Intraoperative Ultrasound Assessment of Carotid Endarterectomy and Carotid Stent Angioplasty

Paul A. Armstrong and Mary E. Ottinger

Abstract

Clinical outcomes after carotid intervention depend in large part on the technical exactness of the procedure. Ultrasonography provides an excellent instrument for quality control following carotid surgical or endovascular intervention. Duplex ultrasound provides both anatomic (real-time B-mode imaging) and hemodynamic (pulsed Doppler spectral analysis) assessment of the repair allowing detection of residual stenosis, lumen debris, plaque dissection, and verification of normal low resistance flow in the distal internal carotid artery after carotid endarterectomy (CEA). Similarly, intravascular ultrasound (IVUS) is ideally suited for monitoring carotid artery stenting (CAS) as this rapid exchange catheter provides high-resolution real-time imaging of the extracranial carotid arteries allowing for calculation of vessel diameter selection of stent landing zones and monitoring the accuracy of stent deployment. Intra-procedural ultrasound imaging will identify abnormalities that should be corrected in approximately 5–10% of cases. Detection and immediate repair of detected abnormalities are associated with improved clinical outcomes similar to reconstructions judged "normal" on initial ultrasound assessment, thereby offering value for these interventions even in high-risk surgical candidates.

Keywords

Carotid endarterectomy • Stent angioplasty • Intraoperative duplex • IVUS • Intraoperative assessment • Intravascular ultrasound • Duplex ultrasound

Introduction

Verification of procedural success after carotid intervention is of critical significance as structural defects can lead to acute thromboembolism or early restenosis. It is incumbent on the vascular specialist to provide some measure of quality control accompanying carotid endarterectomy (CEA) or carotid artery stenting (CAS). Despite careful technique, disease distribution and plaque morphology can lead to residual repair site abnormalities, which often cannot be recognized by visual inspection and pulse palpation [1–4]. Even when procedural angiographic imaging is utilized, minor anatomic defects can be dismissed as "not significant." A repair site defect can result in perioperative stroke by particle embolization or arterial thrombosis; but it can also reduce procedure durability by producing a hemodynamic state conducive to development of initial hyperplasia, which may promote early recurrent stenosis [5–7]. Since the efficacy of carotid interventions is dependent on obtaining a low (≤3%) neurologic event rate, assessment of all carotid reconstructions is essential as a quality assurance measure [2, 4–6].

Arteriography is the accepted technique for assessment of carotid repairs especially stent angioplasty. Documentation of <20% residual stenosis and no visual-

P.A. Armstrong, DO (✉) • M.E. Ottinger, MD
Department of Surgery, Division of Vascular and Endovascular Surgery, University of South Florida, 2 Tampa General Drive, 7th Floor USF Health Building, Tampa, FL 33606, USA
e-mail: parmstro@health.usf.edu; mottinger@health.usf.edu

ized lumen defect are accepted criteria for technical adequacy. Digital subtraction angiography provides dependable information relative to repair site patency and intracranial artery perfusion, but the technique is invasive, requires contrast injection, offers limited hemodynamic information, and may not detect subtle abnormalities such as focal platelet aggregation within the repair site, which can produce stroke and internal carotid artery (ICA) thrombosis. The use of duplex ultrasound for CEA assessment and intravascular ultrasound (IVUS) monitoring during CAS may be superior to angiographic assessment because these diagnostic techniques provide a higher resolution that offers detailed structural information while confirming vessel patency. In particular, duplex ultrasound also affords an anatomic and hemodynamic assessment of any imaged abnormalities, which aids in the decision for immediate repair or observation [4–11]. Intraoperative duplex scanning also provides a baseline study for subsequent surveillance testing for the detection of recurrent carotid stenosis. The intraoperative documentation of a "normal" CEA repair by duplex scanning is associated with a low (<1%) perioperative stroke rate and low (<5%) incidence of recurrent stenosis (Table 11.1) [2–6, 8]. A normal CEA repair site, based on duplex imaging, predicts absence of residual stenosis and is associated with a 1-year restenosis rate of <10% [2, 4, 6]. Outcome analysis of carotid endarterectomy sites with altered blood flow characteristics such as moderate elevation (150–200 cm/s) in peak systolic velocity (PSV) or residual plaque producing <20% lumen stenosis has been shown to reduce the functional patency due to intimal hyperplasia. The natural history of recurrent stenosis is more benign than an atherosclerotic plaque, but progressive intimal hyperplasia can lead to internal carotid artery occlusion. Most contemporary guidelines recommend repair of asymptomatic recurrent stenosis with duplex findings of a >75% diameter reduction (DR) stenosis [2–4]. Treatment is typically with stent angioplasty since reoperation is considered a high-risk condition.

Table 11.1 Clinical reports recommending routine intraoperative duplex ultrasound evaluation of carotid endarterectomy repairs based on the number of unsuspected lesions identified, low (<1%) operative stroke rate, and excellent procedure durability (ICA occlusion, restenosis)

Investigator	CEAs (n)	CEA revisions (%)	ICA occlusions n (%)	Restenosis at 2–3 years (%)
Baker et al. [3]	316	3	3 (1%)	3
Papanicolaou et al. [4]	86	11	2 (2%)	0
Panneton et al. [5]	155	9	0	2
Bandyk et al. [2]	390	8	1 (0.3%)	2
Ascher et al. [6]	650	3	0	2
Schanzer et al. [10]	407	8	0	2

While the goal of periprocedural ultrasound evaluation is the detection of repair site irregularities, a secondary benefit is recognition of abnormal repair site hemodynamics, which carries the potential to cause recurrent stenosis. Following both endarterectomy and stent angioplasty, the likelihood of recurrent stenosis has been shown to be associated with the presence of residual stenosis [1, 2, 4, 10, 12]. The development of in-stent restenosis after CAS is most commonly the result of intimal hyperplasia, and if the condition progresses to a high-grade stenosis, stent occlusion may result. Similar to the adoption of procedural duplex ultrasound for CEA, the application of IVUS has been utilized internationally by vascular interventionists because the imaging modality provides useful information relative to plaque morphology, stent sizing, stent deployment, balloon dilation, and verification of adequate stent expansion [13–17].

Carotid Endarterectomy Duplex Scanning Protocol and Interpretation

Intraoperative duplex scanning of carotid repairs is performed after restoration of ICA blood flow, using a "hockey stick" linear array 10–15 MHz ultrasound transducer enclosed in a sterile plastic sheath. Acoustic coupling for vessel imaging is achieved by ultrasound gel in the sheath and saline in the incision. Imaging is accomplished by placing the transducer over the artery and then slowly moving it along the repair, beginning in the common carotid artery and proceeding distally to the ICA. If a bovine or polyester patch was used for vessel closure, lumen imaging is still possible, but use of a polytetrafluoroethylene (PTFE) patch hampers imaging due to air trapped in the PTFE material. Vessel imaging and velocity spectra recordings can be obtained by orienting the transducer foot pad along the non-patched vessel circumference. With the assistance of a vascular technologist to optimize instrument setting for imaging and pulsed Doppler spectral analysis, the exam time is less than 10 min, including archiving images for the patient medical record. Typically in the transverse and longitudinal planes, examination is performed of the common carotid artery (CCA), carotid bulb, and internal carotid artery (ICA) with B-mode and color flow imaging. The external carotid artery (ECA) is sampled to document patency. Velocity recordings are taken at both proximal and distal surgical endpoints with additional velocity analysis being made of the outflow distal ICA beyond the repair site (Fig. 11.1). The criteria for an "abnormal" duplex scan depends on the site imaged (CCA, carotid bulb, ECA, ICA), focusing on the severity of the anatomic defect and associated alter flow hemodynamics.

Duplex scanning should begin at the proximal CCA to verify normal proximal endarterectomy endpoint. The site of proximal clamp occlusion should be imaged, since focal
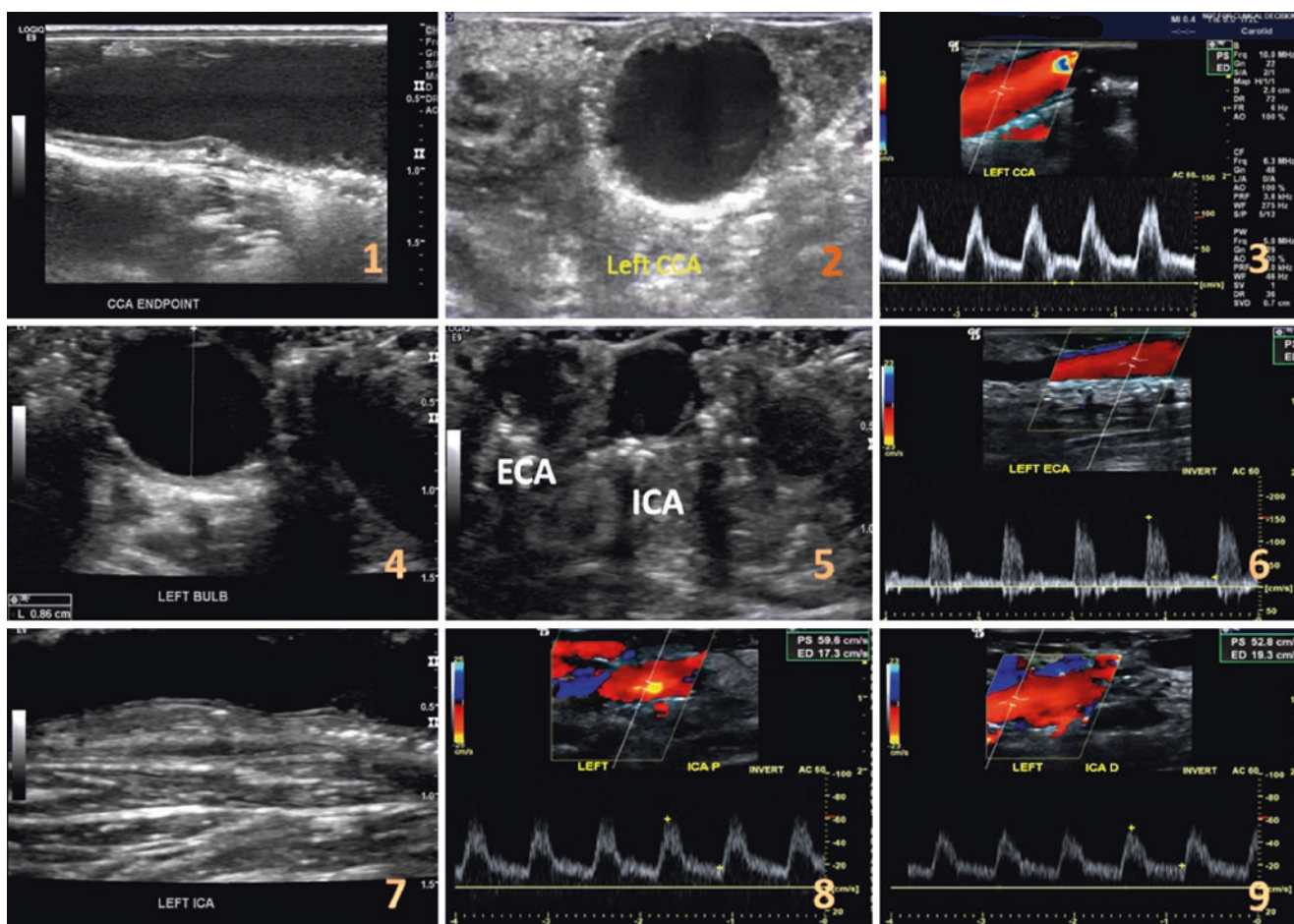
Fig. 11.1 Normal intraoperative CEA repair site duplex scan: Image 1–3, common carotid artery; Image 4–5, carotid bulb region; Image 6, external carotid artery; Image 7–9, internal carotid artery

traumatic wall dissection or plaque injury could have occurred. Scanning then proceeds from proximal to distal to confirm a widely patent lumen and normal velocity spectra. Special attention should be paid to endarterectomy endpoints where residual plaque >2 mm in thickness is abnormal and should be repaired (Fig. 11.2). The normal endarterectomy site should be free of lumen defects and should have no suture stricture, and PSV should be <150 cm/s. Using transverse imaging, the diameter of the proximal ICA (bulb segment) should demonstrate homogenous color flow, and the diameter can be measured, which should be <1 cm, as larger diameter patched segments are prone to aneurysmal dilation and mural thrombus formation. The ECA is imaged to verify patency and presence of distal plaque dissection since the endarterectomy of this vessel is accomplished using an eversion technique for plaque removal. The ECA typically has a high-resistant waveform pattern, oftentimes with an inconsistent diastolic flow pattern based on collateral flow and downstream atherosclerosis. Although uncommon, ECA thrombosis can occur in a heavily diseased vessel. Most surgeons will re-explore the ECA if occlusion or a focal high-

grade stenosis is identified, as acute ECA thrombosis presents potential risk for thrombus extension. The ICA should be scanned as far distal as possible, especially if a shunt was inserted. Normal ICA duplex characteristics include sloped, but sharp rise, to systole with a gradual decline through diastole, low-resistant waveform pattern with diastolic flow above the baseline, absent dicrotic notch, and preservation of the spectral width from proximal to distal with or without a clear acoustic window (Figs. 11.3 and 11.4). When a structural defect is identified in the ICA (plaque edge, suture narrowing, artery kinking), tracking the sample volume through the region allows assessment of changes in PSV. Decision for repair is based on the altered hemodynamics produced by the imaged abnormality, with lesions producing focal elevations of PSV > 150 cm/s considered for repair. Figure 11.5 provides a clinical pathway for intraoperative duplex assessment after CEA. Spasm of the ICA is identified by a narrow lumen on color or power Doppler and moderate elevations of PSV in the range of 150–200 cm/s. The finding of lumen thrombus or PSV > 300 cm/s usually indicates that platelet aggregation

Fig. 11.2 (**a**) Thickened abnormal proximal common carotid endpoint in a diseased artery (**b**) concern for developing filling defect on B-mode imaging which is confirmed as platelet aggregate on color flow assessment
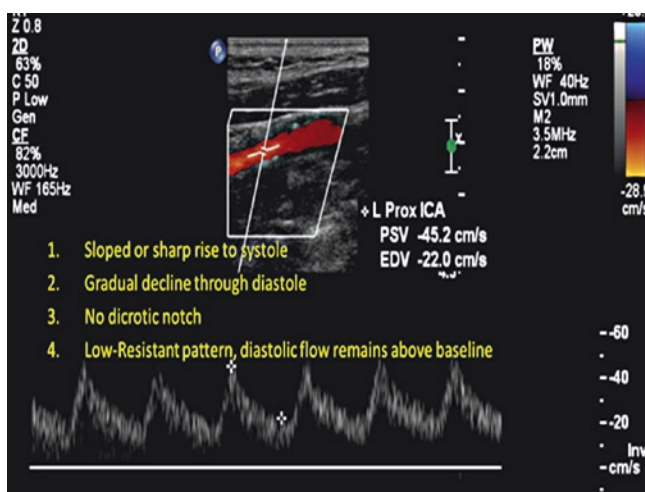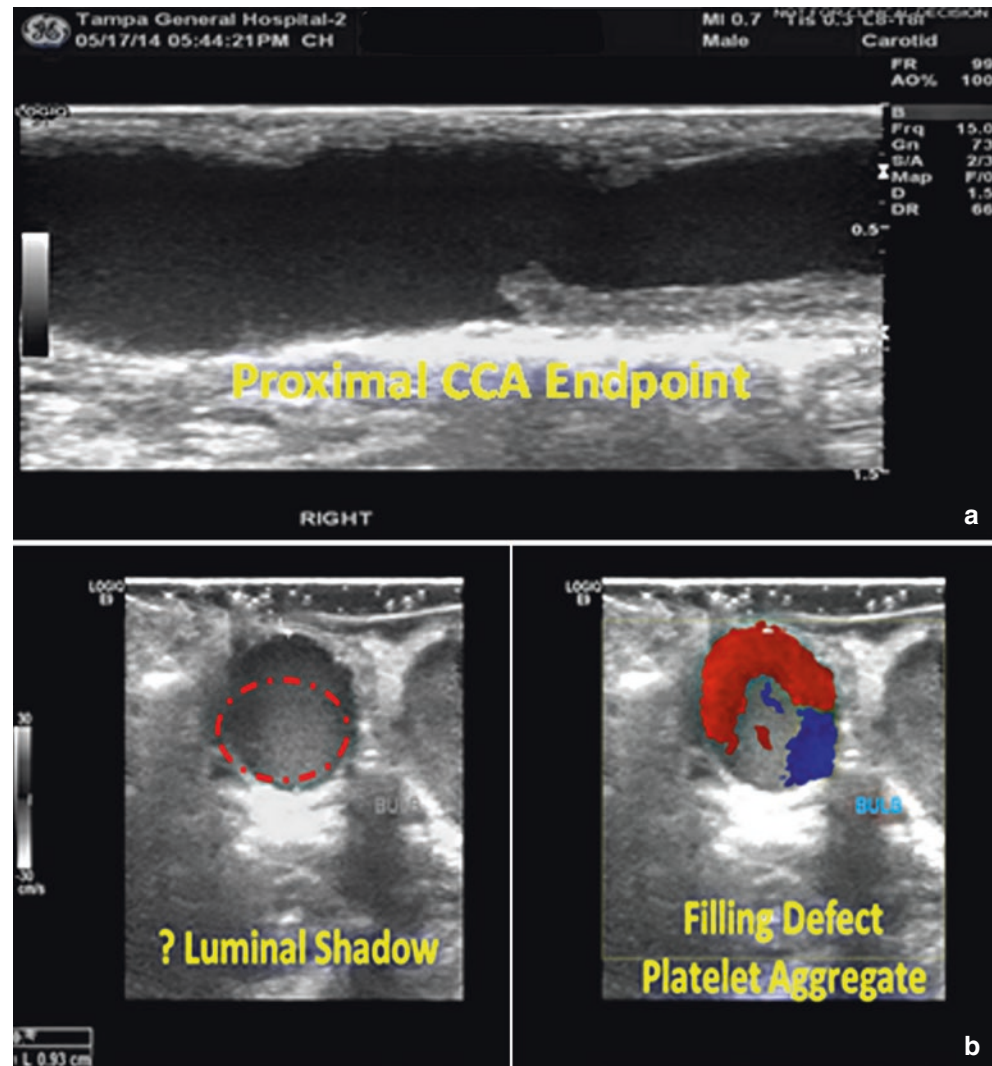

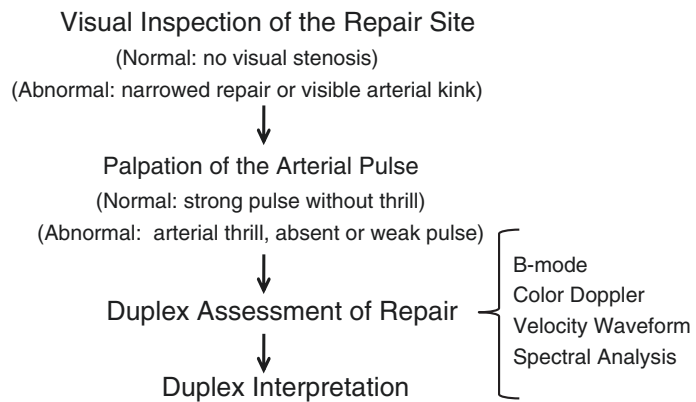**Fig. 11.3** Normal duplex imaging characteristics of proximal ICA

has developed and re-exploration is mandatory [9, 12]. Table 11.2 provides intraoperative criteria for residual stenosis after CEA. Some vascular surgeons may perform angiography when the duplex imaging is abnormal to confirm an anatomic defect prior to proceeding with endarterectomy site re-exploration.

On occasion, increased PSV ≥ 125–150 cm/s with minimal spectral broadening and normal artery imaging can be the result of vasospasm or compensatory collateral flow due to contralateral ICA occlusion. The presence of high diastolic flow in the ICA, i.e., more than 50% of the PSV, may indicate hyperperfusion syndrome with loss of normal intracranial arterial autoregulation. Appropriate therapy for this condition may include meticulous blood pressure control, steroids, and antiseizure drug administration.

The prevalence of endarterectomy site repair, based on duplex testing, is approximately 5% for CCA and ICA
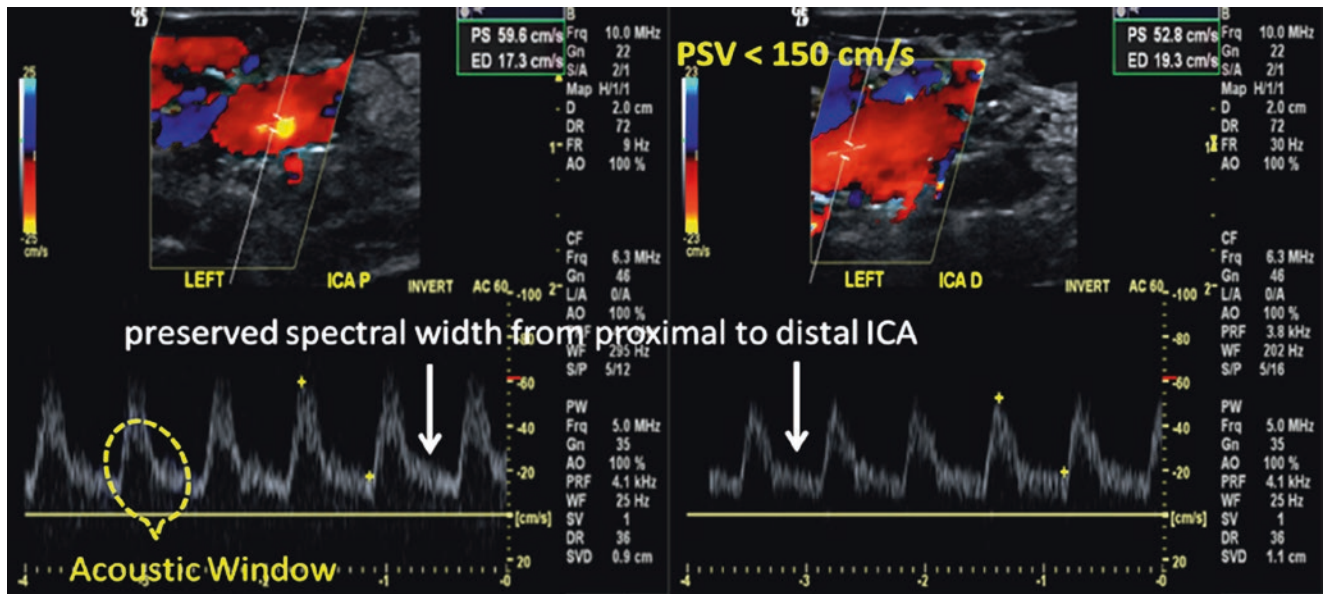
Fig. 11.4 Sagittal view of normal proximal ICA repair site endpoint and normal distal ("beyond repair") ICA

Visual Inspection of the Repair Site

(Normal: no visual stenosis)

(Abnormal: narrowed repair or visible arterial kink)

↓

Palpation of the Arterial Pulse

(Normal: strong pulse without thrill)

(Abnormal: arterial thrill, absent or weak pulse)

↓

Duplex Assessment of Repair — B-mode / Color Doppler / Velocity Waveform / Spectral Analysis

↓

Duplex Interpretation

Fig. 11.5 Algorithm for intraoperative carotid duplex scanning with recommendations for interpretation and management

Category Stenosis	PSV (cm/s)	Vr	Findings	Intervention
Normal	125	<1.4	<2mm plaque shelf thickness no residual plaque or dissection no platelet aggregate or thrombus brisk diastolic flow homogenous color flow	No action required
Moderate	125-150	1.5-2.5	50% x-sectional lumen reduction heterogenous color flow	Consider angiogram or repeat scan
Severe	>150	2.5-4.0	>70% x-sectional lumen reduction disturbed flow pattern-turbulence	Surgical revision

Table 11.2 University of South Florida intraoperative criteria for residual stenosis after carotid endarterectomy

| Arterial diameter reduction	PSV (cm/s)	Spectral characteristics
0–15% (normal)	100	Biphasic waveform No spectral broadening
16–49% (mild)	100–125	Biphasic waveform Spectral broadening in diastole only
50–75% (moderate)	126–150	Spectral broadening through the pulse cycle
>75% (severe)	>150	Spectral broadening through the pulse cycle

defects (Table 11.1) and an additional 3–5% if correction of ECA stenosis/occlusion is included. If the endarterectomy site has normal duplex imaging and velocity spectra findings, the likelihood of repair site thrombosis is extremely low (<1%), as is the detection of >50% DR stenosis within 3 months of the procedure. A 2011 report from the Vascular Study Group of New England indicated that only one-half of vascular surgeons routinely image carotid repairs, with duplex ultrasound being the preferred technique [7]. Routine imaging was not associated with a reduction in operative strokes, but the incidence of restenosis was significantly less.
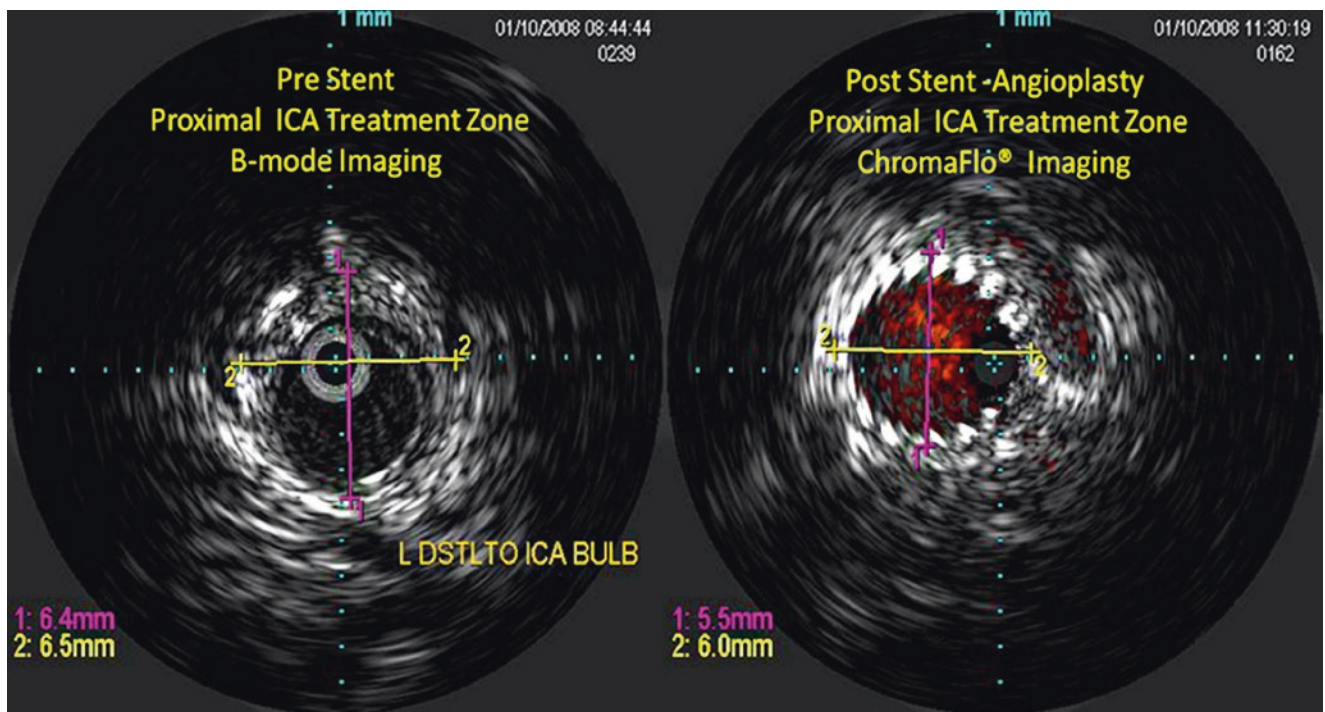
Carotid Stent-Angioplasty IVUS Imaging Protocol and Test Interpretation

The high-resolution (0.1 mm) vessel imaging achieved by the 20 MHz IVUS catheter imaging system has been shown to improve clinical outcomes when used to assess the technical result of peripheral angioplasty procedures [13]. IVUS imaging is used in combination with digital fluoroscopy for monitoring the carotid artery stent-angioplasty procedure. More specifically, IVUS defines vessel character and diameter with an assessment of the treatment zone, which aides in the procedural sizing of the stent and angioplasty balloon. With stent deployment, IVUS can then be employed to interrogate the region of stent angioplasty for residual stenosis or stent deformity. The goal of IVUS imaging is to confirm vessel patency, full stent deployment with an expanded lumen in the region of the atherosclerotic plaque, and no lumen anatomic abnormality [13–17].

The IVUS catheter is delivered to the extracranial carotid bifurcation over a 0.014 in. wire platform after a cerebral protection device is deployed in the distal ICA. While the market presents several catheter choices, all of which offer B-mode real-time imaging, the IVUS Eagle Eye® Platinum catheter (Volcano Corporation, San Diego, CA) combines B-mode real-time imaging with virtual histology (VH®).

This technology provides a 360° color tissue map, which can provide volumetric measures and assess plaque composition. These features allow for a detailed assessment of the treatment zone (Fig. 11.6). This particular brand catheter now comes with radiopaque markers, which allows for a more exact length measure of treatment zones and offers accurate angiographic calibration, if needed. During a carotid stent-angioplasty procedure, IVUS imaging is used to aid the interventionist in estimating disease extent (stenosis length), select appropriate proximal and distal stent landing zones in normal or minimally diseased arteries, and provide accurate vessel diameter measurements of the ICA and CCA for appropriate stent selection. Following stent angioplasty, reinsertion of the IVUS catheter with pull-back imaging alerts the interventionist to abnormalities of stent expansion, which, if judged to be inadequate, allows immediate endovascular treatment. In addition, by utilizing IVUS with Chromaflo® imaging, vessel patency can be confirmed, and dissection or other vessel injury can be excluded (Fig. 11.7). The application of IVUS imaging during the stent-angioplasty procedure provides unique anatomic information for arterial repair using less contrast and fewer angiogram runs without increasing morbidity or sacrificing technical accuracy. The technical success of carotid stent angioplasty has been generally determined by multiplanar digital subtraction angiography, with the goal to achieve <20% residual stenosis relative to the normal distal ICA diameter. Figure 11.8 outlines the University of South Florida's IVUS-guided stent protocol for CAS. Our vascular group and others have adopted IVUS as a quality control assessment of "adequate" stent deployment and balloon angioplasty in the treatment of ICA atherosclerotic occlusive disease, analogous to the use of intraoperative duplex testing during CEA. Following stent angioplasty,
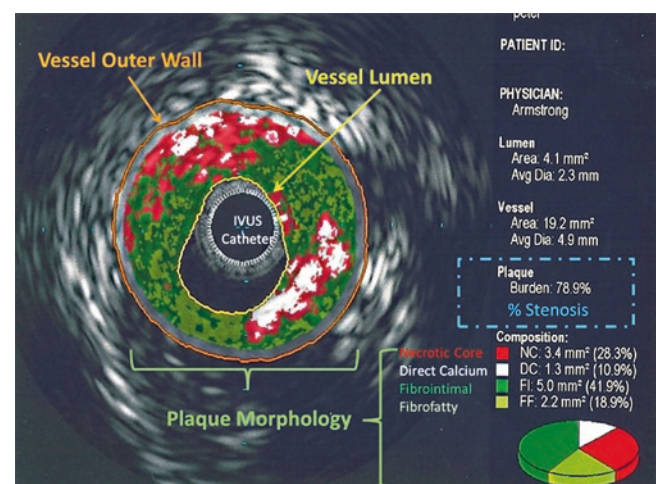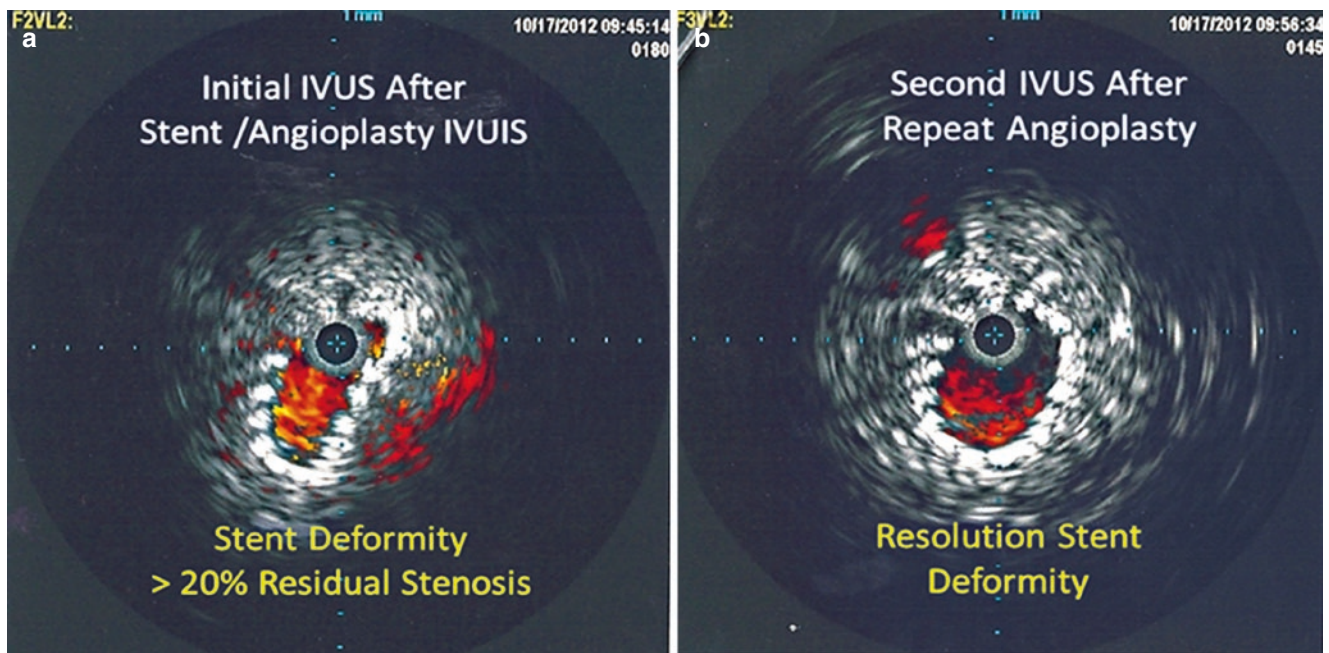

Fig. 11.6 Plaque morphology as mapped by Virtual Histology® in a high-grade (>75%) ICA stenosis

Fig. 11.7 Proximal ICA landing zone diameters with B-mode IVUS and post-stent-angioplasty IVUS with Chromaflo® demonstrating good stent-wall apposition and patency
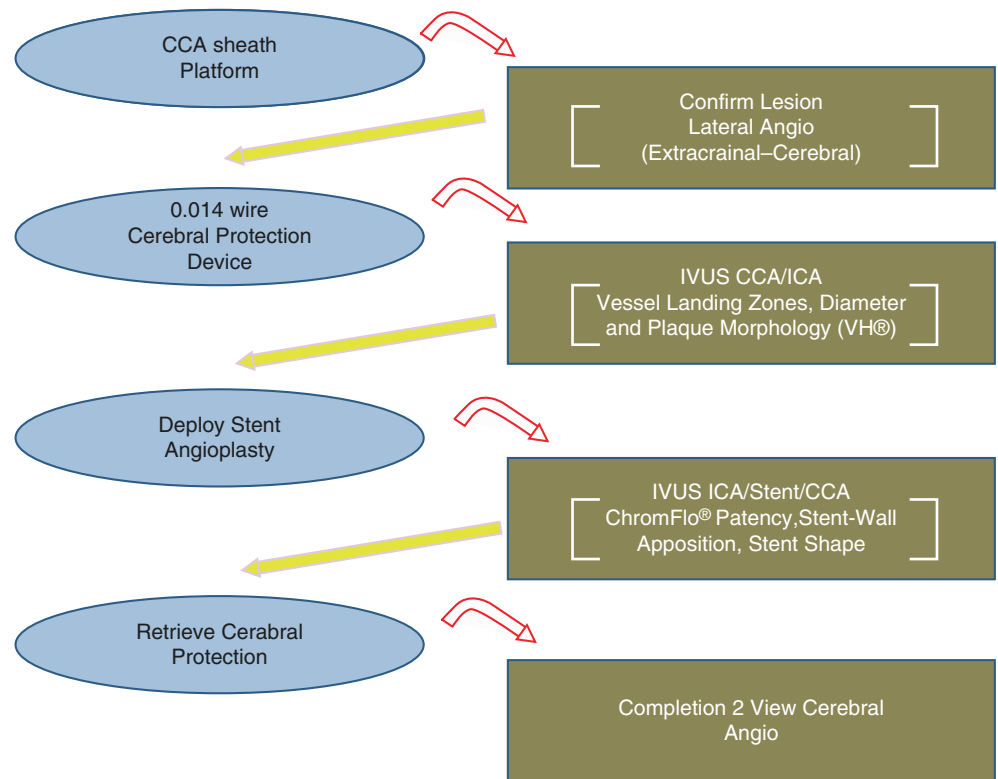
Fig. 11.8 University of South Florida IVUS-guided carotid stent procedural algorithm

Fig. 11.9 Serial IVUS images of ICA stenosis: (**a**) elliptical stent deployment after initial angioplasty exhibiting residual stent stenosis of >20% prompting (**b**) repeat angioplasty based on IVUS assessment <20% to reduce stent deformity/stenosis

real-time B-mode IVUS imaging is performed by positioning the IVUS catheter distal to the stent in the normal ICA and slowly withdrawing the catheter through the stent, visualizing changes in lumen diameter. This maneuver allows identification of regions of poor stent expansion with associated reduction in cross-sectional area (Fig. 11.9). The degree of stent deformation may not be readily apparent by angiography. When IVUS confirms improper stent expansion, defined by an irregular or elliptical stent shape with a residual cross-sectional area reduction of >20% compared to the distal stent, additional balloon angioplasty is performed, typically upsizing the angioplasty balloon 0.5–1.0 mm from the previous size or performing a more prolonged (10 s) balloon angioplasty to expand the carotid bifurcation. Incomplete circular stent expansion after balloon angioplasty is typically caused by calcified carotid bifurcation plaque.

Our vascular group analyzed the anatomic and clinical outcomes of carotid stent angioplasty with and without IVUS monitoring [13]. Retrospective review of carotid stent registry data identified 220 consecutive CAS procedures (215 patients) performed with either digital C-arm fluoroscopy alone ($n = 110$) or in conjunction with IVUS system ($n = 110$). All carotid interventions were conducted with a cerebral protection device. The two groups were comparable for CAS indication, ICA stenosis severity, and atherosclerotic risk factors. All patients were enrolled in an outpatient surveillance program, which included clinical assessment for neurologic events, verification of antiplatelet therapy, and bilateral carotid duplex testing with interpretation according

to previously published velocity spectra criteria for CAS procedures [18]. Duplex ultrasound testing was performed in the PACU, at approximately 1 month, every 6 months for 2 years, and then annually if <50% DR stenosis was present. An abnormal duplex finding of in-stent stenosis in the 50–75% DR category was based on color flow imaging of a stenosis, a peak systolic velocity (PSV) > 150 cm/s, and in-stent stenosis velocity ratio >2. The finding of a >75% DR in-stent stenosis (PSV > 300 cm/s in conjunction with EDV > 125 cm/s) prompted cerebral angiography and re-intervention if a >75% DR lesion was confirmed.

No safety issues were encountered using IVUS catheter imaging prior to and following stent angioplasty, and mean procedure times were similar with angio-alone CAS procedures. IVUS imaging altered procedural conduct by a lower ($p < 0.05$) volume contrast agent injected due to fewer angiogram runs for stent sizing and verification of adequate stent deployment and the use of larger diameter angioplasty balloons (typically 6 mm dia.) for final stent angioplasty, based on assessment of residual in-stent lumen diameter and stent deformation by the atherosclerotic plaque. IVUS assessment identified more residual stent abnormalities, requiring additional endovascular treatment ($n = 12$, 11%) versus performing CAS using angiogram assessment alone ($n = 2$, 1.8%). Duplex testing after carotid stenting demonstrated a low incidence of >50% residual (PSV > 150 cm/s) in IVUS monitored groups (7% versus 18%, $p < 0.01$). This difference persisted during patient surveillance with a higher freedom from >50% DR in-stent stenosis at 36 months in the

angio- + IVUS group (94%) than in angio-alone group (78%), indicating a more durable carotid intervention. Four (3.6%) angio-alone CAS sites developed >75% asymptomatic restenosis and underwent repeat balloon angioplasty with one later developing an asymptomatic thrombosis. In the angio- + IVUS group, two neurologic events (1 stroke, 1 reperfusion injury) occurred within 30 days, while in the angio-alone treatment group, two patients who underwent CAS of symptomatic ICA stenosis developed a new neurologic event >30 days after the procedure (1 stroke, 1 TIA). A 2015 updated review of this prospective CAS registry shows that we have now performed over 400 IVUS-guided CAS interventions with similar procedural-related outcomes reported here. Surveillance has identified one additional stent occlusion associated with a covered stent placed for a carotid aneurysm and two patients with asymptomatic high-grade restenosis (>75% DR) who required endovascular reinvention.

This experience, using IVUS to assess the technical adequacy of CAS, indicates the diseased carotid artery bifurcation can be safely imaged, and the detailed anatomic information afforded by this diagnostic technique is useful for the evaluation of suitable stent landing zones, selection of an appropriate stent size and angioplasty balloon, and confirmation that appropriate artery wall dilation with stent-wall apposition has been achieved and a severe residual stent deformity is not present. The addition of IVUS imaging to CAS procedures did not increase procedure time or produce an adverse event. We believe the information provided by IVUS resulted in more frequent intra-procedural re-interventions and the use of larger diameter angioplasty balloons and contributed to improved long-term outcomes documented by duplex surveillance with less severe in-stent stenosis (based on maximum PSV values) and re-interventions in the angio- + IVUS treatment group. This experience supports our previous recommendation regarding duplex interpretation criteria for grading carotid stent stenosis in that a PSV > 150 cm/s is an abnormal threshold value and correlates with a functional residual stenosis, which may develop into progressive in-stent stenosis [17]. A subsequent investigation, using receiver operating curves from Aburahma et al., validated observed in-stent restenosis of 30, 50, and 80% at PSVs of 154 cm/s, 224 cm/s, and 325 cm/s, respectively. The authors concluded that PSV values were a better predictor of restenosis after CAS [19].

Conclusion

The application of intra-procedural ultrasound to confirm technical exactness of open and endovascular interventions is an appropriate quality measure associated with excellent patient and procedure-related outcomes. The time and expense associated with routine assessment is rewarded by improvement in technical precision of the carotid repair and does not add to procedure morbidity. Ultrasound assessment does require advanced skills in duplex scanning and ultrasound image interpretation. Current training paradigms provide the vascular surgeon treating carotid advanced atherosclerosis with open or endovascular therapies with the necessary expertise to become proficient in duplex ultrasonography. However, some individuals may need to acquire hands-on training for the integration of IVUS as an assessment tool in their practice in order to have confidence in the testing accuracy. Data indicate that vascular surgeons who routinely perform completion imaging studies have lower procedure morbidity and restenosis rates; thus, incorporation of intra-procedural measures for quality assurance, such as duplex ultrasound or IVUS, can be expected to offer additional benefits toward improving clinical outcomes.

Review Questions

1. The sagittal B-mode image (Fig. 11.10) with a 15 MHz linear array probe obtained following right carotid endarterectomy with vein patch angioplasty shows:
   a. Platelet aggregation internal carotid artery
   b. Dissection of the distal carotid bub
   c. Technical error
   d. Mild residual proximal internal carotid artery stenosis
   e. Occluded external carotid artery
2. Normal intraoperative duplex findings associated with the distal internal carotid artery include:
   a. Sloped or sharp rise to systole
   b. Sharp decline through diastole
   c. Distinct dicrotic notch
   d. High-resistant waveform pattern
   e. Peak systolic velocity in the range of 160–225 cm/s
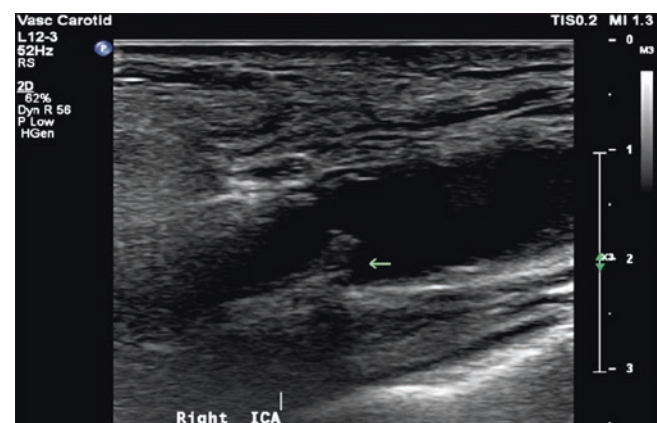

Fig. 11.10   Review Question #1

3. Procedural duplex carotid ultrasound is capable of confirming the following hemodynamic significant conditions, except:
   a. Platelet aggregation at the repair site.
   b. Shunt-related injury of the carotid vessels.
   c. Reperfusion syndrome.
   d. Suture line stenosis.
   e. Procedural duplex can reveal all of the above conditions.

4. Intraoperative left carotid endarterectomy completion duplex of the distal common carotid artery (Fig. 11.11) suggests:
   a. Normal common carotid artery flow
   b. Occluded left internal carotid artery
   c. Moderate left common carotid stenosis
   d. High-grade stenosis left external carotid artery

5. Intravascular ultrasound (IVUS) of the proximal carotid stent (Fig. 11.12) shows:
   a. Occluded distal internal carotid artery
   b. Acute dissection after stent angioplasty
   c. Residual stent deformity of >30%
   d. Normal stent-wall apposition
   e. Occluded external carotid artery
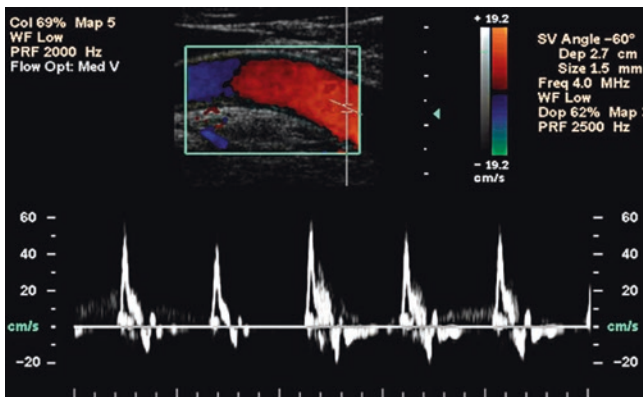
Answer Key

1. c
2. a
3. e
4. b
5. c
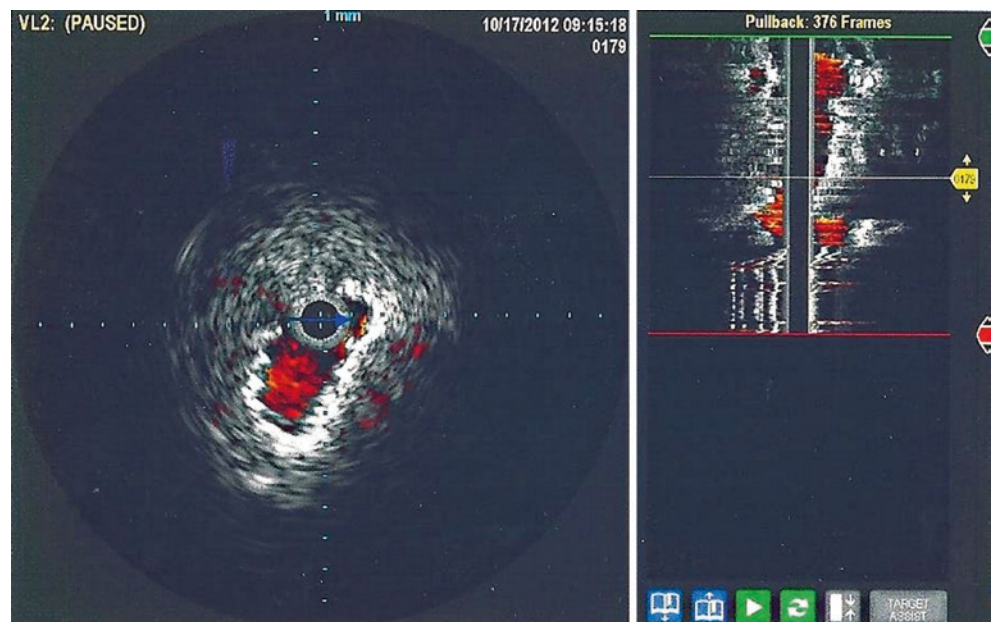

Fig. 11.11 Review Question #4

Fig. 11.12 Review Question #5

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