Sonographic Examination of the Carotid Arteries[1]

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Ultrasonography (US) of the carotid arteries is a common imaging study performed for diagnosis of carotid artery disease. In the United States, carotid US may be the only diagnostic imaging modality performed before carotid endarterectomy. Therefore, the information obtained with carotid US must be reliable and reproducible. Technical parameters that can affect the accuracy of carotid US results include the Doppler angle, sample volume box, color Doppler sampling window, color velocity scale, and color gain. Important factors in diagnosis of atherosclerotic disease of the extracranial carotid arteries are the intima-media thickness, plaque morphology, criteria for grading stenosis, limiting factors such as the presence of dissection or cardiac abnormalities, distinction between near occlusion and total occlusion, and the presence of a subclavian steal. Challenges to the consistency of carotid US results may include lack of a standard protocol, poor Doppler technique, inexperience in interpretation of hemodynamic changes reflected in the Doppler waveform, artifacts, and physical challenges. Hindrances in the classification of problematic carotid artery stenoses may be overcome by following a standard protocol and optimizing scanning techniques and Doppler settings.

Abbreviations: CCA = common carotid artery, ECA = external carotid artery, ICA = internal carotid artery, PSV = peak systolic velocity, PW = pulsed wave

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Introduction

Cerebrovascular disease (stroke) is the third leading cause of death in the United States, accounting for approximately 400,000 new cases diagnosed each year and over 163,000 deaths in 2002 (1). Ultrasonography (US) of the carotid arteries is the modality of choice for triage, diagnosis, and monitoring of cases of atheromatous disease. This is an operator-dependent examination that requires a good understanding of Doppler physics and hemodynamic physiology. The accuracy of carotid US hinges on following standard guidelines and practicing meticulous scanning techniques. There are several pitfalls that may mislead the operator to falsely interpret color and spectral Doppler findings.

In this article, we discuss standard guidelines for carotid US, optimal scanning techniques and Doppler settings, and US diagnosis of extracranial atherosclerotic carotid disease, including characteristic gray-scale, color, and spectral Doppler appearances as well as operator- and patient-related pitfalls.

Standard Protocol

Our suggested protocol may be modified by each institution with respect to their clinical settings and requirements.

Patient Position

The patient may lie down in the supine or semisupine position with the head slightly hyperextended and rotated 45° away from the side being examined.

Transducer

Higher-frequency linear transducers (>7 MHz) are ideal for assessment of the intima-media thickness and plaque morphology, while lower-frequency linear transducers (<7 MHz) are preferred for Doppler examination. In a short muscular neck, if imaging with a linear transducer is impossible, a curved-array transducer (<7 MHz) may be helpful to document the anatomy of the carotid bifurcation with color Doppler US.

Imaging

The extent, location, and characteristics of atherosclerotic plaque in the common carotid artery (CCA) and internal carotid artery (ICA) should be documented with gray-scale imaging. The vessels should be imaged as completely as possible, with caudal angulation of the transducer in the supraclavicular region and cephalic angulation at the level of the mandible. Color Doppler imaging should be performed to detect areas of abnormal blood flow that require Doppler spectral analysis. Pulsed wave (PW) Doppler spectral analysis should be performed, and the velocity of blood flow in the mid-CCA and proximal ICA as well as proximal to, at, and immediately distal to the diseased areas should be measured (2). Evaluation of the external carotid artery (ECA) should be performed, as it is a source of bruit and differences in the Doppler appearance of the ECA and ICA improve observer confidence that the bifurcation vessels have been correctly identified. Color and PW Doppler imaging of both vertebral arteries should also be performed to rule out the presence of a subclavian steal. The topography of the plaque, velocity information, and interpretation of the results by the radiologist can be conveniently recorded in a standardized format (Fig 1).

Limitations

Physical challenges such as a short muscular neck, a high carotid bifurcation, tortuous vessels, calcified shadowing plaques, tracheostomy tubes, surgical sutures, postoperative hematoma or bandages, central lines, inability to lie flat in respiratory or cardiac disease or to rotate the head in patients with arthritis, and uncooperative patients may limit the results of carotid US examination.

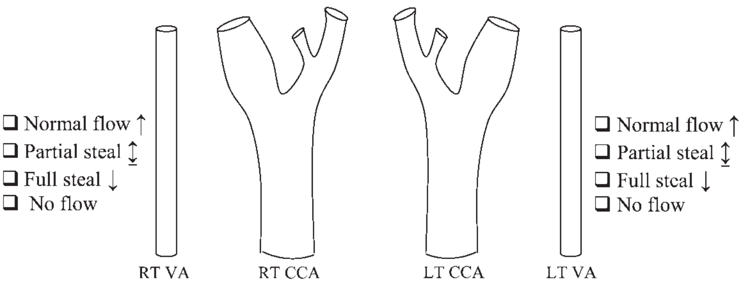
Optimal Scanning Techniques and Doppler Settings

Doppler Equation

US equipment calculates the velocity of blood flow according to the Doppler equation:

$$\Delta f = \frac{2f_0 \, V \cos\theta}{C} ,$$

Patient's Name:……………………………………………...Patient's ID…………….
Examination Date:………………..Clinical Indication:……………………...............
Sonographer:……………



RIGHT			Doppler angle (θ)	LEFT			Doppler angle (θ)
CCA-PSV (cm/sec)				CCA-PSV (cm/sec)			
ICA (cm/sec)	PSV			ICA (cm/sec)	PSV		
	EDV				EDV		
ICA/CCA (PSV ratio)			N/A	ICA/CCA (PSV ratio)			N/A

Interpretation:

Radiologist, MD

Figure 1. Suggested format for documentation of the results of carotid US. Graphic representation of the plaque is important for follow-up examinations. *EDV* = end-diastolic velocity, *ID* = identification, *LT* = left, *N/A* = not applicable, *PSV* = peak systolic velocity, *RT* = right, *VA* = vertebral artery.

where Δf is the Doppler shift frequency, f_0 is the transmitted ultrasound frequency, V is the velocity of reflectors (red blood cells), θ (theta, also referred to as the Doppler angle) is the angle between the transmitted beam and the direction of blood flow within the blood vessel (the reflector path), and C is the speed of sound in the tissue (1540 m/sec). Since the transmitted ultrasound frequency and the speed of sound in the tissue are assumed to be constant during the Doppler sampling, the Doppler shift frequency is directly proportional to the velocity of red blood cells and the cosine of the Doppler angle (3).

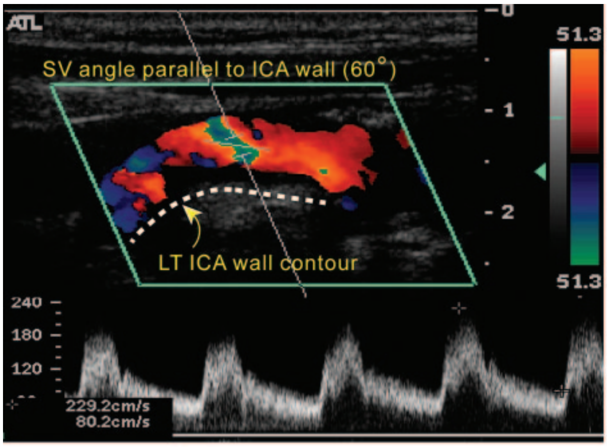
Doppler Angle

The angle θ affects the detected Doppler frequencies. At a Doppler angle of 0°, the maximum Doppler shift will be achieved since the cosine of 0° is 1. Conversely, no Doppler shift (no flow) will be recorded if the Doppler angle is 90° since the cosine of 90° is 0. The orientation of the carotid arteries may vary from one patient to another; therefore, the operator is required to align the Doppler angle parallel to the vector of blood flow by applying the angle correction or angling the transducer.

Sample Volume Box and Angle Correction

The US machine calculates the velocity from the Doppler shift frequency reflected from red blood cells within the sample volume box. In most cases, sonographers will experience some uncertainties in estimating the flow angle and positioning the sample volume box. If the Doppler angle is small (<50°), this uncertainty leads to only a small error in the estimated velocity. If Doppler angles of 50° or greater are required, then precise adjustment of the angle correct cursor is crucial to avoid large errors in the estimated velocities (3,4).

Figures 2, 3. **(2)** Location and angle of the sample volume in a diseased ICA with soft plaque. *LT* = left, *SV* = sample volume. **(a)** Color Doppler image shows the sample volume angle incorrectly aligned with the wall contour of the ICA. The PSV reading in the ICA is 229 cm/sec, resulting in overestimation of the degree of stenosis as more than 70%. **(b)** Color Doppler image shows the sample volume angle correctly aligned with the flow vector (the contour of the soft plaque). The resultant PSV reading in the ICA is 161 cm/sec; thus, the degree of stenosis was reclassified as 50%–69%. **(3)** Location of the sample volume box in a tortuous artery. Color Doppler image shows a tortuous left *(LT)* ICA. The change in the color depiction of the ICA is not due to a change in blood flow velocity but instead reflects changing direction of the blood flow relative to the Doppler angle of incidence. To sample the velocities at points *B* and *C*, the color box and angle of incidence require operator correction of the Doppler angle of incidence by steering the color box or angling the transducer. In this case, the correct position of the sample volume box is at point *A*.



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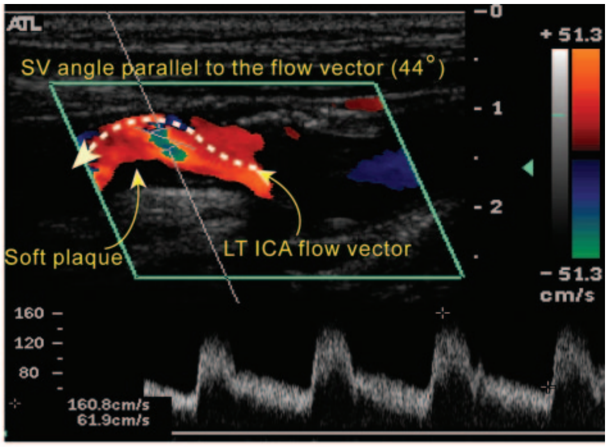

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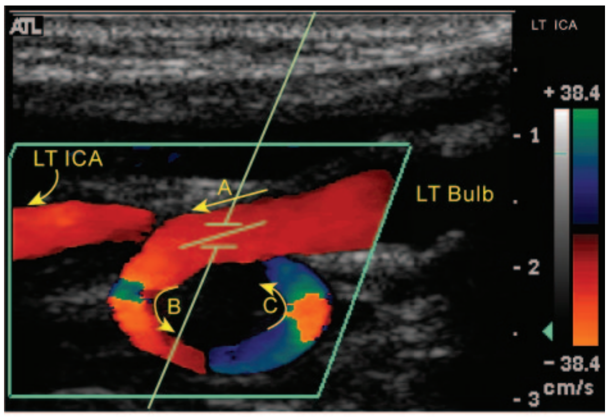


3.

The Doppler angle should not exceed 60°, as measurements are likely to be inaccurate. Our preferred angle of incidence is 45° ± 4. Consistent use of a matching Doppler angle of incidence for velocity measurements in the CCA and ICA reduces errors in velocity measurements attributable to variation in θ. Incorrect assignment of the Doppler angle of incidence with the direction of blood flow is a common source of operator error.

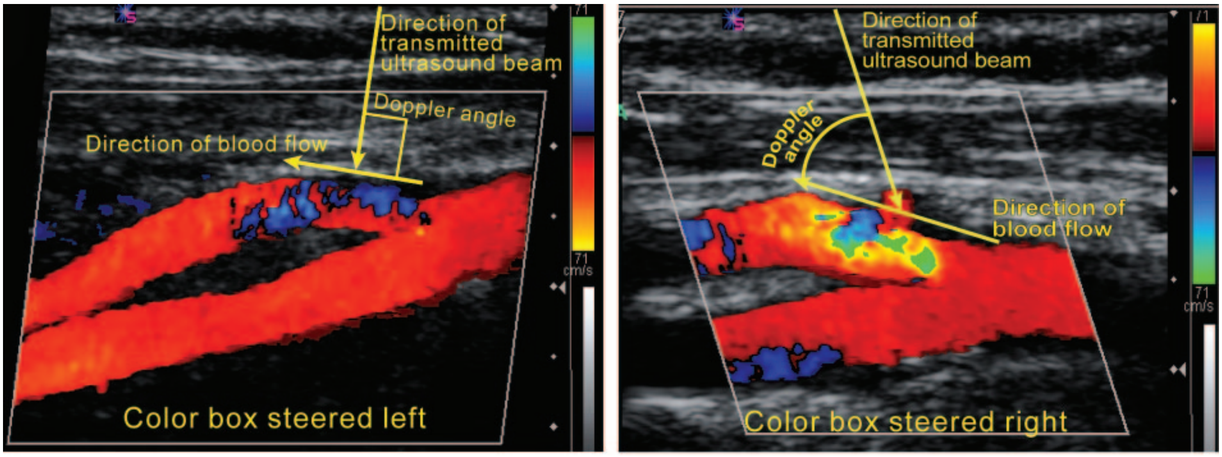
The optimal position of the sample volume box in a normal artery is in the mid lumen parallel to the vessel wall, whereas in a diseased vessel it should be aligned parallel to the direction of blood flow (Fig 2). In the absence of plaque disease, the sample volume box should not be placed on the sharp curves of a tortuous artery, as this may result in a falsely high velocity reading (Fig 3). If the sample volume box is located too close to the vessel wall, artificial spectral broadening is inevitable.

Spectral Broadening

Spectral broadening results from turbulence in the blood flow. Spurious spectral broadening can result from a large Doppler angle, a large sample volume box (>3.5 mm), a sample volume box located close to the vessel wall, or a high PW Doppler gain setting. The size of the sample volume box (also known as the gate) is normally kept between 2 and 3 mm. If the gate is too small (<1.5 mm), the Doppler signal may be missed. Increasing the gate is helpful in searching for trickle flow or trying to obtain a Doppler signal behind a shadowing calcified plaque.

Color Doppler Parameters

Color is a display of the reflected Doppler frequencies from red blood cells.



a. b.

Figure 4. Adjustment of the color Doppler sampling window. **(a)** Color Doppler image shows that the leftward position of the color Doppler sampling window results in a poor Doppler angle of incidence to the direction of blood flow in the proximal ECA. The result of an angle of incidence of almost 90° is ambiguous color display in this segment of the ECA. **(b)** Color Doppler image shows that correcting the angle of incidence by changing the position of the color Doppler sampling window or angling the transducer improves depiction of this area and is crucial for accurate velocity measurements.

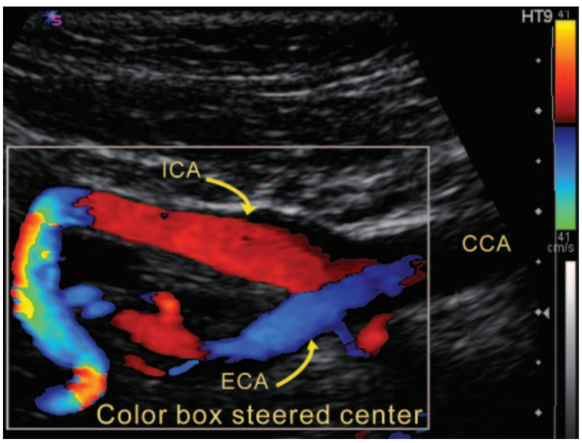
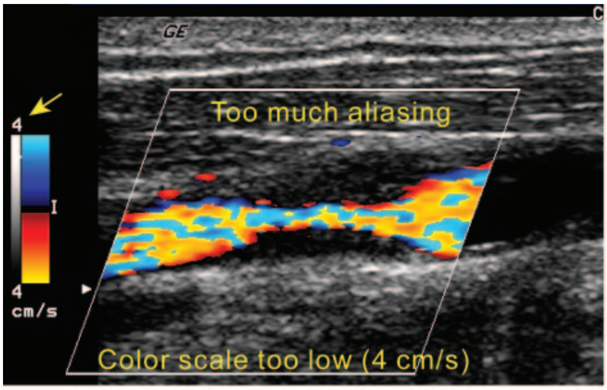


Figure 5. Adjustment of the color Doppler sampling window in a tortuous ICA. Color Doppler image shows the color Doppler sampling window steered to the "center" or "straight" position to increase color sensitivity in those segments of the artery that subtend angles of more than 60° to the Doppler beam. Red and blue regions represent blood flow toward and away from the transducer, respectively.

Color Doppler Sampling Window.—The color Doppler sampling window (also known as the color box) is positioned over the artery to be interrogated. The size of the color Doppler sampling window is adjusted to include all regions of interest. Adjustment of the angle of incidence can be achieved by changing pre-set color box angles from left to center or right, as well as angling the transducer to ensure that the Doppler angle of incidence is less than 60° to the direction of blood flow (Figs 4, 5).

Color Velocity Scale Control.—The color velocity scale is the most important parameter of the carotid US color Doppler setup. The color velocity scale is an operator-defined range of velocities that requires adjustment, analogous to the window width and level of a gray-scale image. It is not synonymous with the pulse repetition frequency (PRF), but the PRF is related to the velocity scale setting, so that increasing the velocity scale increases the PRF and vice versa (3,5–7). The image frame rate may appear slow if a very low color velocity scale is applied, since the PRF decreases and the time between transmit pulses in a pulse packet increases (3).

If the velocity of blood flow exceeds ½ the PRF (Nyquist limit), then the direction and velocity are inaccurately displayed and flow appears to change direction (aliasing). Aliasing can be advantageously used to demonstrate high or low flow and turbulence. If the color velocity scale is set below the mean velocity of blood flow, aliasing throughout the vessel lumen makes it impossible



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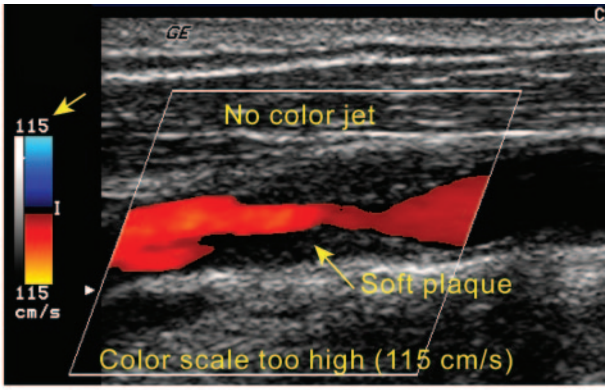
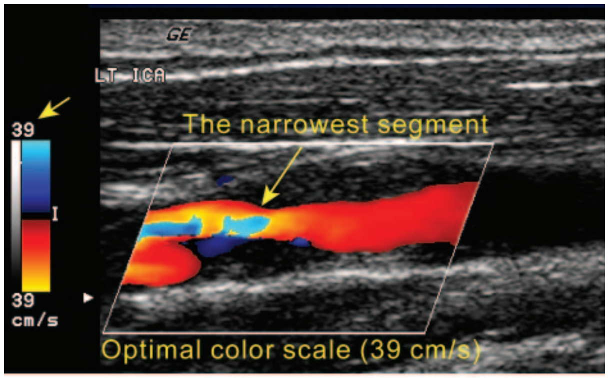


b.

Figure 6. Adjustment of the color scale in a carotid artery stenosis. **(a)** Color Doppler image obtained with the color scale set too low (4 cm/sec) shows aliasing in the entire segment of the ICA. **(b)** Color Doppler image obtained with the color scale set too high (115 cm/sec) shows no aliasing. **(c)** Color Doppler image obtained with the optimal color scale setting shows the region of highest velocity, which corresponds to the narrowest segment of the ICA. Velocity sampling should be performed at this site.



c.

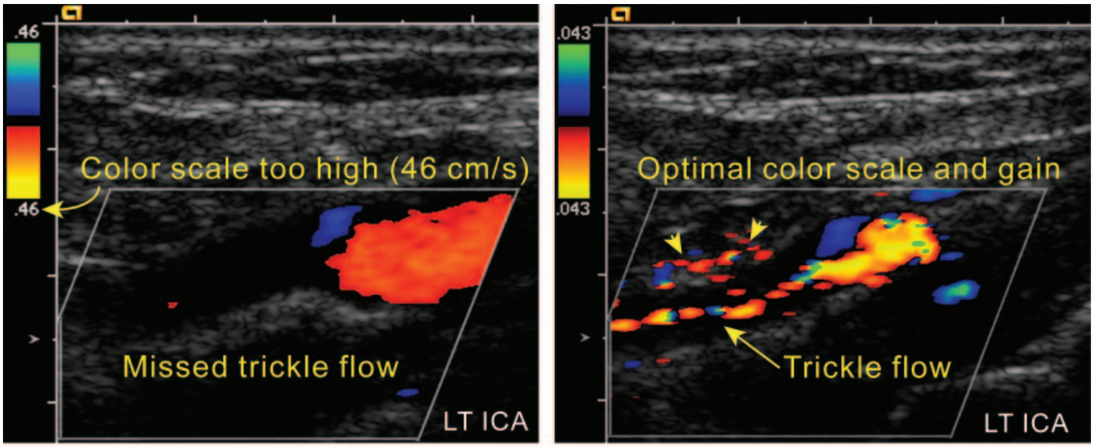
to identify the high-velocity turbulent color jet associated with a tight stenosis. Conversely, if the color velocity scale is set significantly higher than the mean velocity of blood flow, aliasing may disappear, resulting in a missed stenosis (Fig 6).

In a near occlusion, blood flow velocity may be slower than the usual color velocity scale range thresholds, resulting in a false-positive appearance of an occlusion. In this setting, the area of interest should be re-evaluated by using very low color velocity settings (<15 cm/sec) to enhance detection of trickle flow in a near occlusion (Fig 7). If this setting does not reveal detectable flow, contrast material–enhanced imaging (computed tomographic [CT] angiography, gadolinium-enhanced magnetic resonance [MR] angiography, or conventional angiography) may be required to differentiate near occlusion from total occlusion (8,9).

In a normal carotid US examination, the color velocity scale should be set between 30 and 40 cm/sec (mean velocity). In a diseased artery, however, the color velocity scale should be shifted up or down according to the mean velocity of blood flow to demonstrate aliasing only in systole.

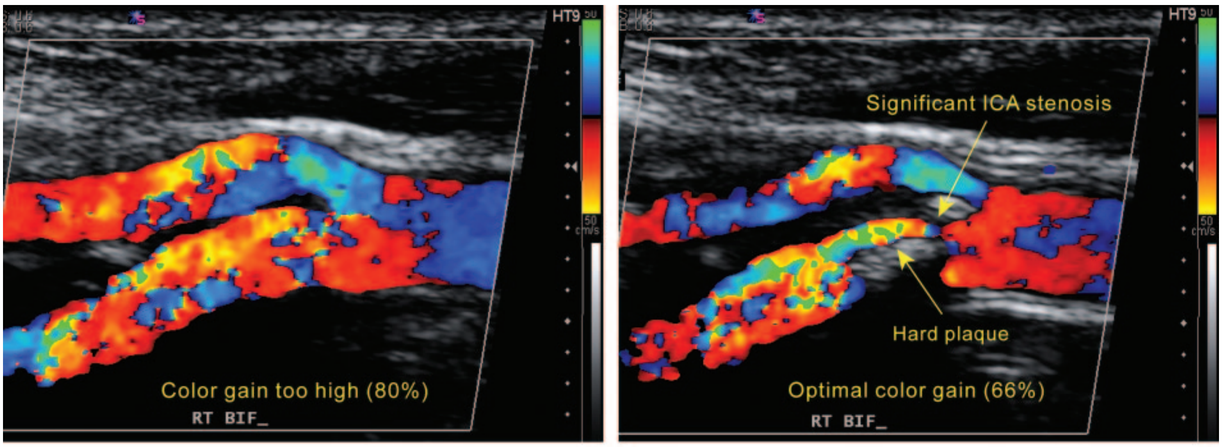
Color Gain Control.—The color gain should be set so that color just reaches the intimal surface of the vessel. If the color gain setting is too low, trickle flow may go undetected. If a high color gain setting is applied, “bleeding” of the color into the wall and surrounding tissues may limit visualization of the plaque surface and may result in misalignment of the angle correction with the direction of blood flow during a PW Doppler examination (Fig 8). Although measurement of the intima-media thickness and the initial survey should always be performed on a gray-scale image, color bleeding artifact may mask the eddy flow at the surface of an ulcerated plaque.

Other Doppler Parameters.—The manufacturer’s guidelines should be followed for other Doppler parameters such as color threshold, color persistence, baseline, wall filter, and PW Doppler scale and gain.



a. b.

Figure 7. Adjustment of the color scale in a near occlusion. **(a)** Color Doppler image obtained with the color scale set at 46 cm/sec shows a false-positive appearance of absent flow in the left ICA. **(b)** On a color Doppler image obtained with the color scale setting lowered to 4 cm/sec, trickle flow is evident, thus indicating the correct diagnosis of a near occlusion in the left ICA. Note the color noise in the background (arrowheads), which is a reassuring indicator of the optimal color gain setting for low-velocity flow.



a. b.

Figure 8. Adjustment of the color gain. **(a)** Color Doppler image obtained with the color gain set at 80% shows marked turbulence in both the ICA and ECA, but no luminal narrowing is evident. **(b)** On a color Doppler image obtained with the color gain lowered to 66%, the anatomy of the bifurcation is demonstrated more accurately. The improved demonstration of the anatomy aids accurate placement of the sample volume box on the narrowest segment, with subsequent alignment of the Doppler angle parallel to the flow vectors.

US Diagnosis of Extracranial Atherosclerotic Carotid Disease

Intima-Media Thickness

The intima-media thickness of the extracranial carotid arteries is a measurable index of the presence of atherosclerosis (10,11). The intima-media thickness of the CCA is thought to be associated with risk factors for stroke. The bifurcation intima-media thickness and the presence of plaque are more directly associated with risk factors for ischemic heart disease (12). Intima-media thickness measurements must be obtained from a gray-scale image, not from a color Doppler image. We recommend use of higher-frequency linear transducers (>7 MHz) with compound and harmonic imaging to reduce the near field artifacts (13). Intima-media thickness measurements may be obtained at the near or far wall of the CCA, bulb, and ICA. Only the intima (echogenic layer) and the media (echo-poor layer) are included

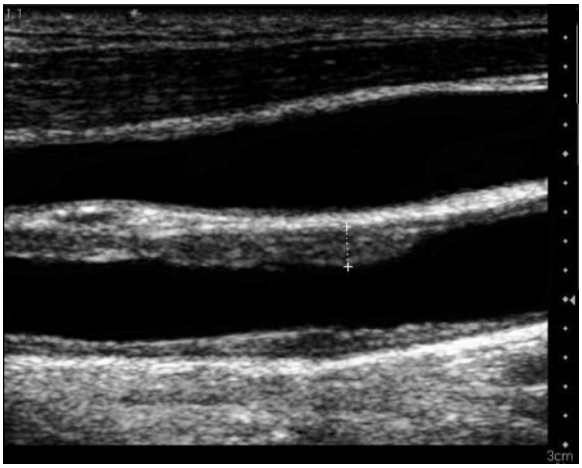


Figure 9. Measuring the intima-media thickness in the left CCA. Gray-scale US image shows the cursors placed perpendicular to the long axis of the CCA to include only the intima and media in the thickness measurement. In this case, the distance between the cursors is 2.8 mm.

Figure 11. Heterogeneous plaque. Gray-scale US image shows a heterogeneous plaque in the proximal right ICA. Note the irregular surface of the plaque, which contains echogenic and echo-poor areas. This type of plaque is considered unstable with the potential for inducing a transient ischemic attack or cerebrovascular accident.

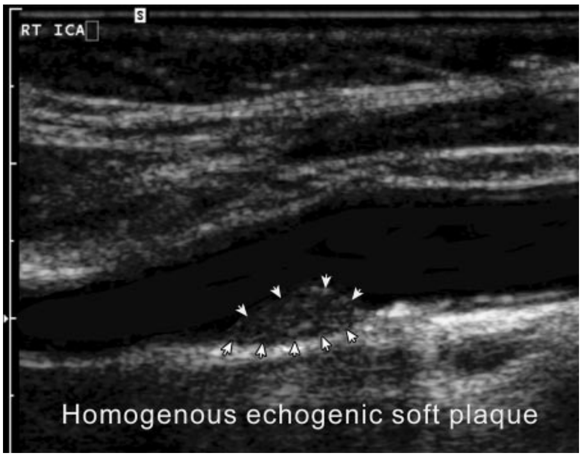


Figure 10. Homogeneous plaque. Gray-scale US image shows an echogenic soft homogeneous plaque in the proximal right ICA. Note how smooth the surface of the plaque is (arrowheads). This smoothness may indicate that the plaque is stable.

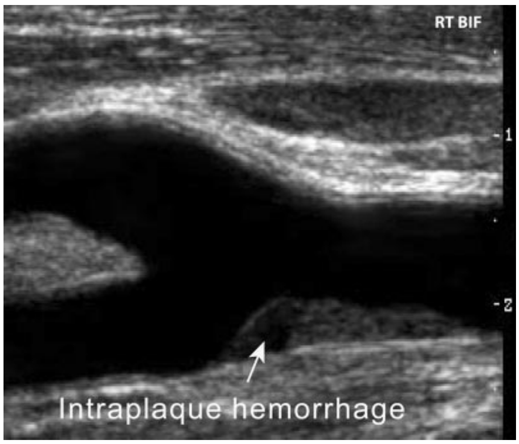


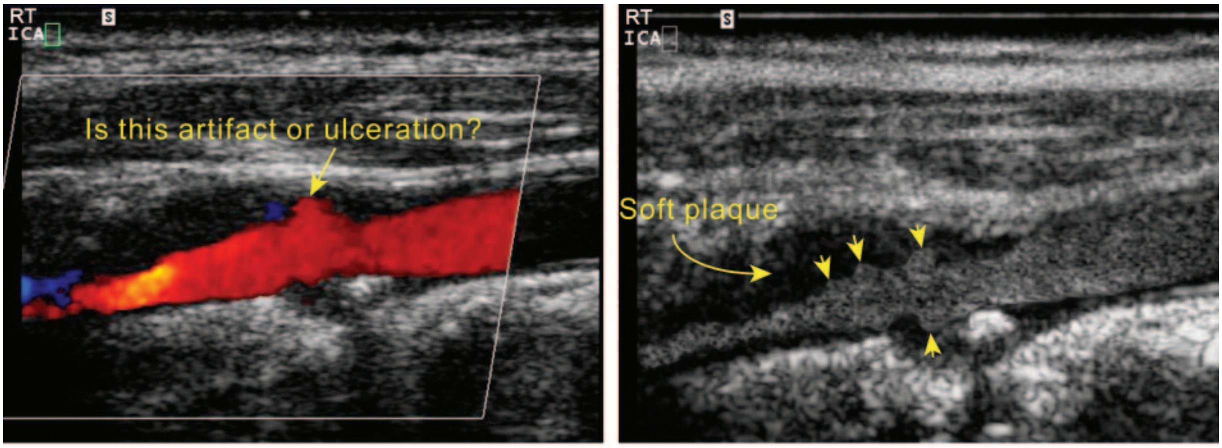
Figure 12. Intraplaque hemorrhage. Gray-scale US image shows a plaque containing an echo-poor area (arrow), which may be due to hemorrhage or lipids. In contrast to fat deposits, intraplaque hemorrhage is associated with a rapid increase in the size of the plaque, which is more likely to become symptomatic.

in the measurement (Fig 9). Increased intima-media thickness has also been reported as a physiologic effect of aging (14). An intima-media thickness of less than 1 mm is normal.

Plaque Morphology

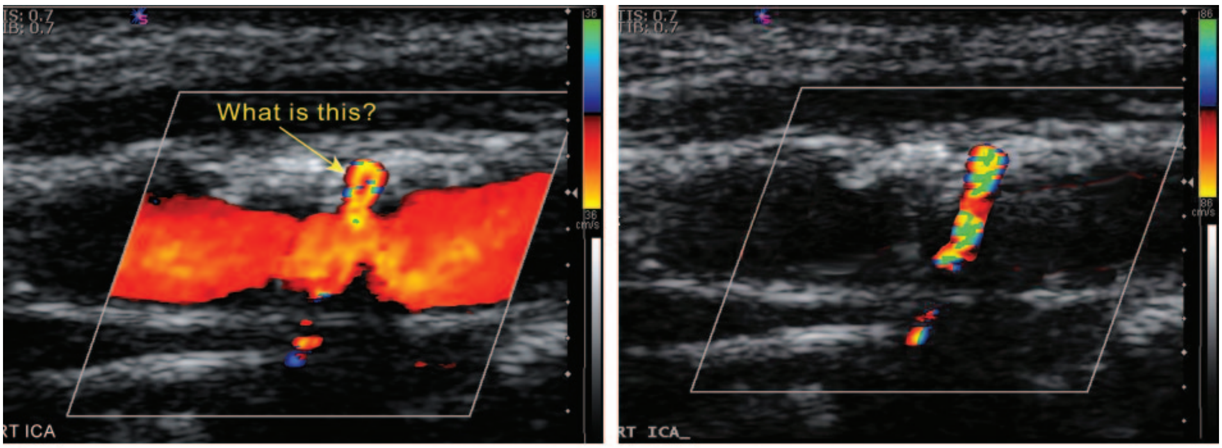
An important component of carotid US is to adequately document the location, internal characteristics, and surface detail of plaque. Plaque can be simply characterized as homogeneous or heterogeneous. Homogeneous plaques may be fibrous (soft) or calcified (hard) and have a uniform internal architecture with a smooth surface contour (Fig 10). Heterogeneous plaques and ulcerated plaques are unstable or friable with the potential for embolic transient ischemic attacks and cerebrovascular accidents (Fig 11). These symptomatic plaques have lower calcium content but larger amounts of intraplaque hemorrhage and lipid, which make them appear hypoechoic (15–17). Plaques associated with amaurosis fugax are more hypoechoic than plaques causing transient ischemic attacks or cerebrovascular accidents. Hypoechoic plaques are more likely to be symptomatic than hyperechoic ones (15–17) (Fig 12).

Ulcerated plaques may be detected by demonstrating eddy flow within the plaque depressions



a. b.

Figure 13. Comparison of color flow and gray-scale flow imaging of a diseased ICA. **(a)** Color Doppler image of the right ICA shows a moderate amount of plaque in the proximal ICA with questionable eddy flow at the plaque surface. The questionable eddy flow could be due to bleeding of color or ulceration in the plaque. **(b)** Gray-scale flow image shows an irregular plaque surface (arrowheads) with several depressions. In addition, the true lumen of the ICA is narrower than it appears on the color Doppler image.



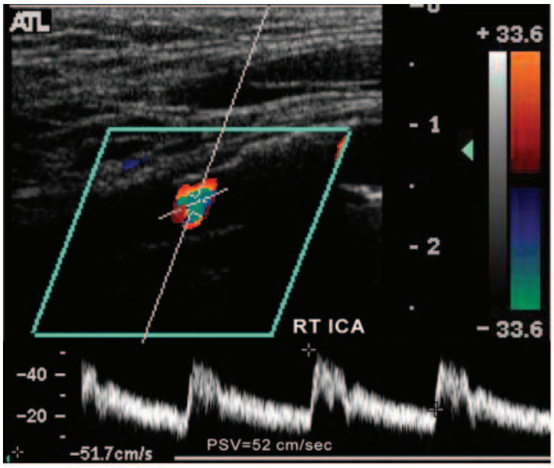
a. b.

Figure 14. Differentiation of ulcerated plaque and twinkle artifact. **(a)** Color Doppler image of the right ICA shows a moderate amount of hard plaque in the proximal ICA with some questionable flow at the plaque surface. **(b)** Color Doppler image obtained in diastole with the color scale setting increased to 86 cm/sec shows that the color flow has disappeared, but the color artifact from the hard plaque continues to twinkle.

at color Doppler or gray-scale flow imaging (18). Gray-scale flow imaging is a non-Doppler technique that displays the true movement of blood cells and the surrounding tissues simultaneously without the distraction of color-related artifacts (19) (Fig 13). Color flow within the plaque surface must be differentiated from artifactual bleeding of color due to high color gain, motion artifact, low color scale, or twinkle artifact. The twinkle artifact, which is a random strong reflection of the incident ultrasound beam at a rough surface formed by hard plaque such as cholesterol deposits, may be mistaken for blood flow within the plaque. The twinkle artifact is independent of the color velocity scale and cardiac cycle. With increasing color velocity scale, the color flow within the ulcerated plaque will disappear while the artifactual color from the cholesterol deposits will continue to twinkle (20) (Fig 14). This is an easy method of differentiating one from the other.

Color or PW Doppler interrogation may prove difficult or indeed impossible in the presence of circumferential shadowing calcified plaque. If the color and PW Doppler information is lost directly behind the shadowing calcified plaque, the operator should interrogate the artery from anterior to

Figure 15. Circumferential calcified plaque in the proximal ICA. **(a)** PW Doppler image of the right ICA obtained immediately distal to a circumferential shadowing plaque shows no sign of turbulence, and the PSV is within normal limits. Therefore, there is unlikely to be a significant stenosis behind the calcified plaque. **(b)** PW Doppler image of the proximal right ICA shows a tardus-parvus waveform. A severe proximal stenosis behind the shadowing plaque is suspected; therefore, evaluation with another imaging modality is required. **(c)** PW Doppler image of the right ICA shows spectral broadening (turbulence) with an elevated PSV. These results may be due to a high degree of stenosis immediately proximal to the point of sampling; therefore, further investigation with another imaging modality is required.



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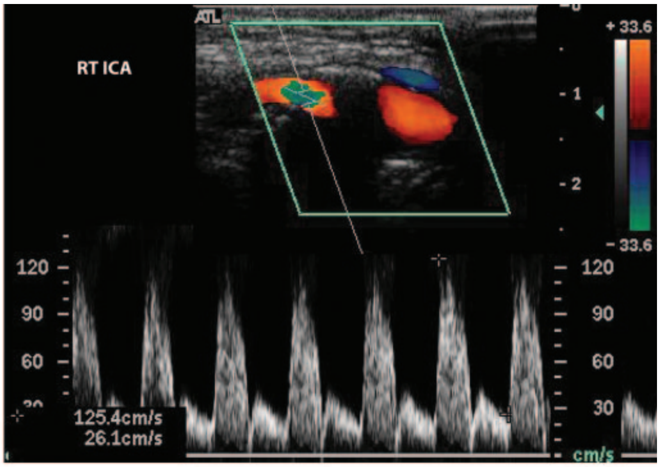

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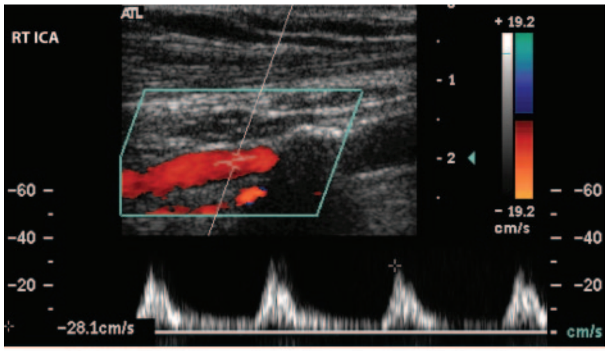


b.

posterior to access a noncalcified segment. In the event that the shadowing plaque is circumferential, the Doppler examination will be limited. In this situation, the length of the shadowing segment may be measured. If the shadowing segment is less than 1 cm and no turbulent flow is demonstrated beyond the plaque, there is unlikely to be a significant stenosis (>50%) behind the shadowing segment. If damped or turbulent flow is demonstrated distal to the plaque, then a tight stenosis is suspected and should be confirmed with another imaging modality (Fig 15). If the shadowing segment is longer than 2 cm, the degree of stenosis is indeterminate and other imaging modalities are recommended.

ICA and CCA Stenosis

The criteria for grading ICA and CCA stenosis are provided in Table 1 (21). The ICA PSV and the presence of plaque at gray-scale or color Doppler imaging are primary parameters for the grading of ICA stenosis. If the degree of stenosis is indeterminate according to the primary parameters, then additional parameters including the ICA/CCA PSV ratio and the ICA end-diastolic velocity will be taken into consideration. If the CCA is stenotic, the PSV of the nonstenotic segment of the CCA (point A) proximal to the stenotic segment (point B) may also be measured to calculate the $ICA/CCA_{point\ A}$ PSV ratio and the $CCA_{point\ B}/CCA_{point\ A}$ PSV ratio.

Sonographic features of a severe ICA or CCA stenosis may include the following: PSV greater than 230 cm/sec, a significant amount of visible plaque (≥50% lumen diameter reduction on a gray-scale image), color aliasing despite a high color velocity scale setting (≥100 cm/sec), spectral broadening, poststenosis turbulence at color Doppler and PW Doppler imaging, color bruit artifact in the surrounding tissue of the stenotic artery, end-diastolic velocity of greater than 100 cm/sec, ICA/CCA PSV ratio of 4.0 or greater, and finally a high-pitched sound at PW Doppler imaging (Fig 16).

Limitations

A velocity difference of greater than 20 cm/sec between the right and left CCAs indicates asymmetric flow, which may be normal or due to a proximal stenosis, tandem lesions, distal obstruction, or dissection. Carotid US is not the proce-

Table 1
Criteria for Diagnosis of ICA Stenosis with Gray-Scale and Doppler US

	Primary Parameters		Additional Parameters*	
Degree of Stenosis (%)	ICA PSV (cm/sec)	Degree of Plaque† (%)	ICA/CCA PSV Ratio	ICA EDV (cm/sec)
Normal	<125	None	<2.0	<40
<50	<125	<50	<2.0	<40
50–69	125–230	≥50	2.0–4.0	40–100
≥70 but less than near occlusion	>230	≥50	>4.0	>100
Near occlusion	High, low, or undetectable	Visible	Variable	Variable
Total occlusion	Undetectable	Visible, no detectable lumen	NA	NA

Source.—Reference 21.
*EDV = end-diastolic velocity, NA = not applicable.
†Estimated value based on the diameter reduction at gray-scale and color Doppler imaging.

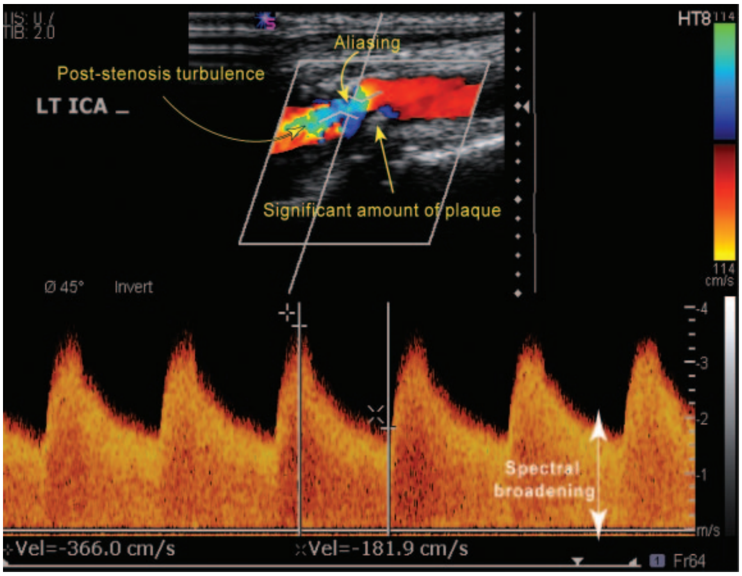


Figure 16. Severe stenosis (70% to near occlusion) of the ICA. Duplex US image of the left ICA shows a high PSV (366 cm/sec), a significant amount of visible plaque, the presence of aliasing despite a high color scale setting (114 cm/sec), color flow turbulence immediately distal to the stenotic segment, broadening of the PW Doppler spectrum, and a high end-diastolic velocity (182 cm/sec).

dure of choice for diagnosis of dissection because detection of the intimal flap has not been reliable and because the intimal tear may be too high in the ICA to be assessed with carotid US. Findings that might be encountered at carotid US include the following: visualization of the flap at gray-scale imaging, reversed flow in the true channel and antegrade flow in the false channel at color Doppler imaging, and a damped high resistive flow pattern proximal to the dissection at PW Doppler spectral imaging. Such findings may require alternative imaging modalities, such as MR or CT angiography, to assist in diagnosis.

Normal flow in the CCA is usually greater than 45 cm/sec. High flow (>135 cm/sec) in both CCAs may be due to high cardiac output in hypertensive patients or young athletes. Low flow (<45 cm/sec) in both CCAs is likely to be secondary to poor cardiac output from cardiomyopathies, valvular heart disease, or extensive myocardial infarction. Arrhythmias can be a real problem. The PSV value will be low if measured after a premature ventricular contraction, and it will be high after a compensatory pause. Measurements of the ICA and CCA velocities after differing rhythms can alter the ICA/CCA PSV ratio. The PSV should be measured after a regular beat. If this is not possible, the result will be limited.

An abnormal mid-systolic deceleration in the PW Doppler waveform of the right CCA and ICA may be due to a partial or complete right subclavian steal (22). Severe stenosis in the innominate

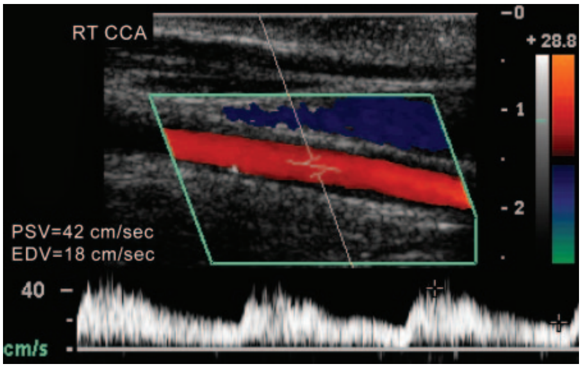


Figure 17. Severe stenosis of the innominate artery. PW Doppler spectral image of the right CCA shows a tardus-parvus waveform, which is suggestive of a severe stenosis proximal to the point of sampling. A severe stenosis of the innominate artery was subsequently demonstrated at angiography. *EDV* = end-diastolic velocity.

artery may manifest as a tardus-parvus waveform (a prolonged systolic acceleration time with low PSV) in the right CCA and ICA (Fig 17). This waveform generally indicates a severe stenosis proximal to the point of sampling. Imaging with an alternative modality may be recommended to determine the exact location of the stenosis.

Contralateral carotid disease or vertebrobasilar disease may alter the overall flow dynamics (7). The absolute velocity in an individual vessel must be correlated with the overall cardiovascular status of the patient and the caliber of the vessel.

Near Occlusion and Total ICA Occlusion

The distinction of near occlusion versus total occlusion is clinically extremely important. Patients with near occlusion may be surgical candidates, while patients with total occlusion are not. The number of false-positive interpretations due to lack of flow detection can be reduced by attention to the technical detail but cannot be eliminated. Alternative imaging modalities such as catheter angiography or multisection CT angiography may be helpful to distinguish between total and near occlusions (23,24). The hallmark of a near occlusion is the "string sign" or "trickle flow" at color Doppler imaging (Fig 18). Power Doppler US may also be helpful with older equipment in searching for trickle flow; we have found no diagnostic advantage for power Doppler imaging over color Doppler imaging at our institution. Recommendations for optimal color and PW Doppler imaging parameters to enhance the detection of

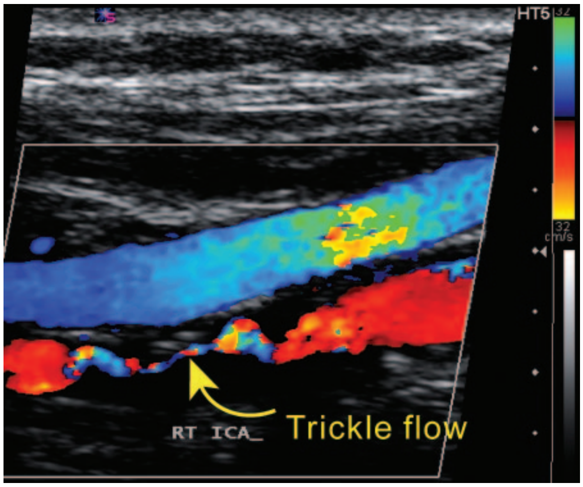


Figure 18. Trickle flow in the ICA. Color Doppler image shows a narrow patent channel (the string sign) in the right ICA. This finding is suggestive of near occlusion of the ICA.

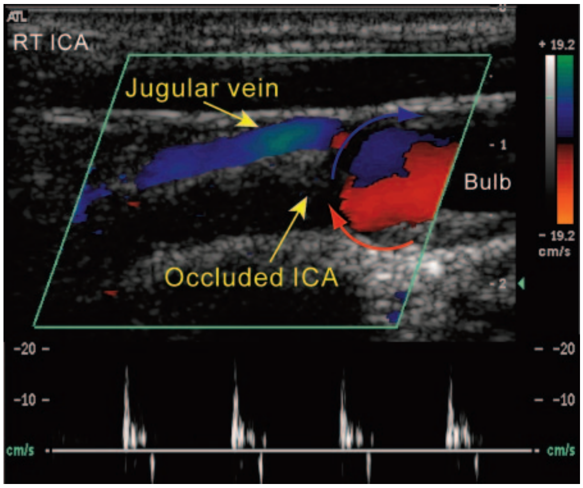


Figure 19. Thud flow. Color Doppler image of the right ICA and carotid bulb shows no flow in the ICA lumen and reversed flow in the bulb at the point of occlusion. The red and blue arrows indicate the direction of the reversed flow at the point of obstruction (thud flow). The PW Doppler spectrum also demonstrates thud flow, which manifests as damped systolic flow and reversed flow in early diastole.

trickle flow in near occlusions are provided in Table 2.

When a single patent vessel beyond the carotid bifurcation is identified, the operator must confidently determine if the vessel represents the ICA or the ECA. The single most reliable parameter for differentiating the ECA from the ICA is the presence of ECA branches in the neck. The temporal tap maneuver involves tapping on the superficial temporal artery and looking for reflected flow in the ECA. This has not proved reliable, as

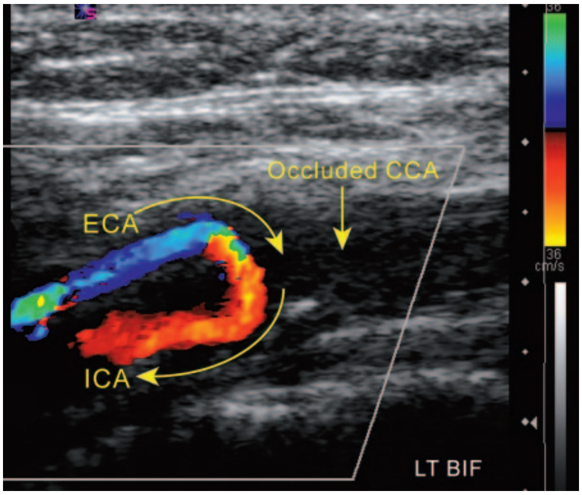


Figure 20. Internalization of the ECA. Color Doppler image of the left carotid bifurcation shows no flow in the distal CCA. The ICA and ECA are both patent, but flow in the ECA is reversed to supply antegrade flow in the ICA above the level of the occluded CCA. The curved arrows indicate the direction of blood flow from the ECA to the ICA.

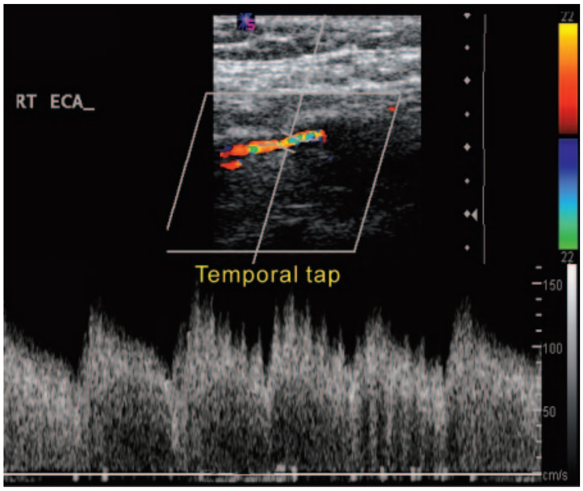


Figure 21. PW Doppler spectrum in internalization of the ECA. PW Doppler spectral image shows a reversed low resistive flow pattern with delayed systolic acceleration (tardus wave) in the ECA. The patient had an occluded CCA. In addition, reflections from the temporal tap maneuver are demonstrated as ripples in the Doppler spectrum.

Table 2
Optimal Color and PW Doppler Imaging Parameters for Enhancing Detection of Trickle Flow in Near Occlusion of the ICA

Parameter	Recommended Setting
Transducer frequency	<7 MHz
Color box	Steer to the center or straight position
Sample volume box	Steer to the center or straight position
Focal zone	At the level of the diseased segment
Color velocity scale	Decrease to <15 cm/sec
PW Doppler scale	Decrease to <15 cm/sec
Color Doppler gain	Increase to the point of visible background noise
PW Doppler gain	Increase to the point of visible background noise
Wall filter	Decrease to low
Color threshold	Increase to ≥80%
Sample volume gate	Increase to ≥2.5 mm

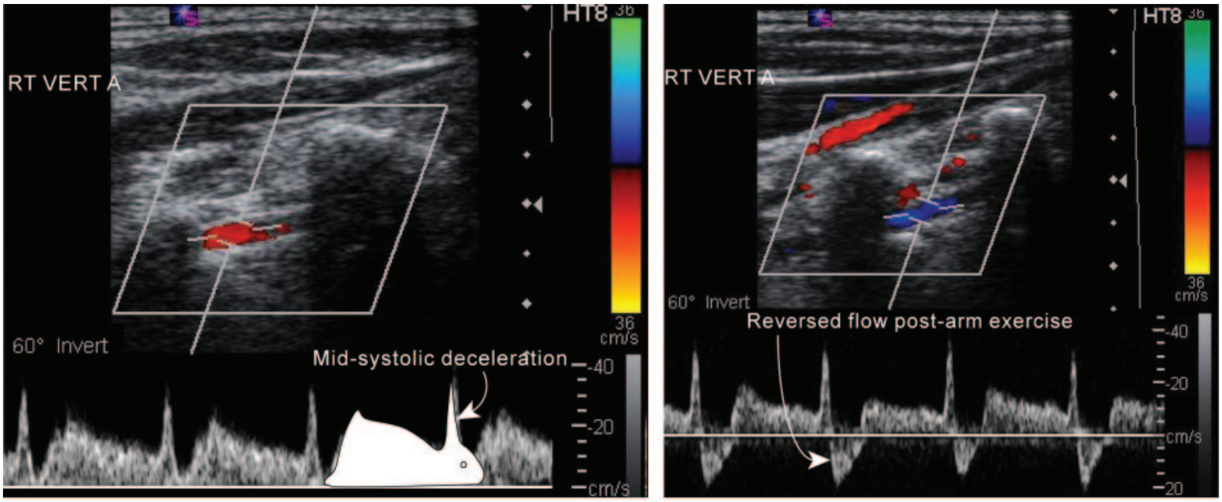
the reflected flow from tapping on the temporal artery can also be detected in the ICA and CCA (25).

In a total ICA occlusion, there is a characteristic "to-and-fro" flow pattern at the point of occlusion known as "thud flow" at color Doppler and PW Doppler imaging (Fig 19). Other findings are direct visualization of a thrombus at gray-scale imaging, absent flow at color Doppler imaging, and damped resistive flow in the CCA at PW Doppler imaging (externalization of the CCA).

In near or total occlusion of the CCA, reversal of flow direction in the ECA via collateral vessel recruitment to a patent ICA may occur (internalization of the ECA) (Fig 20). In this setting, velocities may be low, which may necessitate changing the velocity settings in order to detect the flow (Fig 21).

ECA Stenosis

The ECA is an important collateral pathway in patients with ipsilateral ICA occlusion and recurrent symptoms; this may influence the surgical decisions involving revascularization of the stenotic ECA (26). However, an isolated ECA stenosis may not be clinically significant, with no need to change patient care.



a. b.

Figure 22. Occult and partial subclavian steal. **(a)** PW Doppler spectral image of the right vertebral artery shows midsystolic deceleration with antegrade late-systolic velocities (occult steal). **(b)** PW Doppler spectral image obtained after the patient exercised the right arm (by opening and closing the hand for 2 minutes). The Doppler spectrum shows midsystolic deceleration with retrograde late-systolic velocities. The subclavian artery "steals" blood from the vertebral artery to supply the ischemic arm.

Vertebral Artery and Subclavian Steal

Carotid US can show patency, direction of blood flow, and, to some extent, relative size of the left versus right vertebral arteries. Carotid US is not accurate for identification of a focal stenosis in the vertebral artery. Congenital and acquired occlusions or near occlusions can all appear alike.

Identification of the vertebral artery is achieved by locating the CCA in a sagittal view and sweeping the transducer laterally to the transverse processes of the cervical spine, where the vertebral artery can be demonstrated with color Doppler imaging. Since the vertebral artery is located deep in the neck, increasing the color Doppler gain may aid visualization. PW Doppler spectral analysis of the vertebral artery provides necessary information to demonstrate the presence of a subclavian steal. On the basis of the hemodynamic changes in the vertebral artery, there are three types of subclavian steals.

In occult steal (minimal hemodynamic changes), PW Doppler imaging may show antegrade flow with midsystolic deceleration, which may temporarily convert to a more abnormal waveform (with reversed late-systolic flow) in response to reactive hyperemia in the ipsilateral arm after arm exercise (27) (Fig 22).

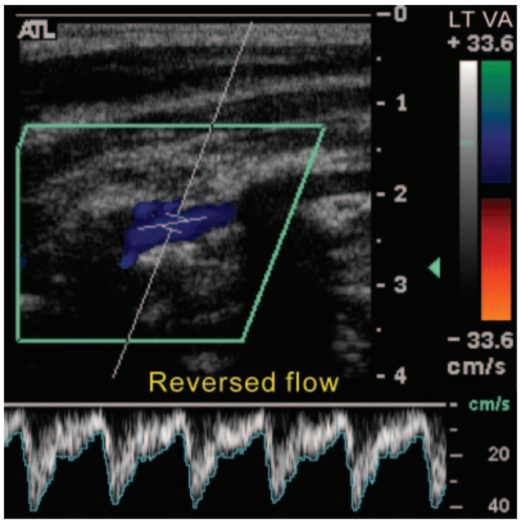


Figure 23. Complete subclavian steal. PW Doppler spectral image of the left vertebral artery shows completely reversed flow.

Partial subclavian steal corresponds to moderate hemodynamic changes. The PW Doppler spectrum shows partially reversed flow. The PW Doppler spectrum in occult and partial subclavian steal may resemble the profile image of a rabbit (the "bunny rabbit" sign) (27).

In complete (full) subclavian steal, flow in the vertebral artery is completely reversed (Fig 23). This may be associated with ischemic symptoms in the ipsilateral arm.

Conclusions

Carotid US offers a noninvasive evaluation of the extracranial neck portions of the carotid and vertebral arteries for atherosclerotic disease. Standardized technical parameters, scanning methods, Doppler analysis, and interpretation enhance the accuracy and reproducibility of the results.

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