Diagnosing Carotid Stenosis by Doppler Sonography

State of the Art

Diana Gaitini, MD, Michalle Soudack, MD

Objective. The goal of this review article is to present the state of the art in the clinical applications and technical performance and interpretation of carotid sonographic examinations. ***Methods.*** Relevant publications regarding color and duplex Doppler sonography (CDDS) of the carotid arteries extracted from a computerized database (MEDLINE) and from references cited in these articles not appearing on the Internet were reviewed. ***Results.*** The ability to quickly and efficiently identify stenosis in the carotid artery is an important goal for clinicians and vascular surgeons. Identification of potentially treatable carotid stenosis enables selection of appropriate candidates for endarterectomy or stent implantation. Advances in performance and interpretation of carotid sonographic studies over the last 20 years have been driven by technological improvements in gray scale and CDDS examinations and have made carotid sonography an important means to reach this goal. On the basis of CDDS, intima-media thickness measurements and plaque location and characterization on gray scale imaging, flow disturbance and areas of stenosis on color Doppler sonography, and flow velocities on spectral Doppler sonography are obtained. The degree of the diameter of a stenosis of the internal carotid artery is the main parameter used for therapeutic approaches. Advantages and limitations of the method are included. ***Conclusions.*** Carotid sonography is a unique imaging method for the investigation of carotid abnormalities. Noninvasive, accurate, and cost-effective, it provides morphologic and functional information. It is increasingly becoming the first and often the sole imaging study before endarterectomy, whereas costly and invasive procedures are reserved for special cases. ***Key words:*** carotid artery stenosis; carotid sonography; Doppler sonography.

Abbreviations

ACAS, Asymptomatic Carotid Atherosclerosis Study; CCA, common carotid artery; CDDS, color and duplex Doppler sonography; CEA, carotid endarterectomy; DSA, digital subtraction angiography; ECST, European Carotid Surgery Trial; EDV, end-diastolic velocity; ICA, internal carotid artery; IMT, intima-media thickness; MRA, magnetic resonance angiography; NASCET, North American Symptomatic Carotid Endarterectomy Trial; PSV, peak systolic velocity; SRU, Society of Radiologists in Ultrasound

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Address correspondence to Diana Gaitini, MD, Unit of Ultrasound, Department of Medical Imaging, Rambam Medical Center, Ha'aliya 8, PO Box 9602, Haifa 31096, Israel.

E-mail: d_gaitini@rambam.health.gov.il

Stroke is one of the leading causes of death in western countries. One third of cases are fatal, and survivors usually have prolonged or irreversible disabilities. Four of 5 of the ischemic events are caused by atherosclerotic diseases, with most changes affecting the carotid bifurcation.[1]

Two randomized studies, the North American Symptomatic Carotid Endarterectomy Trial (NASCET) and the European Carotid Surgery Trial (ECST), were performed in symptomatic patients to examine the efficacy of carotid endarterectomy (CEA) in patients with high-grade (≥70%) internal carotid artery (ICA) stenosis based on the angiographic estimation of the degree of stenosis. It was proved that these patients did benefit from carotid surgery compared with the group receiving conservative treatment.[2–5] On the basis of a recent pooled analysis in subgroups of patients with stenosis of 50% to 69%, CEA should also be considered.[6,7] The Asymptomatic Carotid Atherosclerosis Study (ACAS) in patients with asymptomatic high-grade carotid stenosis (≥60%) showed a 5.8% risk reduction of stroke at 5 years after endarterectomy and concluded that CEA was beneficial when performed in centers where morbidity and mortality were 3% or less.[8–10] There is a debate going on about whether and which subgroups of patients with an asymptomatic ICA stenosis should undergo surgery, and risk stratification is necessary to identify these patients.[8,11,12]

Because of their superficial location, the extracranial carotid arteries are optimal for color and duplex Doppler sonography (CDDS). B-mode gray scale sonography allows for imaging of atherosclerotic plaques and intima-media thickness (IMT). Color Doppler sonography allows simultaneous real-time visualization of vascular lesions and associated flow abnormalities, guides cursor position on suspected areas of stenosis, and assists in differentiating between critical stenosis and occlusion. Examination and recording of pathologic findings on gray scale and color Doppler sonography are followed by spectral Doppler hemodynamic analysis.

Doppler sonography is the most common imaging study performed for the diagnosis of carotid disease. However, a wide range of practice patterns among vascular laboratories still exists. Despite technological advances in sonographic equipment, improvements in operator expertise, and accrediting bodies to increase the quality of carotid sonographic examination, there is still no uniformity in practice and interpretation between different centers and even between different operators in the same laboratory. Therefore, standardized protocols are highly recommended for reproducibility and reliability of information provided by carotid sonography.[13]

Indications for Carotid Sonographic Examination

Candidates for evaluation of carotid artery stenosis may be divided into 2 groups: symptomatic and asymptomatic. The first group comprises patients who have had a neurologic event secondary to cerebral ischemia, specifically those who have had amaurosis fugax or a transient ischemic attack or a minor stroke, and may benefit from CEA.[2–5] Additional indications are suggestive carotid dissection, particularly after trauma and in patients after endarterectomy, and a stent with neurologic symptoms. The asymptomatic group comprised patients with a pulsatile neck mass or cervical bruit and patients before major vascular surgery; some centers follow patients having endarterectomy and stents routinely and not just when they become symptomatic. Regarding carotid sonography for screening before major cardiovascular surgery, in a recent study by Ascher et al[14] on 3708 patients who underwent open heart surgery and preoperative carotid duplex sonography, patient age was found to be the most significant risk factor for the prevalence of carotid disease, confirming previous studies. They concluded that carotid screening before open heart surgery (coronary artery bypass graft and valve replacement) should be recommended for all patients older than 60 years and for patients younger than 60 years with 2 or more major risk factors: hypertension, diabetes, and smoking. However, the discussion is still going on about whether asymptomatic patients with combined coronary and carotid artery stenosis should undergo carotid surgery at all and whether staged or synchronous procedures confer any overall benefit.[15] Carotid screening may be cost-effective in a patient population in which the prevalence of severe carotid stenosis exceeds 4.5%.[16]

Technical Considerations and Data Interpretation

Standard protocols include carotid examination with a high-resolution linear array transducer (7 MHz or broad spectrum 5–12 MHz). Three modalities must be used: B-mode gray scale imaging, color flow Doppler, both on transverse and longitudinal planes, and spectral Doppler velocities on longitudinal planes.

B-Mode Gray Scale Imaging

Imaging of the entire common carotid artery (CCA), the carotid bifurcation, the ICA as distal as possible, and the external carotid artery is the first step in carotid sonographic examination. It is the best method for measuring IMT and showing atherosclerotic plaques. Mean IMT is calculated in the CCA between 2 interfaces: blood-intima and media-adventitia. Intima-media thickness measurement can be performed either manually or by computer software. In the manual method, multiple measurements are made by placing electronic cursors at multiple sites and averaging values. In the computerized method, 3 measurements are made on the far wall at anterior, lateral, and posterior projections and averaged.[17,18] Normal IMT is less than 0.8 mm. Intima-media thickness increases with age; a thickness of 0.8 to 1.0 mm is considered indeterminate. A thickness of 1.1 mm or greater is actually a more accepted abnormal value (Figure 1). Measurement of the IMT can be technically challenging, and considerable quality assurance measures need to be taken. This emphasizes the need to standardize the method of measuring carotid IMT. Intima-media thickness is considered a marker of early atherosclerosis and is the only sonographic parameter recommended by the American Heart Association to be used routinely when screening for cardiovascular risk.[18] Despite the importance of IMT measurements as an indicator of arteriosclerotic changes, IMT is not routinely included in the examination of the symptomatic patient when looking for stenosis, and testing IMT does not influence the decision of carotid surgery.

Evaluation of plaque location and characteristics is an important part of the standard carotid duplex sonographic examination. Plaque definition both in the carotid bifurcation and along the ICA includes size with its corresponding hemodynamic alteration, surface, and echogenicity. A classification of atherosclerotic plaques according to these parameters was proposed (Table 1).[19] According to hemodynamics, the plaque was classified on a scale from H1 to H5: H1 being mild, less than 50% diameter reduction; H2, moderate, 50% to 69% diameter stenosis; H3, severe, 70% to near occlusion; H4, critical, near occlusion; and H5, occluding, total occlusion. According to plaque echogenicity, it was classified into P1, homogeneous; and P2, heterogenous; S1 to S3 indicated surface characteristics, from smooth (S1) to irregular with a surface defect of less than 2 mm (S2) and ulcerated with a defect of greater than 2 mm (S3). Ulcerated lesions are associated with intraplaque hemorrhage; 50% to 70% of patients with this type of plaque have hemispheric symptoms.[20] Characteristics of the plaque are independent parameters, unrelated to plaque size and stenosis diameter percentage, which should be taken into account for therapeutic planning when the patient is symptomatic and the diameter of the stenosis does not reach the threshold of 70%.[19,20] It should be noted that Table 1 is an overall classification of plaques but not one that is routinely applied clinically or systematically included in the examination report of carotid duplex sonographic examination. A plaque estimate of diameter percentage reduction is considered a primary parameter, together with ICA peak systolic velocity (PSV) for the diagnosis of the degree of ICA stenosis (Table 2).[13]

Figure 1. Intima-media thickness in the CCA measured between blood-intima and media-adventitia interfaces. **A**, Normal IMT (0.6–0.8 mm). **B**, Moderately thickened (1–1.5 mm).

A **B**

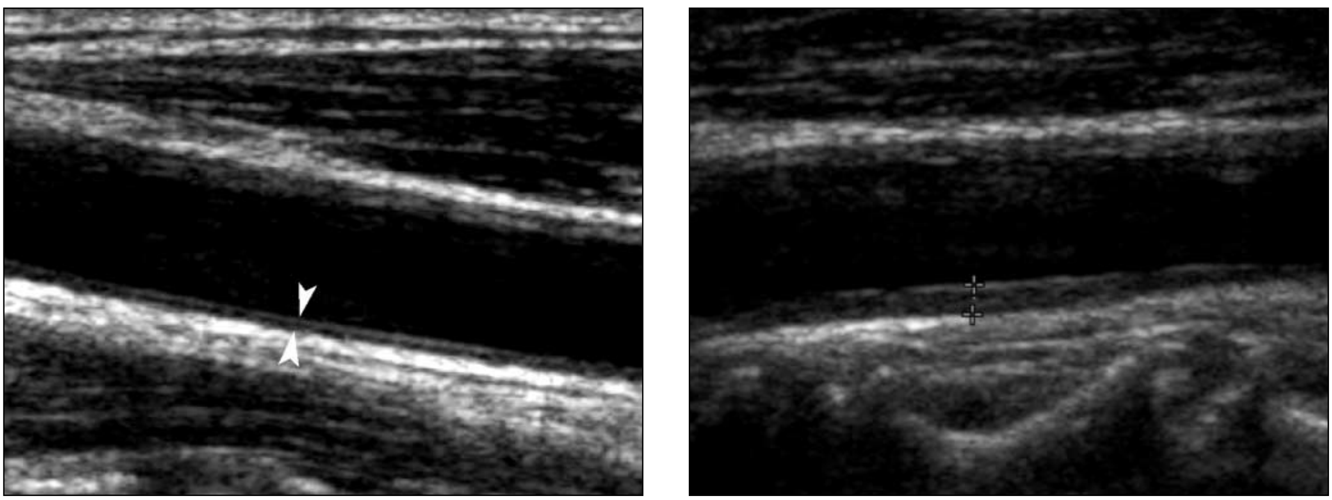


Table 1. Classification of Plaque

Hemodynamic (% Stenosis Diameter)	Morphologic	By Surface
H1, mild (<50%)	P1, homogeneous	S1, smooth
H2, moderate (50%–69%)	P2, heterogeneous	S2, irregular (defect <2 mm)
H3, severe (70%–95%)		S3, ulcerated (defect >2 mm)
H4, critical (95%–99%)		
H5, occluding (100%)		

From Thiele et al.[19]

Color Doppler Imaging

Color Doppler sonography provides a "road map" for the identification of ICA origin and course and is especially useful for tortuous arteries, high bifurcations, and differentiation between severe stenosis and occlusion. Areas of stenosis are seen as a reduced lumen with a red to blue shift due to "aliasing," a Doppler artifact occurring when velocities are higher than the pulse repetition frequency. Red represents flow toward the transducer, within the range of the pulse repetition frequency, whereas blue represents velocities beyond the range of the pulse repetition frequency and not reversed flow. Poststenotic areas may have a mosaic color Doppler pattern due to multiple velocities and flow reversal in a boundary separation zone.[21–23] In the face of a nearly occluded lumen, a narrow hairline string of color through the plaque called the "string sign" may be seen. Power Doppler sonography may aid in the visualization of the residual lumen because of its higher sensitivity to lower velocities.[24,25]

Spectral Analysis

Flow velocity is the main parameter for evaluating the severity of carotid stenosis. On the B-mode gray scale image, the cursor is placed in the center of the carotid lumen at an angle of 60° or less for Doppler spectral display of the carotid flow (duplex). Flow velocity must be sampled through the whole area of presumed stenosis until the distal end of the plaque is seen to ensure that the site of the highest velocity has been detected. The data presented by various validation studies relating Doppler sonographic velocity recording to angiographic stenosis percentage show a considerable spread of values, which is present on the so-called scattergrams. This means that for any given degree of angiographic stenosis, a wide range of associated blood flow velocities is recorded. This affects the sensitivity and specificity of the sonographic tests. In addition, it strongly affects the positive and negative predictive values. Depending on whether the patients are symptomatic or asymptomatic (related to both the risk of subsequent stroke and the anticipated benefit from CEA) some authors, such as Moneta et al,[26,27] recommend adjusting the interpretation to reflect these relative risks. It is recommended that every vascular laboratory should check the results of its different sonography equipment. Practitioners should be aware that machines are not necessarily calibrated in the same way and phantoms are not routinely used to check.[13] Another important recommendation to achieve greater reliability in the perfor-

Table 2. Spectral Doppler Velocities and Plaque Estimate Correlated With Degree of ICA Stenosis Diameter

Stenosis, %	ICA PSV, cm/s	Plaque Estimate, %	ICA/CCA PSV Ratio	ICA EDV, cm/s
Normal	<125	NA	<2	<40
<50	<125	<50	<2	<40
50–69	125–230	>50	2–4	40–100
70, near occlusion	>230	>50	>4	>100
Near occlusion	High/low/ undetectable	Visible	Variable	Variable
Total occlusion	NA	Visible, no detectable lumen	NA	NA

From Grant et al.[13] NA indicates not applicable.

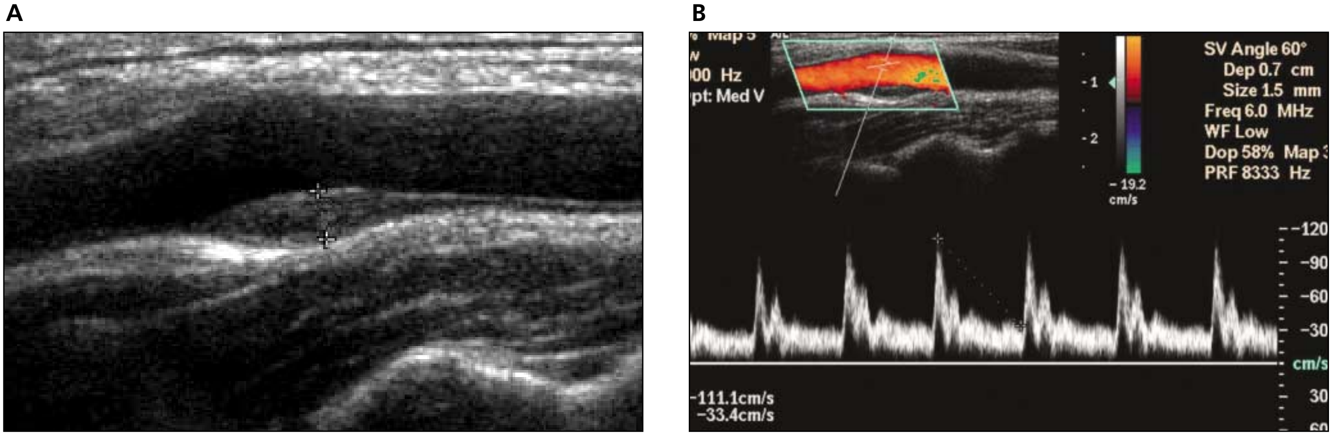
mance of carotid sonography is to follow a consistent protocol, in accordance with the standards of one of the accrediting bodies.[13] Several classifications of carotid stenosis degree have been proposed, according to PSV and end-diastolic velocity (EDV) in the ICA and PSV ICA/CCA ratios.[26–38] It is clear that choosing a velocity threshold affects sensitivity and specificity of the test; with lowered thresholds, sensitivity increases whereas specificity decreases, and vice versa. Achieving high sensitivity comes at the price of lowered specificity.

A multidisciplinary panel of experts under the auspices of the Society of Radiologists in Ultrasound (SRU) convened in San Francisco, California, on October 22 and 23, 2002, and drew up a recently published consensus statement on the performance of Doppler sonography for the diagnosis of ICA stenosis.[13] According to this panel, stenosis degree in the ICA was classified into 5 categories based on 2 primary parameters, ICA PSV and plaque size, and 2 secondary parameters, ICA/CCA PSV ratio and ICA EDV (Table 2). The ICA/CCA PSV ratio is helpful when high ICA velocities are registered in hyperdynamic states such as in young patients or when flow changes are induced by severe bilateral ICA stenosis or proximal CCA stenosis or occlusion. Probably the most important use for the carotid ratio is for those patients who have low cardiac output and have proportionally lower systolic velocities for a given degree of stenosis. Hemodynamically appreciable stenosis starts at greater than a half-diameter reduction. For clinical applications, identification of 70% to 99% stenosis has the most relevant effect. In a recently published study, Sabeti et al[39] performed a comparative analysis of different flow velocity criteria for the quantification of ICA stenosis with duplex sonography. They concluded that exclusion of 70% to 99% angiographic stenosis could be achieved with sensitivity of up to 98%. Obviously, the threshold was put low enough so that this high sensitivity was achieved at the cost of lowered specificity. The SRU thresholds were chosen to provide a reasonable balance between sensitivity and specificity.

Each category has its recommended therapeutic approach according to NASCET and ACAS.[2,5,8–10] For stenosis of 50% or less (Figure 2), medical therapy is recommended for symptomatic patients. For 50% to 69% stenosis, the recommended treatment is medical therapy and CDDS follow-up every 6 months to detect progression that may warrant surgery.[32] The results of the NASCET trial showed that patients with moderate stenosis may also benefit from surgery.[5] For stenosis of 70% or greater (Figure 3) and for near occlusion, 95% or greater diameter reduction, 2 trials, NASCET and ECST, established the benefit of CEA in symptomatic patients. A limitation regarding treatment based on duplex findings may be that no direct validation data have been used to relate the velocity criteria to patient benefit from CEA. Patients with carotid near occlusion are distinct from those with 90% to 95% stenosis and have a lower risk of stroke on medical treatment and a marginal benefit from endarterectomy.[6] With regard to outcome in these patients, actual

Figure 2. Small plaque, lying between the sonographic cursors, homogeneous and with a smooth surface (H1, P1, S1 [Table 1]) in the proximal ICA (**A**) without signs of hemodynamically appreciable stenosis (PSV, <125 cm/s) (**B**).

A **B**



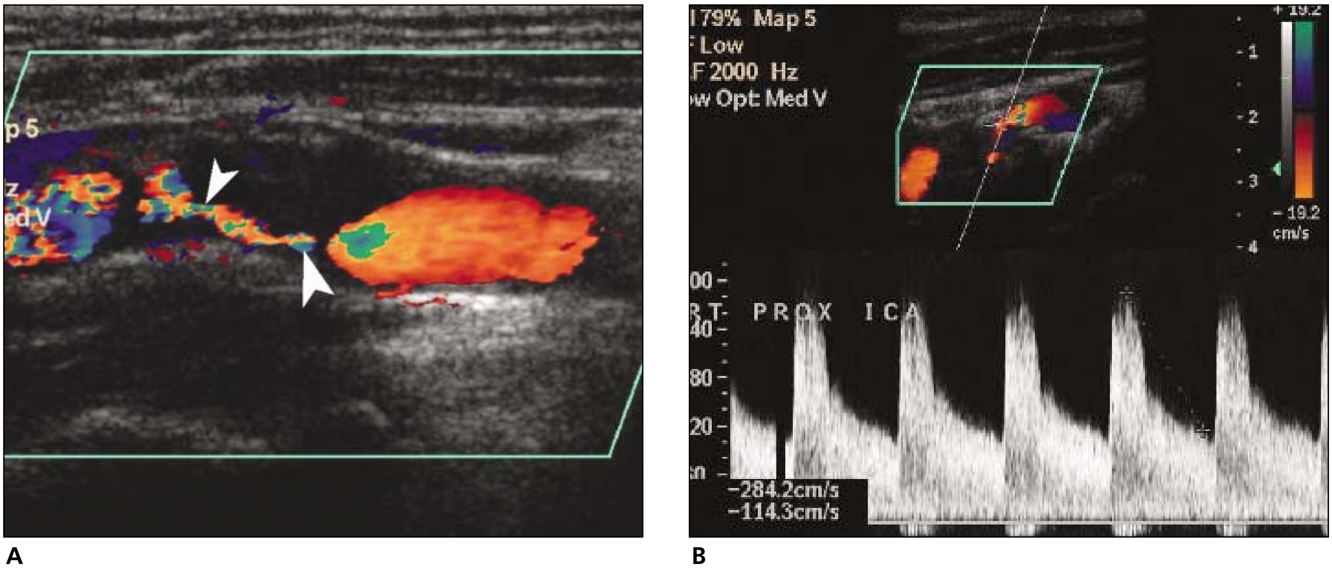


Figure 3. Large plaque causing high-grade (>70%) ICA stenosis. **A**, Aliasing phenomenon on color Doppler sonography due to high velocities in the center of the stenotic lumen and poststenotic flow disturbances. **B**, On spectral display, high systolic and diastolic velocities are shown (PSV, 284 cm/s; EDV, 114 cm/s).

results are mixed but, importantly, typically not as good as with lesser degrees of stenosis. The ACAS study used 60% diameter stenosis or less for the surgical threshold and recommended surgery for asymptomatic patients with 60% stenosis or greater in centers where the morbidity and mortality of CEA do not exceed 3%.[10] In total occlusion, the arterial lumen is filled by the plaque, and flow is undetectable. Other features of ICA occlusion are increased pulsatility of the CCA with decreased or absent diastolic flow, "internalization" of the external carotid artery due to high diastolic flow, and higher velocities in the contralateral carotid arteries.[38,40] For total occlusion, no surgical options remain.

It should be pointed out that there is more than 1 technique for determining the degree of angiographic stenosis. Specifically, there is the NASCET definition, using the high cervical ICA as the standard,[2] comparing the narrowest portion of the vascular lumen with the normalized lumen distally, as opposed to the University of Washington criteria,[30] the ECST,[3,4] and older North American studies trials, using the anticipated diameter of the carotid bulb as the standard, comparing the narrowest lumen with an estimate of the original lumen in the same area. The method used has implications with regard to selection of thresholds, affecting the reference standard and recommendations for CEA. The NASCET angiographic method of carotid stenosis measurement should be used as the reference standard for comparison with sonographic findings.[13]

Another issue that should be addressed regarding reference standards for velocity criteria is the lack of validation data that directly relate duplex carotid velocities to patient benefits from CEA. Further investigations on this topic may increase the sensitivity and specificity of the Doppler sonographic test.

The differentiation between near and total occlusion is critical for treatment decisions. Because velocity rates may decrease before occlusion, velocity indices are useless for differentiation. After the instrument sensitivity is raised, color and power Doppler sonography may show even minimal residual flow as a few intraluminal color pixels and may allow reliable differentiation. Hetzel et al[41] reported sensitivity of 88% and specificity of 99% for detection of nearly occluded ICA stenosis. This limitation is a promising challenge for sonographic echo-enhancing agents. Furst et al[42] reported sensitivity and specificity of echo-enhanced power Doppler sonography for detection of residual flow of 94% and 100%, respectively, compared with 85% and 92% for the unenhanced test.

Several important unanswered questions that merit future research were identified by the SRU panel. One of them is the need to define the method or the report of duplex sonography in patients after carotid stent placement or endarterectomy.[13] The guidelines for interpreting the examination to assess for restenosis due to intimal hyperplasia or to describe the degree of calcification and the location of stenosis relative to the angle of the mandible should not be the same as those for assessing atherosclerotic plaques before treatment.

Limitations of Color Duplex Sonography

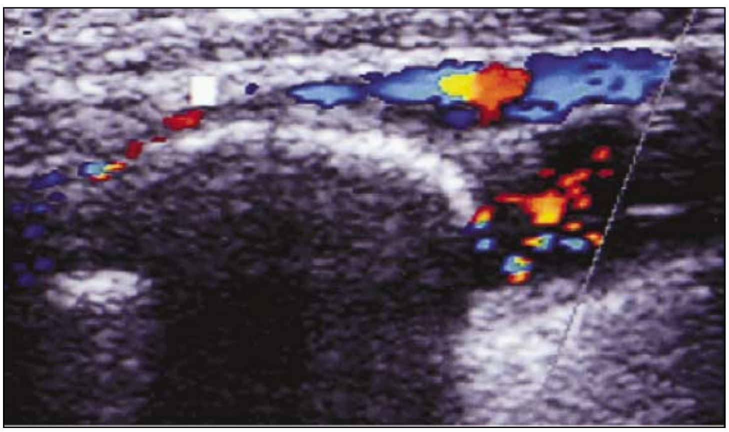
Tortuosity of the ICA due to kinking and coiling secondary to atherosclerosis may deliver a high PSV in the ICA. In such cases, the absence of plaques as a source of increased velocities must be confirmed on gray scale and color flow imaging.

Heavily calcified plaques may act as a barrier to the ultrasound waves and may cause posterior acoustic shadowing. This shadow renders the involved segment inaccessible to gray scale or Doppler examination (Figure 4). In the presence of a circumferential calcified plaque, flow patterns immediately distal to the lesion should be observed: if flow remains normal or moderately disturbed, appreciable stenosis may be excluded.[38] In patients with stenosis high in the neck, unusually long lesions or arterial kinking, other diagnostic tests should be recommended.[32,43,44] Internal carotid artery PSV values are less reliable when variations in cardiovascular physiologic states are present, such as hypertension, high or low cardiac output, aortic abnormalities, and bilateral carotid occlusive processes.[44] As mentioned before, ICA/CCA ratios may be useful in these situations. Substantial distal stenosis, beyond the reach of the ultrasound probe, may be suggested by indirect signs such as increased resistance within the ICA proximal to the lesion.[33] A potential role for sonographic contrast agents, either to improve conspicuity of the lumen or to improve pulsed wave Doppler signals, has been described.[42]

Comparison of the Diagnostic Value of Color Duplex Sonography With That of Other Imaging Tests

Compared with selective intra-arterial digital subtraction angiography (DSA), the "reference standard" test, the sensitivity of CDDS for the diagnosis of 70% carotid artery stenosis to near obstruction varied between 87.5% and 98.6%, and the specificity varied between 59.2% and 75.7%.[32] Other authors reported an overall sensitivity of 91% to 95% and specificity of 86% to 97%.[1] Color and duplex Doppler sonography and DSA have shown agreement in at least 90% of the cases in the grading of stenosis.[45,46] The complication rate for DSA is 1% to 2% for both stroke and death. This rate is notable considering that, in high-expertise vascular surgery centers, the morbidity and mortality of CEA are as low as 1.5%.[47] Computed tomographic angiography and magnetic resonance angiography (MRA), including contrast-enhanced MRA, are noninvasive techniques applied in recent years for the diagnosis of carotid stenosis.[48,49] Contrast-enhanced MRA in general is better than CDDS for occluded vessels and in discriminatory power, at least in 70% to 99% stenosis.[50] Similar calculations for MRA yielded sensitivities between 92.2% and 96.9% and specificities between 57.9% and 75.7%.[32] However, in vivo measurements of plaques correlated better with sonography ($r = 0.8$) than with MRA ($r = 0.7$).[50] Computed tomographic angiography and MRA may complement CDDS when results are indeterminate or discrepant with the clinical diagnosis. The result of the noninvasive test that better correlates with the clinical manifestation should be the more reliable one. Digital subtraction angiography is still occasionally necessary as an arbiter when the results of noninvasive procedures and the clinical diagnosis are not concordant. Results from cost-effectiveness studies[51,52] showed that duplex sonography as a single examination strategy was both less expensive

Figure 4. Heavily calcified plaque at the ICA origin, leading to wide posterior shadowing and preventing color Doppler sonographic examination of the involved segment.



and more effective than nearly all other strategies, including DSA. The combination strategy of CDDS and MRA has a slight benefit in clinical outcome but at extremely high additional costs, in which DSA is inferior for the associated complications.[51–53]

The main drawback of CDDS is the high dependence on technological factors in both performance and interpretation. For the operator to be familiar with the baseline, about 200 examinations are needed, and a considerable larger number are needed for reliable grading of ICA stenosis and knowledge of pitfalls and limitations of the examination.[54]

Conclusions

Color and duplex Doppler sonography is the first imaging examination performed for the diagnosis of carotid stenosis. Because of its dual ability to evaluate both morphologic and hemodynamic abnormalities and its cost-effectiveness, CDDS is usually the only test applied before a therapeutic decision. A standardized protocol of examination, knowledge, and experience among operators and imaging specialists and continuous quality control are necessary to ensure reliable results. The choice of a therapeutic approach is based on the degree of stenosis diameter. Although duplex sonography cannot precisely define the stenosis diameter percentage, a range of stenosis diameters may be achieved with defined diagnostic strata. Additional procedures such as computed tomographic angiography, MRA, and DSA have selected indications. These more expensive or invasive tests are required for definitive diagnosis and therapy management in a small number of patients such as those with discrepant clinical and duplex sonographic findings.

Cost-effectiveness analysis is mandatory for deciding which test strategy is the best for suspected carotid artery stenosis. Duplex sonography as a single examination strategy is optimal for a final diagnosis and a treatment plan for patients with symptomatic carotid artery stenosis; at present, many centers perform surgery solely on the basis of duplex sonographic information.[52] Several important topics merit future research, such as the role of plaque characterization and intima-media thickness measurements, criteria for assessment of patients after endarterectomy or stent placement, and screening for carotid disease in selected patient populations.[13]

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