Carotid endarterectomy is a commonly performed procedure for prevention of stroke related to carotid stenosis. Intraoperative sonography is used to identify potentially correctable technical defects during carotid endarterectomy. The main risk of endarterectomy is perioperative stroke, and great effort has been put into trying to reduce this risk through various surgical techniques and evaluation of the surgical bed. Postoperative carotid thrombosis, or thromboembolization from the arterectomy site, remains a common cause of perioperative stroke and is often related to technical defects in the arterial reconstruction procedure. Re-exploration and repair of any imperfections have the potential to improve outcomes. Intraoperative imaging can identify potentially occult lesions, provide the option for correction, and thus reduce chance of stroke. Familiarity with the spectrum of intraoperative sonographic findings helps correctly identify residual intimal dissection flaps, plaque, thrombi, and stenosis, which may require immediate surgical revision. Our objective is to illustrate the spectrum of intraoperative findings and their importance.

Key Words—carotid; endarterectomy; intraoperative; thromboembolic; vascular; vascular ultrasound

Carotid endarterectomy is a commonly performed procedure indicated for the prevention of stroke secondary to carotid artery stenosis.1–4 It has been established as an effective procedure in the settings of both asymptomatic and symptomatic carotid artery stenosis.5,6 Radiologists are often involved in the diagnosis and grading of carotid artery stenosis through the use of duplex sonography, computed tomographic angiography, magnetic resonance angiography, and catheter angiography.7–9 Carotid artery duplex sonography is often the first and in some cases the only preoperative method for screening of carotid stenosis and for subsequent follow-up looking for interval progression of disease. After carotid endarterectomy, Duplex sonography also plays an important role in monitoring for restenosis and contralateral stenosis.

Postoperative carotid thrombosis or thromboembolization from the arterectomy site is a common cause of perioperative stroke and is often related to technical defects during the surgical reconstruction procedure. These imperfections or defects can be the
The decision to perform imaging to analyze the surgical bed is largely surgeon dependent. One large study from the vascular surgery literature that looked at 650 cases from 2000 to 2003 performed with routine intraoperative duplex sonography showed a very low perioperative combined stroke and mortality rate of only 0.8%, which was thought to be caused by hypoperfusion and evolution of a prior cerebral infarct, rather than a thromboembolic event. A revision rate for major defects based on intraoperative sonography was 2.3%. The authors of that study strongly thought that intraoperative sonography played a major role in improved technical and clinical results, particularly because clinically unsuspected residual lesions could be detected and then immediately corrected. In contrast, a large review from the Vascular Study Group of New England showed no real reduction in the surgical stroke rate or death at 30 days with use of completion imaging. The authors also noted that only half of surgeons used the technique. In that study, restenosis rates at 1 year were noted to be reduced when completion imaging (either duplex sonography or arteriography) was performed. An additional investigation analyzing data from the New York Carotid Artery Surgery Study showed that most surgeons did not use any type of completion imaging, although it is worthwhile to note that this cohort of patients underwent carotid endarterectomy in 1998 and 1999. Since then, ultrasound technology has improved substantially, has become more widely accessible, and therefore is likely used more frequently by vascular surgeons. Despite how often carotid endarterectomy surgery is performed and its proven benefits, there is no consensus regarding completion imaging at the end of the surgical procedure to confirm technical adequacy. Even in the absence of any completion imaging, there is already a high rate of success with endarterectomy and high survival rates. Although the decision to perform intraoperative carotid duplex sonography is ultimately up to the practicing surgeon, being familiar with the spectrum of findings and techniques is useful to those involved with interpreting vascular sonography if the surgeon chooses to have intraoperative guidance.

Methods and Technique

Intraoperative Duplex sonography of the carotid endarterectomy site is performed by our radiologic ultrasound service and the vascular surgery service working in conjunction. In the operating room, the vascular sonographer, accompanied by the attending radiologist, optimizes the ultrasound machine gain and color scale settings and ensures proper positioning of the Doppler interrogation sample.
volume. After the closure of the arteriotomy, while still in the neck cavity, a high-frequency hockey stick–shaped 10–
15-MHz linear ultrasound probe in a sterile plastic sleeve covered with ultrasound gel is then placed directly onto
the artery by the vascular surgeon. The ultrasound gel in the sheath and saline instilled into the exposed neck
cavity provide acoustic coupling. This high-resolution
probe allows for high-quality images with excellent
assessment of the vessel wall and detects residual luminal
defects such as dissection flaps and vessel thrombosis.
Occasionally a lower-frequency probe may be used if there are body habitus limitations or carotid stents requiring
increased penetration. The vascular surgeon handles the
probe and scans along the artery at the site of the arteri-
totomy in both the sagittal and transverse planes.

The evaluation includes grayscale imaging, color
Doppler imaging, and pulse wave Doppler interrogation
of the CCA, ICA, and ECA at less than 60° angle correction (Figure 1 and Video 1). Doppler spectral analysis and color
Doppler imaging identify potential areas of turbulent
flow, velocity abnormalities, and poststenotic waveforms.
The presence of residual stenosis will be assessed by inter-
preting the peak systolic velocities (PSVs), ICA/CCA ratios,
and waveforms. Turbulent waveforms with spectral broad-
ening, increased PSVs, elevated ICA/CCA ratios, and
downstream tardus-parvus waveform morphologic char-
acteristics are suggestive of residual stenosis (Figure 2).
Particular attention is paid to the ends of the endarterectomy
sites to evaluate for subtle dissection flaps. The radiologist
reviews the images in real time with the vascular surgeon
and communicates any unexpected findings. After any
revisions, intraoperative sonography is again performed to
confirm improvement. Although the specific surgical tech-
nique for performing an endarterectomy is variable and
beyond the scope of this article, the endarterectomy
may be performed with or without patch reconstruction.
The patch may be made from native vein or prosthetic
material. The decision to perform additional repair of the
ECA is also variable and surgeon dependent.

Spectrum of Findings

A normal study is associated with a high negative predictive
value for perioperative repair site failure. Abnormal find-
ings may be classified as “major” or “significant” versus
“minor” or “insignificant” defects. The criteria for defining
a defect as major or significant versus minor or insignificant
has not been uniform in prior studies (Table 1). Generally
though, the consensus in these studies is that
minor technical defects are often insignificant and need
not be revised, whereas major defects, particular when
there are both grayscale and spectral abnormalities, should
be revised. The discrimination between minor and major
abnormalities has been controversial, however, and it is
an important distinction because of the additional risk
associated with reclamping and reentering the artery with
a longer anesthesia time, along with the likelihood of
being able to correct the defect while not causing addi-
tional defects. This decision must be weighed by the sur-
geon carefully.

Figure 1. Normal anatomy on intraoperative carotid sonography. The
large white arrow points to the saline fluid that the surgeon places in the
neck cavity. The medium white arrow shows a reverberation artifact
within the saline fluid. Small white arrows refer to the larger and more
posterior ICA and smaller more anterior ECA. The asterisk indicates the
jugular vein.

Figure 2. Color aliasing within the distal ICA after an endarterectomy.
Note the elevated velocities higher than 300 cm/s, with waveforms that
show turbulent flow and spectral broadening, suggestive of residual
stenosis from a possible fold or thrombus near the distal clamp site.
At revision, this structure was noted to be a residual fold and redundancy
from carotid tortuosity. The excess redundant tissue was excised and
sutured, and another patch was applied to close the arteriotomy.
Panneton et al. reviewed 155 intraoperative duplex carotid sonographic examinations in 149 patients. They used a classification scheme dividing the cases into those with normal, insignificant, or significant abnormalities. Normal included a PSV of less than 125 cm/s, no or minimal visible stenosis, plaque, or thrombus, and no intimal flap or dissection. The group thought to represent insignificant abnormalities included a PSV of less than 125 cm/s but moderate plaque/thrombus or a small intimal flap of less than 3 mm. Preexisting and unchanged ECA stenosis was also thought to be in the insignificant category. The significant abnormality group included a PSV of greater than 125 cm/s, a large amount of plaque or thrombus, or a dissection flap of greater than 3 mm. Using this classification, the study reported that 59% of the cases were normal; 30% had insignificant abnormalities that were not intervened; 9% had significant abnormalities that were intervened; and 2% had major abnormalities that were not intervened. They reported 1 major stroke and 2 reversible ischemic events in the patients from the normal category and 2 major strokes in the patients from the significant abnormality group that were not intervened. None of the patients who had significant abnormalities or were intervened had ischemic strokes. In another series, Ott et al. reported on a group of 74 cases, with 11% having major abnormalities on duplex sonography requiring immediate revision and 34% having minor abnormalities not requiring revision. Ascher et al. also described major residual defects in the CCA as potential sources of thromboembolic disease, which were also successfully revised at the time of the surgery. They used mobile flaps of 2 mm or greater in the ICA and 3 mm or greater in the CCA as indications for surgical revision. Follow-up imaging at 2 weeks and 3 months after surgery showed no new defects in all the revised cases.

<table>
<thead>
<tr>
<th>Investigators</th>
<th>Criteria for a Major or Significant Defect</th>
<th>Criteria for a Minor or Insignificant Defect</th>
<th>Criteria for Intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandyk et al.</td>
<td>Not specified</td>
<td>Not specified</td>
<td>Abnormality on B-mode; abnormal velocity spectra of severe or high-grade stenosis: &gt;180 cm/s, Vr &gt;2.5</td>
</tr>
<tr>
<td>Parsa et al.</td>
<td>Clinically significant; &gt;2-mm residual plaque or mobile dissection/flap; moderate stenosis: PSV &gt;150 cm/s, Vr &gt;2</td>
<td>Not specified</td>
<td>Flaps &gt;2 mm in length, wall dissection, lumen thrombosis; PSV &gt;150–180 cm/s, Vr &gt;2 with 50% diameter stenosis (revision or arteriography); PSV &gt;300 cm/s; definite revision</td>
</tr>
<tr>
<td>Panneton et al.</td>
<td>Significant; marked plaque/thrombus or large intimal flap dissection &gt;3 mm; PSV &gt;1.25 m/s with anatomic lesion</td>
<td>Insignificant; moderate plaque, thrombus, or small intimal flap &lt;3 mm; stable ECA stenosis; PSV &lt;1.25 m/s</td>
<td>Significant defects</td>
</tr>
<tr>
<td>Ascher et al.</td>
<td>Major; &gt;30% luminal ICA stenosis; free-floating clot; dissection; arterial disruption with pseudoaneurysm</td>
<td>Not specified</td>
<td>B-mode: mobile flap ≥2 mm in ICA or ≥3 mm in CCA; &gt;30% luminal diameter reduction, PSV &gt;150 cm/s with a B-mode abnormality</td>
</tr>
<tr>
<td>Sawchuk et al.</td>
<td>Major; intimal flaps &gt;3 mm in length; stenosis &gt;50% in diameter</td>
<td>Minor; intimal flaps &lt;3 mm in length; stenosis ≤50% in diameter</td>
<td>Major defects</td>
</tr>
<tr>
<td>Mays et al.</td>
<td>Major; severe flow disturbance (&gt;150 cm/s)</td>
<td>Minor; mild or moderate flow disturbance (100–150 cm/s)</td>
<td>PSV &gt;150 cm/s with spectral broadening; B-mode abnormality (flap or debris ≥2 mm)</td>
</tr>
<tr>
<td>Mullenix et al.</td>
<td>Not specified</td>
<td>Not specified</td>
<td>ICA PSV &gt;125 cm/s; ICA/CCA Vr &gt;2.0; spectral broadening; B-mode flap in ICA&gt;2 mm; other major: severe kink or intravascular thrombus</td>
</tr>
</tbody>
</table>

Vr indicates velocity ratio.
To evaluate our experience, a retrospective review through our reporting system was performed, yielding 168 intraoperative carotid sonographic examinations performed from 2010 through 2012. A comparison of the reports and images was made to the surgical reports, with surgical findings used as the reference standards. Of our 168 cases reviewed, 113 (67.3%) were normal examinations with no abnormality reported. Fifty-five of 168 (32.7%) documented at least 1 abnormality. The abnormalities reported included intimal dissection flaps, residual stenosis with high velocities, substantial atherosclerotic plaque or thrombus, and focal wall irregularities or kinking. Twenty-four (43.6%) of these 55 “abnormal” cases were surgically revised at the time of the study, representing 14.4% of the 168 sonographic cases. Overall, abnormal findings on intraoperative carotid sonography were common, occurring in 32.7% of our cases and leading to an immediate surgical revision in 14.3% of all endarterectomies, similar to the previously published studies as described above. This article describes the spectrum of abnormalities encountered but does not conclude as to whether there was an effect on long-term clinical outcomes or postoperative mortality. We present what abnormalities were noted intraoperatively and which findings were considered significant by the surgeon to prompt an immediate surgical revision.

**Normal Postoperative Appearance**

The normal appearance of the patulent carotid bulb after surgery should be recognized. The lumen will be widely patent, and there should be no residual plaque (Figure 3). Many variations exist regarding the surgical technique for carotid endarterectomy. As mentioned, patching is surgeon dependent, with some using native vein patching and some using synthetic patching to reduce the incidence of late postendarterectomy stenosis.28 Other methods to correct abnormalities include segmental resection of the ICA, reanastomosis of the ICA, and reimplantation of the ICA. There may be echogenic foci in the wall, sometimes with a “ring-down” artifact, consistent with surgical sutures at the patch site (Figure 4). Occasionally, there may be air trapped at the patch site, particularly if there is prosthetic patching with the use of polytetrafluoroethylene material (Figure 5 and Video 2).

At the repair site, there is often a small ledge plaque that remains at the proximal end point at the start of the endarterectomy repair site. This plaque should be small and nonmobile (Figures 6–8). An increase in ipsilateral blood flow after carotid endarterectomy has also been reported and can be expected in patients with substantial ICA stenosis preoperatively.29 Appropriate pulsed wave
Doppler waveforms should show a rapid systolic upstroke with a PSV of less than 150 cm/s and continuous diastolic flow and color flow during the entire cardiac pulse cycle.

**Intimal Medial Flaps and Dissection**

Intimal dissection flaps are among the most frequently encountered abnormalities. Intimal dissection flaps are seen as linear echogenic projections into the lumen and can be mobile. They can usually be well seen on grayscale imaging and best appreciated in real time. Although dissection flaps can be associated with turbulent flow, small intima fronds that move with each cardiac cycle may not be associated with flow abnormalities (Figure 9 and Video 3). Forty-eight (28.6%) of our 168 intraoperative carotid sonographic examinations showed dissection flaps, which constituted 87.3% of the abnormal cases. Twenty-two (45.8%) of these 48 dissection flaps were immediately surgically revised. As proposed by Panneton et al²⁰ and confirmed by the surgeons at our institution, a useful cutoff for the size of a significant dissection flap is 3 mm in length. Revision in this setting would generally involve attempting to remove the dissection flap. Oftentimes the flaps are repaired with tacking sutures. The decision for the surgeon of whether to revise an endarterectomy on the basis of a small dissection flap in the range of 3 mm must be balanced with the risk of additional arterial clamping, arteriotomy, and a longer anesthetic time. In general, though, flaps of 3 mm and larger are generally repaired (Figure 10 and Video 4). Small intimal flaps may show healing without revision.²⁴ No relationship has been found between the presence of a small finding and the subsequent development of residual or recurrent stenosis, occlusion, or a bruit in any artery. Therefore, these minor findings are presumed to be benign and need not require additional re-exploration for surgical repair.²⁴ Flaps may be seen in the CCA, ICA, or ECA (Figure 11 and Videos 5 and 6).

**Figure 6.** Expected appearance of ledge plaques. Intraoperative carotid sonography shows a circumferential ledge plaque at the proximal end of the endarterectomy site (white arrows). Note that the ledge is demarcated by a sharp, linear border and is nonmobile.

**Figure 7.** Ledge plaque (white arrow) in another patient. Distal to this site, the lumen is patent and free of plaque.

**Figure 8.** Ledge plaque without flow disturbance. A, Gray scale sonography again shows a triangular step-off at the proximal end of the endarterectomy site in the distal CCA (white arrow). B, Color Doppler imaging of the same area shows homogeneous flow with appropriate waveforms and velocities.
Residual Stenosis
Minor stenotic defects are generally considered to result in less than 30% luminal narrowing. Residual ICA or CCA stenosis was found in 6 (3.6%) of our cases: 10.9% of the abnormal cases. Intraoperative residual stenosis would have the same appearance as preoperative stenosis, including an elevated PSV. If the same criteria are used for standard carotid duplex sonography, a PSV of greater than 125 cm/s would signify greater than 50% stenosis, and a PSV of greater than 230 cm/s would signify greater than 70% stenosis. Velocities of greater than 300 cm/s are considered the result of severe stenosis. As with standard carotid sonography, care must be taken to consider the grayscale appearance and to ensure a proper scale and Doppler angle. Two (33%) of our cases with residual stenosis were surgically revised with larger-patch angioplasty. Moderately elevated PSVs (150–200 cm/s) without grayscale abnormalities, except for possibly luminal narrowing, may be due to arterial spasms. There may be a role for administering a vasodilator with repeated flow measurements to prevent unnecessary revision.

Thrombus
An acute thrombus was seen in only 1 (0.6%) of our cases. Complete thrombosis is a rare occurrence and in our case was seen in the setting of a small (2.9-mm) dissection flap within the distal CCA. This thrombus appeared as an initially subtly echogenic area adjacent to the dissection flap without flow in that portion of the lumen. In this case, the artery was reentered and the thrombus and dissection flaps removed. Thrombus forming on a dissection flap represents the dreaded thromboembolic complication that intraoperative carotid duplex is designed to prevent and can potentially lead to perioperative stroke (Figure 12 and Video 7).

Focal Residual Plaque
Focal residual atherosclerotic plaque in the surgical bed was a rarely reported abnormality in our series but may have been underreported. We reported it in only 1 (0.6%) of our cases, and it was not surgically revised. Focal residual plaque would appear in the surgical bed as focal material, greater than 2 mm in thickness, against the arterial wall without a flap to suggest dissection (Figure 13 and Videos 8, 9A, and 9B). Substantial residual plaque may also be a source leading to subsequent ICA occlusion if not surgically revised.

Figure 9. Transverse (A) and longitudinal (B) grayscale images show a small linear intimal flap of less than 3 mm within the ICA just distal to the carotid bifurcation (calipers in A and white arrow in B). Echogenic suture material can be seen on the longitudinal image within the anterior wall. This flap was not revised.

Figure 10. Dissection flap. Longitudinal intraoperative sonography shows a thick dissection flap in the proximal bulb along the posterior wall, which measured greater than 3 mm and was mobile (calipers). This flap was revised. At exploration, an elevation of the intima was noted, which was subsequently tacked down with a suture.
Isolated ECA Findings
Isolated ECA abnormalities were identified in 10 (10%) of our cases. These findings included ECA intimal dissection flaps in isolation and constituted 10 (18.2%) of the 55 abnormal cases. The dissection flaps were seen in the proximal ECA, and 3 (30%) of the 10 were revised. The consideration for ECA revision includes the proximity to the CCA and ICA lumen and the surgeon’s perception of the threat to the CCA and ICA lumen (Figure 14 and Videos 10A and 10B). At least 1 older series showed a higher rate of thrombosis of the ECA with attempts at revision, although with improved surgical and sonographic developments, further investigation is warranted to show a possible benefit in revision of these lesions.22,32,33

Figure 11. Revision of a dissection flap. A. Transverse intraoperative sonography shows a thin mobile flap in the ICA after endarterectomy. Since this flap was larger than 3 mm, another arterectomy to the patch was performed, and a 4-mm flap was discovered and subsequently repaired (white arrow). B. Follow-up sonography after revision shows the lumen without residual plaque or a flap (large white arrow). Also shown is air in the saline wash within the neck cavity (small white arrow).

Limitations
Intraoperative duplex sonography requires technical hands-on skill and is operator dependent. A drawback with performing intraoperative sonography is the potential increase in surgical and anesthesia time. There is the potential for a considerable delay while waiting for the ultrasound team to come to the operating room and in the time it takes to perform the sonographic examination. For example, Ascher et al22 reported a mean scanning time of 10 ± 3 minutes. The time could be decreased by good preoperative coordination and communication. An ultrasound machine that is already present in the operating room and available to the surgeon could improve efficiency. There is also the additional technical cost that would be incurred. Theoretically, an increase in time could lead to an increase in ischemic events because of increased arterial cross-clamping time associated with re-exploration and revision.2,32 In addition, some older studies have questioned the safety of revision and suggested that repair of technical defects could be associated with increased postoperative stroke.22,32 However, this suggestion is controversial with improved ultrasound technology and smaller, higher-resolution probes. Potentially, defects of uncertain significance may lead to unnecessary re-exploration. Further rigorous investigation is needed to better triage which patients may benefit from completion imaging with intraoperative carotid sonography, rather than add to cost, risk, and potentially unnecessary re-exploration.

Figure 12. Residual thrombus. Color and pulsed wave Doppler intraoperative carotid sonography shows elevated velocities, turbulence, and spectral broadening associated with residual plaque and thrombus within the ICA lumen. This thrombus was revised with a larger patch.
Conclusions

The surgeon may choose to use intraoperative carotid duplex sonography in some cases during carotid endarterectomy. For those interpreting vascular sonography, it is important to be familiar with the spectrum of findings in the surgical bed during carotid sonography. Although the use of intraoperative sonography has not yet been broadly integrated, we observed that it affected surgery in some cases by ensuring the technical adequacy of the repair site and detecting clinically important residual lesions. Intraoperative sonography can provide additional confidence when there is a specific concern as to the technical adequacy of the surgery. It may positively affect outcomes in a selective subset of patients with clinically unsuspected residual defects. Recognition of normal and abnormal sonographic findings, and the understanding of the significance of these findings, is important for anyone interpreting vascular sonography.

References


