. In published

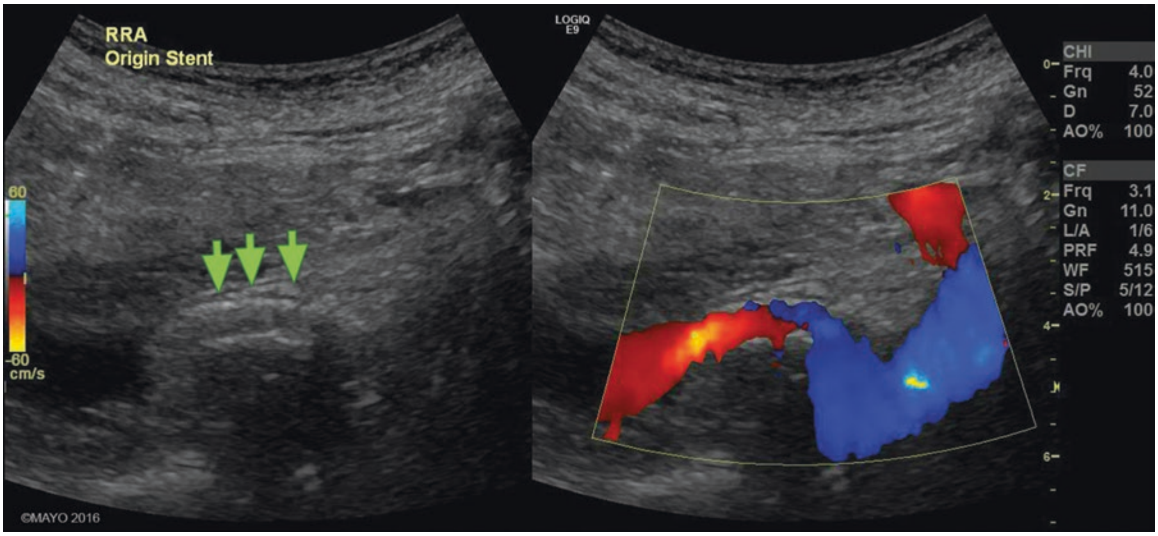


Fig. 12.4 Gray scale and color flow Doppler ultrasound of the right renal artery. Occasionally, the stent can be discretely visualized in gray scale as hyperechoic lines delineating the metallic struts (*arrows*). Color flow Doppler confirms patency of the stent. By permission of Mayo Foundation for Medical Education and Research. All rights reserved

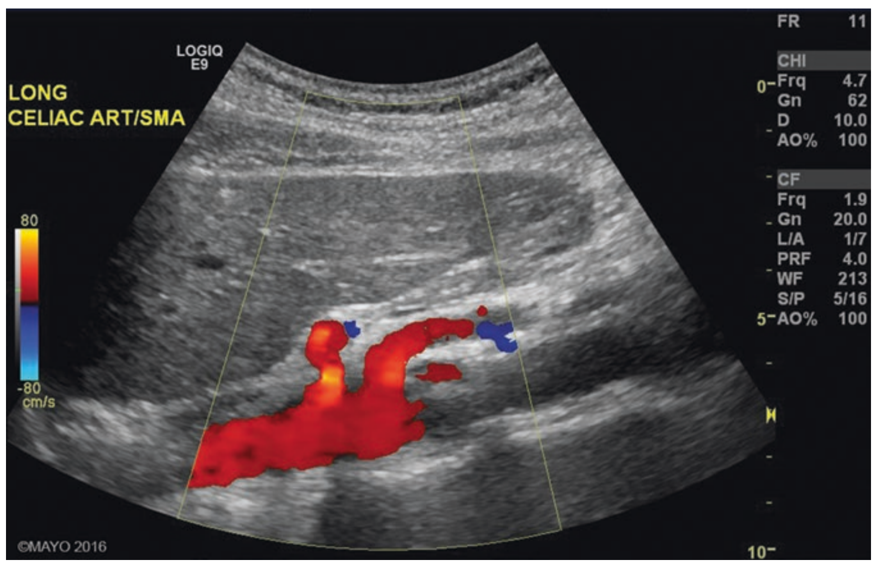


Fig. 12.5 Color Doppler ultrasound of the mesenteric arteries. The celiac and superior mesenteric arteries are best identified in the midline longitudinal plane using color Doppler. By permission of Mayo Foundation for Medical Education and Research. All rights reserved

series of ultrasound evaluation for mesenteric artery disease, the mesenteric arteries have been successfully identified in 83–98 % of patients [3–5].

The renal arteries arise from the lateral wall of the aorta about 1–2 cm below the SMA. The right renal artery originates from the anterolateral wall and subsequently courses behind the IVC. Occasionally, it may be difficult to obtain optimal Doppler angle from an anterior approach as the artery courses perpendicular to the beam, and a lateral approach may be necessary for better Doppler angle of insonation. The left renal artery typically has its origin from the posterolateral aorta. A helpful landmark is the left renal vein which usually lies anterior to the renal artery. The "banana peel" view optimally demonstrates the renal artery origin from a coronal plane using the liver as a window (Fig. 12.6). Accessory renal arteries are a challenge for ultrasound evaluation because of its small size and are not infrequently missed. Otherwise, the renal arteries are identified in most patients referred for evaluation, with studies quoting visualization in 84–90 % of patients [6]. With experienced sonographers who are highly skilled, this number should be in the higher end of the spectrum. From a lateral approach, segmental renal artery waveforms are obtained and resistive of indices (RIs) are calculated. Screening views of the kid-

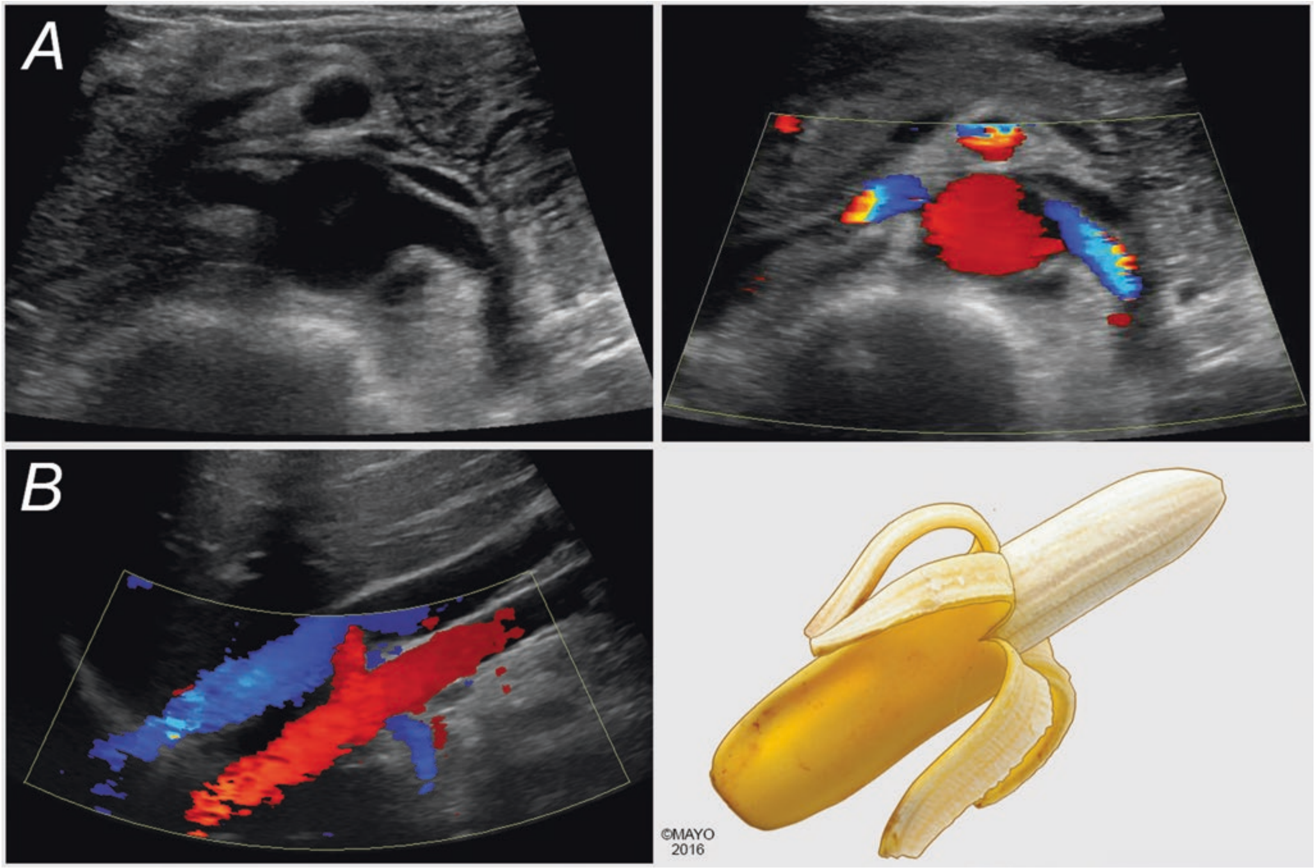


Fig. 12.6 Gray scale and color Doppler of the renal arteries origin. The renal arteries origin can be found with the transducer in transverse plane midline (**a**). Alternatively, the coronal plane using the liver as a window can be used to obtain the coveted "banana peel" image where the renal arteries origin from the aorta resemble peeling of a banana (**b**). By permission of Mayo Foundation for Medical Education and Research. All rights reserved

neys are obtained to evaluate for renal mass, renal size and hydronephrosis. Measurements of PSV and EDV are obtained at the origin, proximal, mid, and distal segments. When a stent is present, at least two velocities are obtained at the origin and proximal segment.

Mesenteric Arteries

The normal celiac artery and SMA have distinct waveforms reflecting the different end-organ blood supply requirements (Fig. 12.7). The major branches of the celiac artery supply the liver and spleen. These organs have a high demand for arterial flow resulting in a low resistance arterial waveform with substantial flow throughout diastole. The SMA supplies the small bowel and proximal colon. In the fasting state, the Doppler waveform is high-resistance with diminished flow during diastole. In the post-prandial state, due to the normal hyperemic response, the end-organ resistance is decreased, and blood flow is increased for adequate food absorption, resulting in low resistance arterial waveform similar to the celiac artery and increased diameter. The IMA supplies the distal colon and upper rectum, and therefore has a high-resistance waveform, similar to the SMA. The IMA is usually not affected by meals unless this vessel provides important compensatory collateral flow to the SMA

Anatomic variations in the origin of the hepatic arteries, which occur in approximately 20 % of the population, can account for a normal low resistance arterial waveform in the SMA during fasting state. The most common variation 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 lower resistance pattern in the SMA, resembling the waveform of a CA. Confirmation with the patient that fasting directions were followed, along with a normal PSV and the finding of a non-turbulent waveform with a clear systolic window favor the diagnosis of an anatomic anomaly.

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 in patients undergoing abdominal aortography [7]. In that study, a PSV of

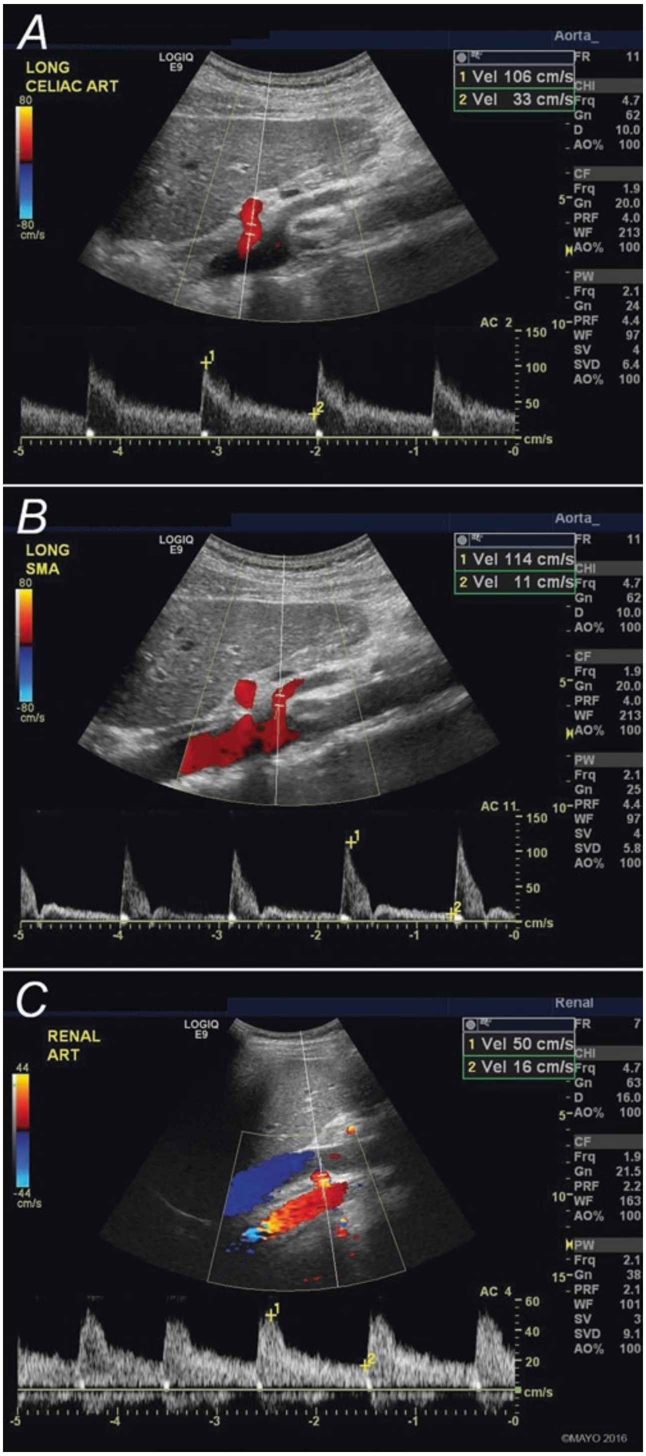


Fig. 12.7 Normal mesenteric and renal spectral Doppler waveform. The celiac artery has a low resistance waveform reflecting the constant high blood supply to the liver and spleen with persistent flow throughout diastole (**a**). The superior mesenteric artery has a high resistance waveform in fasting state with diminished flow through diastole (**b**) and a low resistance waveform during post-prandial state reflecting the increased blood flow necessary for food absorption. Similarly to the liver, the kidneys require constant high blood flow, consequently the normal renal artery waveform will have a low resistance pattern (**c**). By permission of Mayo Foundation for Medical Education and Research.

>275 cm/s for the SMA and >200 cm/s for the CA accurately detected stenosis greater than 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. 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 [3]. 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.

Other velocity criterion has been proposed in the literature. A retrospective study has identified EDV greater than 45 cm/s as the most accurate predictor of a greater than 50 % SMA stenosis [8]. The same group later published a prospective study validating this finding with sensitivity of 90 % and specificity of 91 %. The same parameters for a greater than 50 % stenosis in CA are, respectively, 93 % and 100 % [5].

More recently, a retrospective study of 153 patients who underwent angiography to evaluate chronic mesenteric ischemia reported 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 %) and for the celiac 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 [9].

Only a few studies have validated the criteria for IMA stenosis given its limited relevance in clinical practice. A PSV higher than 200 cm/s was found to diagnose a greater than 50 % stenosis with a specificity of 90 % and specificity of 97 % [4]. In another study an IMA PSV of 250 cm/s predicted greater than 50 % stenosis with 95 % of accuracy or 270 cm/s could predict a greater than 70 % stenosis with accuracy of 92 %. In our laboratory, we use 275 cm/s to diagnose 70 % or greater stenosis based on our previous experience review [10]. The data concerning previous studies and the established criteria for SMA, CA, and IMA stenosis are summarized in Tables 12.1, 12.2, and 12.3.

There are no available studies validating duplex ultrasound criteria for mesenteric fenestrations or branches. Identification of stenosis and kinks is of paramount importance to identify target vessels at risk for occlusion. Because fenestrated and branched stent-grafts have multiple radiopaque markers to help guide accurate device deployment, computed tomography angiography often allows limited evaluation of branch-vessel stenosis due to associated metallic artifact and small

Table 12.1 Most accurate cutoff points to diagnose stenosis of the superior mesenteric artery in different studies

–	Design	Stenosis grade	Cutoff (cm/s)	Sb (%)	St (%)	PPV (%)	NPV (%)	Ac (%)
Moneta (1993) [3]	Prospective	≥70 %	PSV ≥ 275	92	96	80	99	96
Zwolak (1998) [5]	Prospective	≥50 %	PSV ≥ 300	60	100	100	73	81
AbuRahma (2012) [9]	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 sensibility, *St* specificity, *PPV* positive predictive value, *NPV* negative predictive value, *Ac* accuracy, *PSV* peak systolic velocity, *EDV* end-diastolic velocity

Table 12.2 Most accurate cutoff points to diagnose stenosis of the celiac artery in different studies

–	Design	Stenosis grade	Cutoff (cm/s)	Sb (%)	St (%)	PPV (%)	NPV (%)	Ac (%)
Moneta (1993) [3]	Prospective	≥70 %	PSV ≥ 200	87	80	63	94	82
Zwolak (1998) [5]	Prospective	≥50 %	PSV ≥ 200	93	94	96	88	93
			EDV ≥ 55	93	100	100	89	95
AbuRahma (2012) [9]	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 sensibility, *St* specificity, *PPV* positive predictive value, *NPV* negative predictive value, *Ac* accuracy, *PSV* peak systolic velocity, *EDV* end-diastolic velocity

Table 12.3 Most accurate cutoff points to diagnose stenosis of the inferior mesenteric artery in different studies

–	Design	Stenosis grade	Cutoff[a]	Sb (%)	St (%)	PPV (%)	NPV (%)	Ac (%)
Pellerito (2009) [4]	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) [9]	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 sensibility, *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

vessel size. In most practices, correlation of CTA and duplex ultrasound is used for surveillance. There is no well-established criterion to identify in-stent stenosis within renal and/or mesenteric fenestrated branches. Similarly, there is no consensus on which duplex criteria should be used to define significant recurrent stenosis that requires re-intervention.

There is evidence in the literature that the duplex criterion used to diagnose stenosis in native arteries may overestimate stenosis in stented vessels. 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 in the absence of stenosis. A retrospective study compared mean PSV before and after stenting of the SMA and found post-stenting PSVs higher than 275 cm/s, despite reduction in pressure gradients and satisfactory arteriographic image [11]. Similar findings were published by Baker et al. [10]. In our experience [12], 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, Figs. 12.8 and 12.9). This is similar to

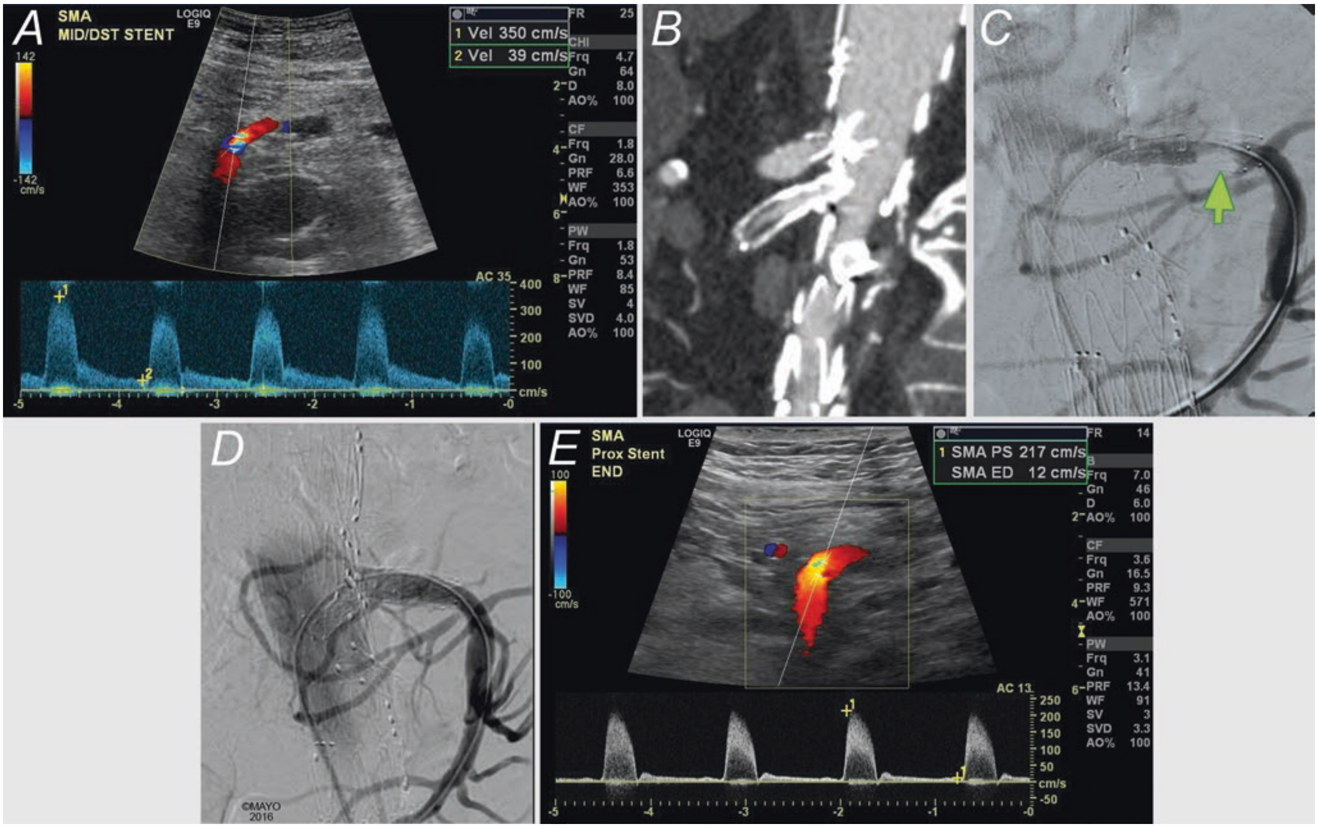


Fig. 12.8 Duplex ultrasound of fenestrated endograft with a superior mesenteric artery stent showing elevated velocities consistent with in-stent stenosis (**a**). Correlation with CTA (**b**) and catheter angiogram (**c**) confirmed a significant stenosis. Angiogram post angioplasty and redo stenting shows resolution of stenosis with widely patent SMA stent (**d**) and normal velocities on ultrasound (**e**). By permission of Mayo Foundation for Medical Education and Research. All rights reserved

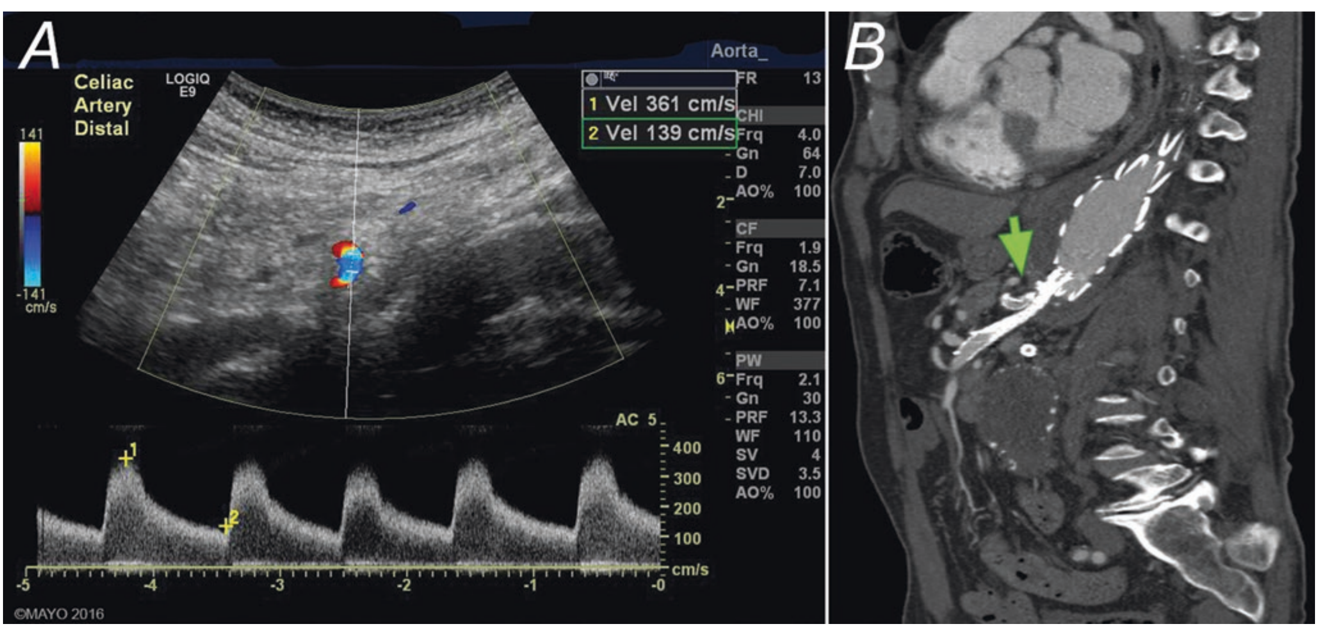


Fig. 12.9 Duplex ultrasound and computed tomography angiography (CTA) of fenestrated endograft with a celiac artery stent. Spectral Doppler demonstrates elevated peak systolic velocity of 361 cm/s associated with turbulence and color aliasing (**a**). In our experience, elevated velocity greater than 270 cm/s is indicative of 50 % or greater stenosis. Correlation with CTA in sagittal view confirmed stent kink and luminal narrowing (*arrow*) at the site of high velocities (**b**). By permission of Mayo Foundation for Medical Education and Research. All rights reserved

previously reported findings proposing 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) [13]. Interestingly, in our experience the majority of patients with less than 50 % in-stent stenosis had velocities in the normal range, with a mean stented superior mesenteric artery PSV of 260 cm/s.

Renal Arteries

The general principles of renal duplex scanning are similar to those for other sites. The renal artery can be visualized with B-mode and color-flow imaging. Spectral Doppler waveforms for velocity measurements are obtained within the stent and native artery to characterize flow pattern and identify stenosis. The stent can be discretely identified in some patients with favorable body habitus. Similar to the mesenteric arteries, a localized flow disturbance with elevated velocity is indicative of high-grade stenosis. One of the main challenges in renal duplex scanning is to locate the renal artery and to obtain a satisfactory pulsed Doppler evaluation. These vessels are especially difficult to visualize because of its small size, deep location, and variable anatomy. As previously discussed, the study can be limited in the presence of obesity, bowel gas, limited scanning window, and respiratory motion.

The normal renal artery waveform reflects low vascular resistance in the renal bed with persistent flow throughout diastole (see Fig. 12.7). Presence of renal artery stenosis results in focally increased renal artery peak systolic velocity. Normal renal arteries typically have a PSV of less than 180 cm/s. Several studies have published the criteria to diagnose greater than 60 % renal artery stenosis suggesting a threshold velocity of 180 cm/s and 200 cm/s with high sensitivity and specificity [14, 15]. The renal artery to aortic ratio (RAR) can also be used to diagnose renal artery stenosis. A RAR of 3.5 or greater has been reported to diagnose renal artery stenosis with high sensitivity. At the Mayo Clinic, criteria for native renal artery stenosis greater than 60 % include primarily a PSV >200 cm/s. In patients with PSV between 180 and 200 cm/s, stenosis is suggested if other suspicious findings are present such as elevated aortorenal ratio, post-turbulent waveform, significant drop in velocity at the mid and distal segment and/or tardus parvus waveform in segmental arteries. Renal artery occlusion is indicated by absence of flow in a visualized segment of renal artery (Fig. 12.10). Occlusion is suspected when the renal arteries cannot be discretely identified despite adequate visualization of the expected area.

Duplex scanning of the renal artery hilum is used to identify tardus parvus waveforms with delayed systolic upstroke, which may be associated with a hemodynamically significant renal artery stenosis. Using a flank approach, pulsed Doppler waveforms are relatively easy and quick to be obtained in the renal artery hilum. Several renal artery hilar parameters have been described including acceleration time (AT), acceleration index (AI), early systolic peak (ESP), and tardus/parvus pattern. The specificity for hilar parameters is greater than 90 % in most reports, but sensitivity varies greatly between 32 and 93 % [16, 17].

Ultrasound evaluation of the renal parenchyma has also been used to predict clinical outcomes of renal revascularizations. Measurements of kidney length and evaluation of parenchymal flow patterns are utilized frequently as surrogate markers of renal parenchymal disease. Doppler waveforms taken from segmental arteries reflect renovascular resistance. Some of the parameters that have been used to quantify renovascular resistance include end-diastolic ratio (EDR: end-diastolic velocity/peak systolic velocity) and the renal-resistive index (RRI: peak systolic velocity—end-diastolic velocity/peak systolic velocity). Elevated renal parenchymal resistance is associated with low EDR and high RRI and correlates with severe renovascular parenchymal disease, which predicts less favorable results with renal artery revascularization. Rademarcher and associates reported on the use of RRI to predict outcomes of renal artery angioplasty and stenting in a prospective study. RRI greater than 0.80 was associated with no improvement in renal function, blood pressure or kidney survival, thereby identifying patients who were unlikely to respond to revascularization [18].

Similar to the mesenteric arteries, criterion for stented renal arteries has not been established. Controversy remains whether the criterion for native artery is adequate to evaluate restenosis in stented renal arteries (Fig. 12.11). A study in patients treated with fenestrated stent-grafts has proposed a revised criterion for renal artery stenosis (>60 %) consisting of PSV >280 cm/s, with sensitivity of 93 % and specificity of 100 %. For RAR, the proposed criterion was a ratio of >4.5, which had sensitivity of 83 % and specificity of 89 % [19].

An important aspect to consider when evaluating post-stent examinations is stability over time. In the absence of validated established criteria, an examination shortly after the procedure is helpful to establish a baseline, which serves for comparison with future studies. 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.

Contrast-Enhanced Ultrasound

Contrast-enhanced ultrasound (CEUS) is an emerging technique with potential advantages over standard color Doppler ultrasound. The contrast media utilized consists of stabilized

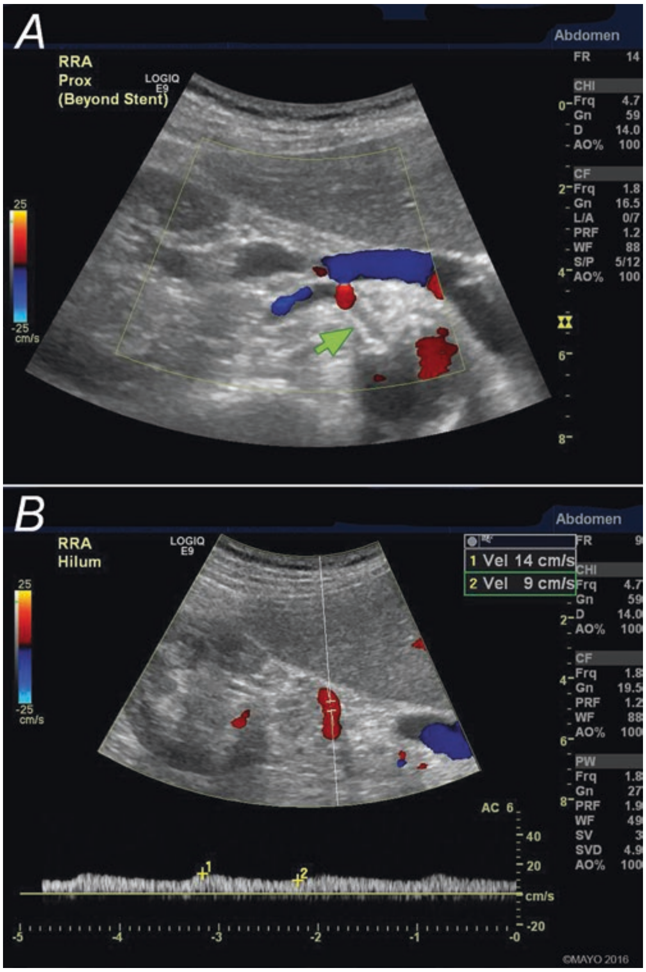


Fig. 12.10 Color Doppler ultrasound of an occluded renal artery stent. Color Doppler demonstrates the absence of flow within a well depicted renal artery stent (**a**, *arrow*). Color flow is demonstrated in the distal renal artery with low velocity and a tardus parvus waveform (**b**) which are secondary findings associated with a proximal occlusion. By permission of Mayo Foundation for Medical Education and Research. All rights reserved

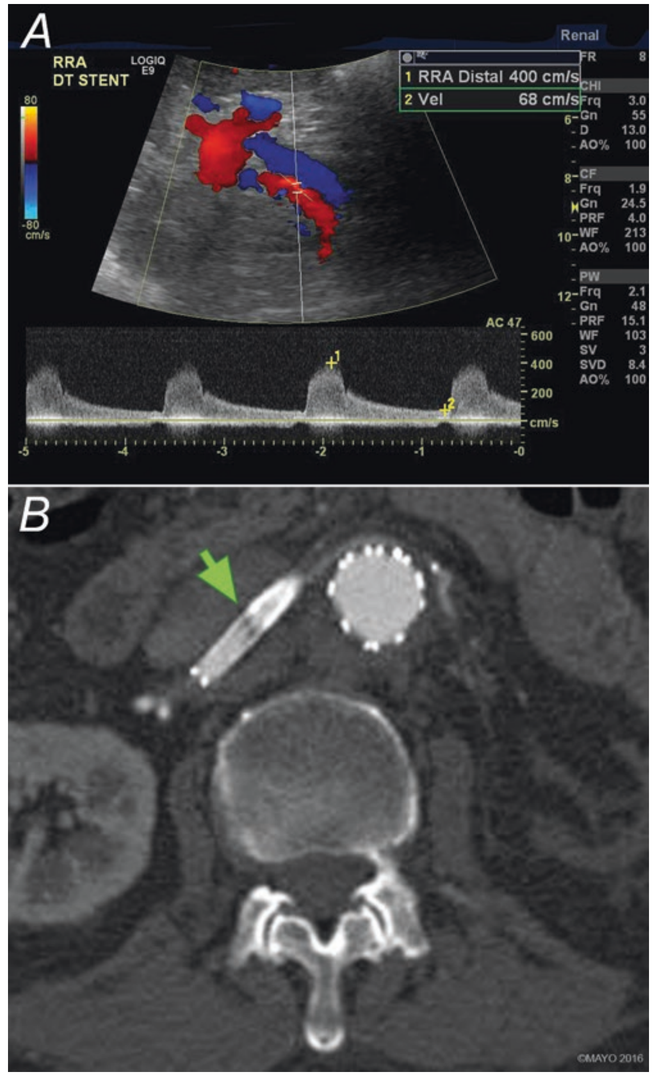


Fig. 12.11 Duplex ultrasound and CTA of a right renal artery stent in a patient with fenestrated endograft. Elevated velocity in the distal right renal artery stent up to 400 cm/s (**a**) is indicative of recurrent in-stent stenosis. CTA demonstrates stenosis with filling defect (**b**, *arrow*) in the stent corresponding to the area of high velocity. By permission of Mayo Foundation for Medical Education and Research. All rights reserved

microspheres of sulfur hexafluoride or perfluorocarbon encapsulated by phospholipid shell. These are blood pool agents without extravascular distribution excreted by the respiratory system. It does not affect the kidneys and therefore can be safely used in patients with renal impairment. Typical dose administered is between 1 and 2.5 ml followed by a 5 ml saline bolus. It is important to point out that ultrasound contrast is not FDA-approved for use in endograft evaluation. It has been used for cardiac evaluation and recently approved for evaluation of liver lesions. The intravascular contrast is believed to improve detection of endoleaks. It has been shown to be as accurate as CTA or some showing even superior results with the added information regarding flow direction and hemodynamics to better understand the endoleak. It is also comparable to CTA for aneurysm diameter measurement and evaluation of target vessels during surveillance [20–22].

Other Issues

Median Arcuate Ligament Compression

Median arcuate ligament compression can affect velocity measurements in the celiac axis and cause compression, fracture, or dislodgement of celiac stents. During expiration, there is dynamic compression of the celiac artery which resolves or significantly improves during inspiration. The unclear pathophysiology and significance of the anatomic

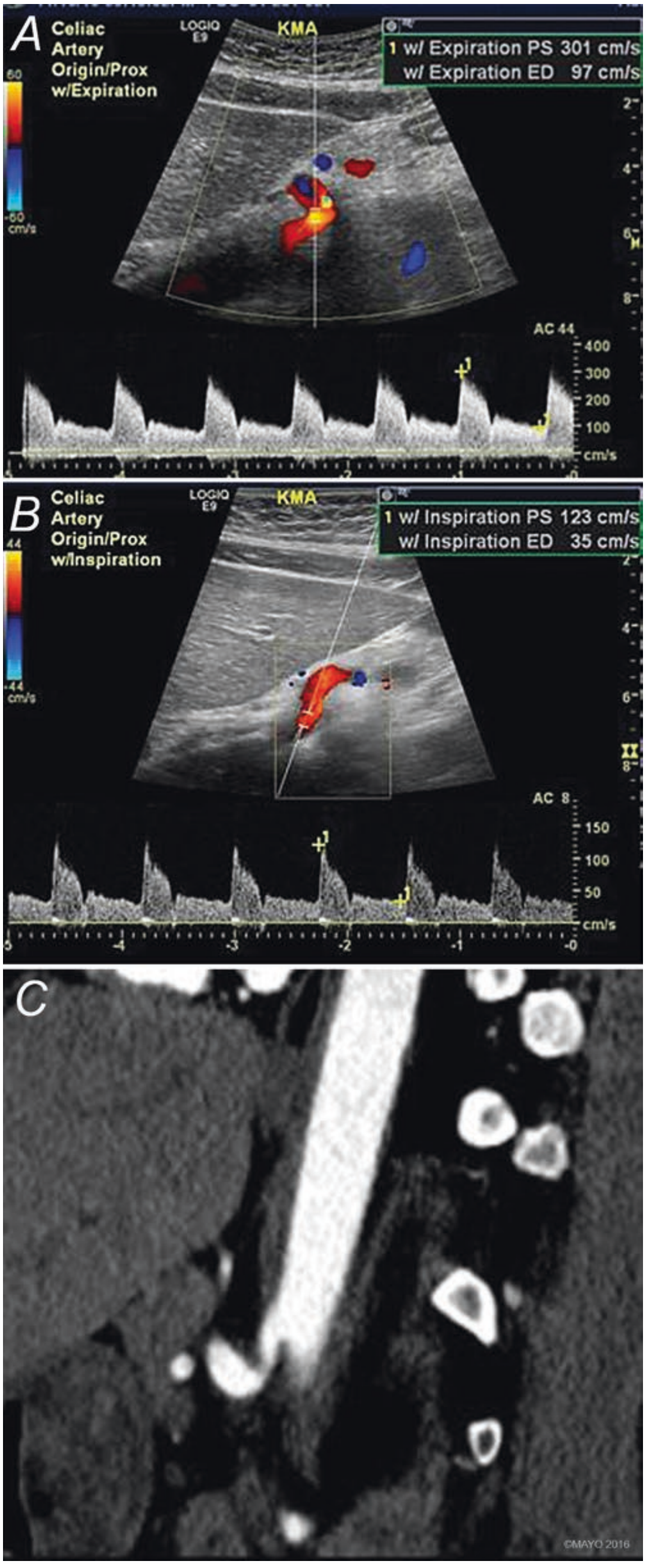


Fig. 12.12 Duplex ultrasound shows dynamic compression of the celiac artery during expiration (**a**) and normalization during inspiration (**b**). CT correlation (**c**) confirms the typical "hook" appearance related to median arcuate ligament compression during expiration. These findings in the appropriate clinical context are suggestive of median arcuate ligament compression syndrome. By permission of Mayo Foundation for Medical Education and Research. All rights reserved

finding in this entity is supported by the fact that asymptomatic individuals in the general population have celiac axis compression, between 24 and 57 % expiration [23, 24]. Furthermore, although immediate relief has been widely reported with surgical decompression, the long-term success is poor with high recurrence rates. 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 can be well documented with duplex ultrasound. Typical finding is elevated PSV during expiration, above 250 cm/s, with improvement or resolution during inspiration (Fig. 12.12). Occasionally, the velocity during inspiration diminishes but remains above the threshold for significant stenosis indicating an underlying degree of fixed stenosis, which can develop overtime. Commonly, another imaging modality such as CTA or magnetic resonance angiography (MRA) is used to anatomically delineate and confirm the diagnosis.

Conclusion

Duplex examination is widely used in the diagnosis and follow-up of mesenteric and renal artery disease and in patients undergoing fenestrated, branched and parallel grafts. It is well accepted as the first screening study in patients with symptoms of chronic mesenteric ischemia and renal artery stenosis and is widely used for pre and post evaluation of patients undergoing endovascular treatment of complex aortic aneurysm repair. 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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