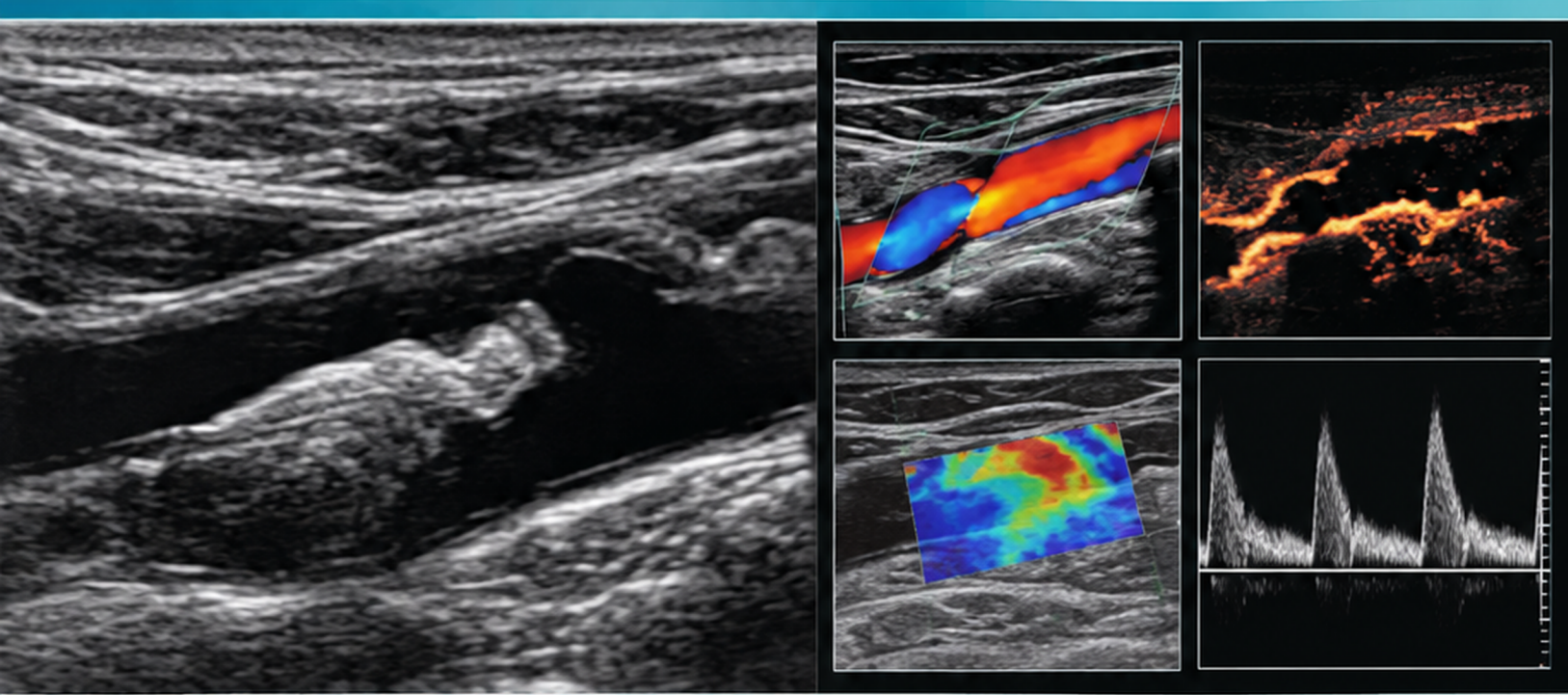


Carotid Ultrasound:

Conventional and Emerging Technology Approaches



Jim Baun
2026

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Introduction

Carotid ultrasound remains a cornerstone of noninvasive vascular assessment, providing direct information about arterial anatomy, atherosclerotic plaque, and the hemodynamic significance of internal carotid artery stenosis. Conventional triplex imaging—combining grayscale, color Doppler, and spectral Doppler analysis—has long served as the primary approach for detecting and grading carotid disease. Its principal limitation, however, is that the degree of luminal narrowing alone does not fully characterize the biological behavior of atherosclerotic plaque or the broader cardiovascular risk of the patient.

Recent ultrasound technologies extend carotid assessment beyond stenosis grading toward evaluation of plaque vulnerability and vascular function. Contrast-enhanced ultrasound, microvascular flow imaging, and shear wave elastography provide additional information about plaque neovascularization, surface characteristics, and tissue stiffness, while measurements such as carotid intima-media thickness, arterial wall stiffness, and wall shear stress offer potential tools for cardiovascular risk stratification. Together, these conventional and emerging approaches support a more comprehensive, multiparametric assessment of carotid atherosclerotic disease.

Role of Ultrasound in the Management of ASVD

The conventional clinical role of carotid ultrasound is centered on the detection and characterization of atherosclerotic disease and the prevention of ischemic stroke. By combining anatomic imaging with hemodynamic assessment, carotid ultrasound is used to identify and quantify arterial stenosis, evaluate plaque burden and morphology, recognize associated flow abnormalities, and monitor patients following therapeutic intervention. The examination may also identify abnormalities involving the vertebral and subclavian circulation as well as less common carotid and perivascular pathology.

Conventional Triplex Ultrasound Approach

Traditional carotid duplex/triplex imaging combines grayscale anatomy, color Doppler imaging, and spectral Doppler waveform analysis. Together, these techniques provide complementary information about vessel structure, plaque, and global hemodynamics and remain the foundation for noninvasive evaluation and grading of extracranial internal carotid artery stenosis.

Grayscale Imaging

Grayscale, or B-mode, imaging provides the anatomic foundation of the carotid ultrasound examination. Before Doppler techniques are used to evaluate flow and quantify stenosis,

grayscale imaging establishes vessel anatomy, identifies atherosclerotic disease, and documents structural abnormalities involving the arterial wall and surrounding tissues. Its principal contributions include the following.

Overview of carotid vascular anatomy

Grayscale imaging provides a longitudinal and transverse survey of the common carotid artery, carotid bulb, bifurcation, and proximal internal and external carotid arteries. Vessel course, caliber, wall configuration, and anatomic relationships can be evaluated before Doppler interrogation. Establishing this anatomic overview is particularly important for recognizing vessel tortuosity, locating the bifurcation, and determining where subsequent color and spectral Doppler sampling should be performed.

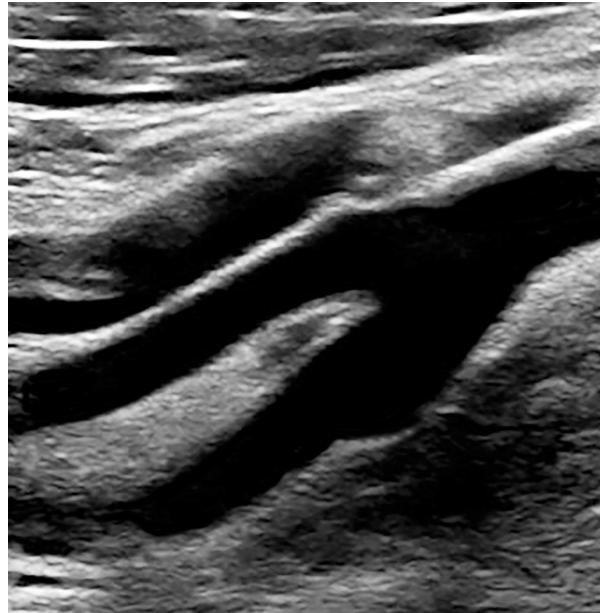


Figure 1. Grayscale demonstration of carotid vascular anatomy.

Longitudinal B-mode image through a normal carotid bifurcation demonstrates the vessel walls and residual lumen, providing the anatomic foundation for subsequent color and spectral Doppler assessment.

Plaque presence and overall plaque burden

A primary role of grayscale imaging is the detection of atherosclerotic plaque and documentation of its distribution throughout the accessible carotid circulation. This 2-dimensional imaging modality demonstrates whether plaque is focal or more extensive, identifies the arterial segments involved, and provides an overall assessment of plaque burden. It also allows the examiner to appreciate the relationship between plaque and the residual arterial lumen, complementing the hemodynamic information subsequently obtained with Doppler techniques.

Plaque morphology and echogenicity

Grayscale imaging demonstrates the structural appearance of plaque, including its internal echogenicity, homogeneity or heterogeneity, surface contour, and the presence of highly reflective or calcified components. These characteristics provide information about plaque composition and may suggest features associated with plaque instability. However, visual

interpretation of plaque morphology is inherently subjective, and grayscale appearance alone has important limitations in reliably distinguishing vulnerable from stable plaque. Specific morphologic characteristics and methods of plaque classification are discussed in the following section.

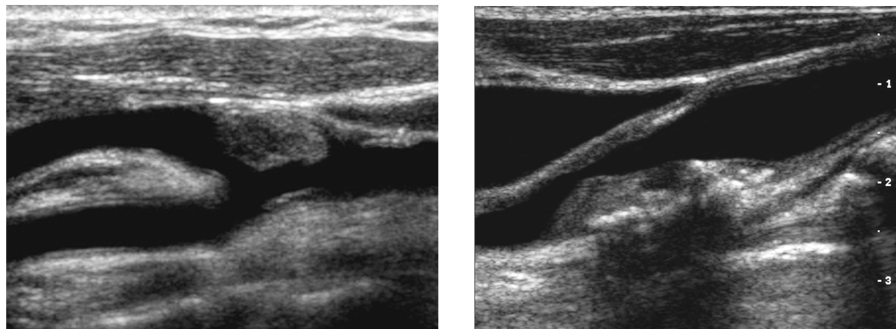


Figure 2. Grayscale appearance of carotid atherosclerotic plaque.

The left image demonstrates a relatively homogeneous, soft plaque with predominantly low-level echogenicity. The right image demonstrates a complex heterogeneous plaque with mixed echogenic components and greater structural irregularity.

Arterial wall abnormalities

Grayscale imaging permits direct visualization of the carotid arterial wall and may demonstrate changes in wall thickness, contour, or integrity. These findings may accompany atherosclerotic disease or represent other vascular abnormalities. Evaluation of the arterial wall also provides the structural basis for more specialized measurements, such as carotid intima-media thickness, an application that may be used in assessing and quantifying overall cardiovascular risk.

Less common structural pathology

Although atherosclerotic disease accounts for the majority of carotid ultrasound examinations, grayscale imaging may reveal less common abnormalities that alter the normal vascular anatomy. These include arterial dissection and masses arising near the carotid bifurcation, such as carotid body tumors or paragangliomas. Recognition of these abnormalities is an important secondary role of the grayscale survey and may prompt more focused Doppler assessment or additional diagnostic imaging.

Plaque Morphology and Vulnerability

Plaque morphology is clinically important because the risk of cerebrovascular sequelae is not determined solely by the degree of luminal narrowing. Certain structural features are associated with plaque instability and may increase the likelihood of thromboembolic events. The concept of the vulnerable plaque therefore shifts attention from stenosis severity alone toward the composition and structural integrity of the plaque itself.

Definition and clinical relevance of vulnerable plaque

A vulnerable plaque is an atherosclerotic lesion with structural characteristics associated with an increased risk of rupture, embolization, and downstream ischemic event. Identification of these lesions is clinically important because thromboembolic risk may be increased even when the degree of stenosis is not severe. In this context, plaque characterization may provide

information that complements conventional stenosis grading, particularly when considering risk in patients who are asymptomatic or have moderate luminal narrowing.^{1 2}

Histologic features associated with plaque vulnerability

Vulnerable plaques commonly contain a lipid-rich, necrotic core covered by a relatively thin fibrous cap. Inflammatory infiltration may weaken the fibrous cap and contribute to structural instability. Additional features include neovascularization, intraplaque hemorrhage, and disruption of the plaque surface. These histologic characteristics help explain why two plaques producing a similar degree of stenosis may differ substantially in their potential for rupture or embolization.³

Neovascularization and its relationship to intraplaque hemorrhage, plaque enlargement, and surface disruption

Neovascularization refers to the development of small new vessels within an atherosclerotic plaque. These neovessels may arise from the arterial wall and/or vasa vasorum and are often thin-walled and fragile. Their tendency to leak can produce intraplaque hemorrhage, which may accelerate plaque enlargement and contribute to further structural weakening. Progressive instability may eventually lead to surface disruption or ulceration, increasing the potential for thrombus formation and embolization.⁴

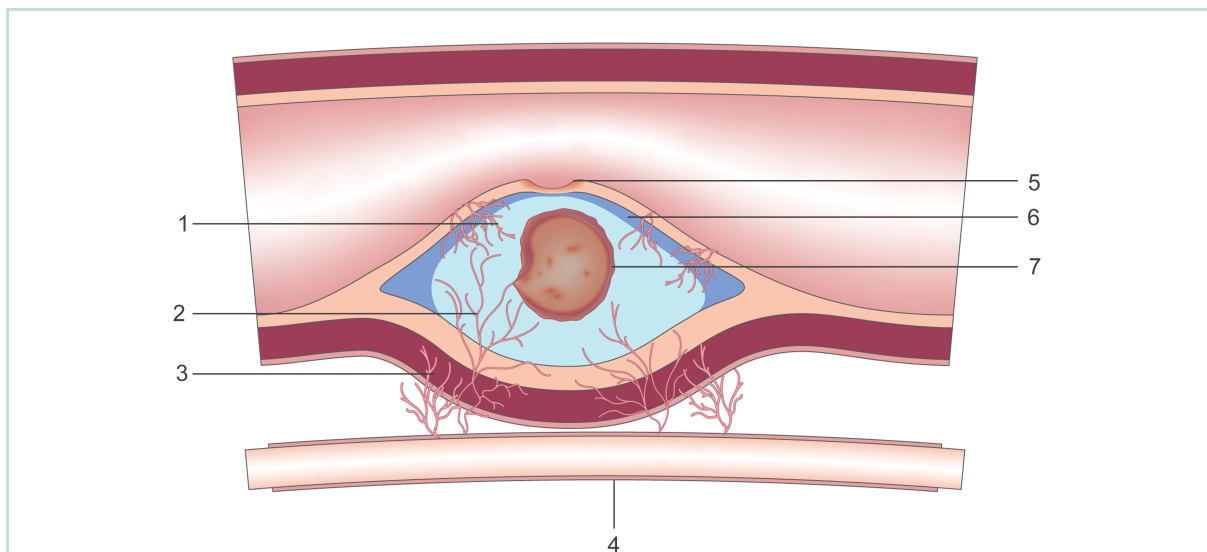


Figure 3. Vulnerable carotid plaque—illustration.

Schematic depiction of structural features associated with plaque vulnerability, including (1) neovessels of epithelial origin, (2) neovessels arising from the vasa vasorum, (3) vasa vasorum, (4) adjacent capillary, (5) fibrotic cap fissure representing plaque ulceration, (6) thin fibrous cap, and (7) intraplaque hemorrhage.

Limitations of subjective grayscale plaque classification

Although grayscale imaging can demonstrate differences in plaque echogenicity, homogeneity, calcification, and surface appearance, visual interpretation remains subjective. Multiple studies have found substantial interobserver variability in plaque grading which emphasize the limited predictive value of grayscale appearance alone.^{5 6} These limitations have prompted the development of more standardized classification systems and newer imaging approaches intended to improve the characterization of plaque vulnerability.

Conventional Grayscale Classification Methods

Several approaches have been developed to improve consistency in grayscale plaque characterization. These methods attempt to move plaque assessment beyond purely visual description by standardizing echogenic appearance or applying computer-assisted analysis. Even so, grayscale ultrasound alone has not proven sufficiently feasible, reliable, or valid for consistently distinguishing vulnerable from nonvulnerable plaque in routine clinical practice.

Conventional descriptive categories

One of the simplest approaches is to classify plaque according to its overall grayscale appearance. Common descriptive categories include soft, fibrotic, calcified, and complex plaque. These terms reflect differences in echogenicity and internal composition and provide a practical way to communicate plaque appearance. Their principal limitation is that interpretation depends heavily on the examiner's visual assessment, making reproducibility variable.

Grayscale median (GSM)

Grayscale median analysis is a computer-assisted method that quantifies plaque echogenicity. Conventional image frames are exported, normalized, and analyzed to generate grayscale histograms from which a median value is derived. The goal is to provide a more objective representation of plaque brightness than visual inspection alone. In the source presentation, however, GSM is described as requiring off-board image processing and dedicated software, limiting its practicality in routine vascular laboratory workflow.⁷

Gray-Weale classification

The Gray-Weale system categorizes plaque according to the relative proportions of sonolucent and echogenic components. Type I plaques are predominantly sonolucent with a thin echogenic cap, Type II plaques are substantially sonolucent with small echogenic areas, Type III plaques are predominantly echogenic with small sonolucent areas, and Type IV plaques are uniformly echogenic. The method provides a more structured framework than simple descriptive terminology, but it remains dependent on visual interpretation.⁸

Practical limitations

The principal limitations of conventional grayscale plaque classification are subjectivity, interobserver variability, and workflow complexity. Visual systems may improve descriptive consistency but cannot eliminate examiner dependence, while quantitative methods such as GSM introduce additional processing steps that are not easily incorporated into routine scanning. For these reasons, grayscale plaque characterization remains useful for describing lesion appearance but has limited reliability as a stand-alone method for determining plaque vulnerability.

Color Doppler Imaging

Color Doppler imaging adds a global hemodynamic perspective to the carotid examination by displaying the presence, direction, and relative characteristics of blood flow throughout the carotid bifurcation. Rather than providing the quantitative velocity measurements used for stenosis grading, its principal role is to identify abnormal flow patterns, localize regions of suspected disease, and guide placement of the spectral Doppler sample volume.

Presence and direction of flow

Color Doppler rapidly confirms vessel patency and demonstrates the direction of blood flow within the common, internal, and external carotid arteries. This is especially useful when grayscale findings are equivocal or when markedly reduced flow makes the arterial lumen difficult to assess with grayscale imaging alone. Directional information also helps distinguish expected antegrade flow from abnormal reversal or altered flow pathways.

Flow separation and reversal at the carotid bulb

The carotid bulb is a region of complex geometry in which localized flow separation and transient reversal may occur as part of normal bifurcation hemodynamics. Color Doppler makes these patterns readily visible and helps distinguish expected recirculating flow from disturbances related to focal disease. Recognition of this normal behavior is important to avoid overinterpreting physiologic flow separation as pathologic turbulence.

Turbulent or disordered flow patterns

Atherosclerotic narrowing alters the normally organized flow field and may produce disturbed, multidirectional, or turbulent flow distal to a stenosis. Color Doppler displays these disturbances as rapid spatial changes in encoded flow information and therefore provides a visual clue to the presence and location of significant hemodynamic abnormality.

Localization of high-velocity jets associated with stenosis

One of the most important uses of color Doppler is to identify the focal high-velocity jet created as blood accelerates through a narrowed arterial segment. Localizing this jet allows the examiner to place the spectral Doppler sample volume at the site of maximum velocity, where peak systolic and end-diastolic measurements can then be obtained for stenosis classification. In this way, color Doppler serves as the bridge between structural imaging and quantitative spectral analysis.

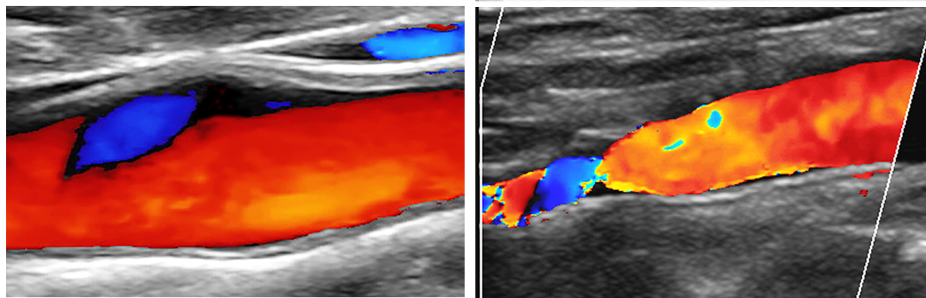


Figure 4. Color Doppler demonstration of normal and abnormal carotid bifurcation hemodynamics.

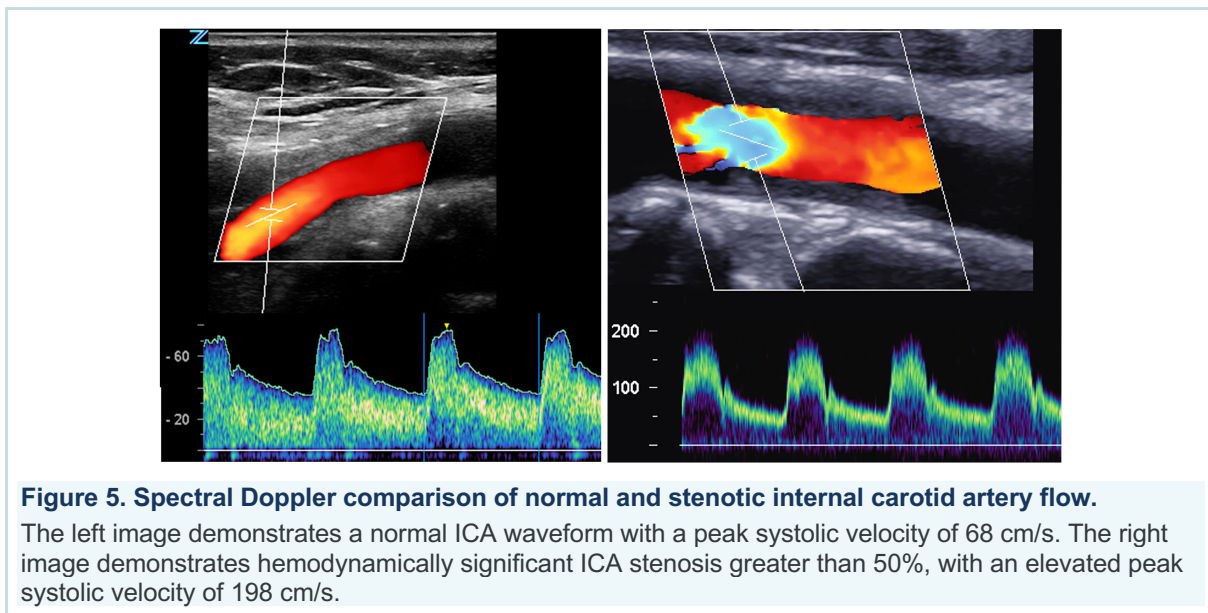
The left image demonstrates physiologic flow separation and localized flow reversal within the carotid bulb. The right image demonstrates a focal high-velocity jet through a stenotic segment with post-stenotic flow disturbance.

Spectral Doppler Waveform Analysis

Spectral Doppler provides the quantitative hemodynamic component of the carotid ultrasound examination. By measuring blood-flow velocity within the internal carotid artery and relating those measurements to findings elsewhere in the examination, spectral analysis permits classification of stenosis severity. Peak systolic velocity, end-diastolic velocity, and the ICA-to-CCA velocity ratio are interpreted together with grayscale plaque findings and the overall hemodynamic pattern rather than as isolated values.

Quantification of ICA stenosis

The principal role of spectral Doppler is to quantify the hemodynamic significance of internal carotid artery narrowing. As luminal diameter decreases, flow velocity generally increases through the stenotic segment. Spectral Doppler captures these changes and provides numerical measurements that can be compared with established diagnostic criteria.



Conventional stenosis categories

Carotid stenosis is conventionally classified into clinically meaningful categories: less than 50%, 50–69%, 70% but less than near occlusion, near occlusion, and total occlusion. These categories provide a standardized framework for reporting disease severity and relating ultrasound findings to clinical management.

Use of velocity criteria with plaque visualization and the overall examination

Velocity measurements are interpreted in combination with grayscale evidence of plaque and other examination findings. The criteria typically used are ICA peak systolic velocity, ICA end-diastolic velocity, the ICA-to-CCA ratio, and visible plaque burden. This combined approach is important because no single Doppler measurement should be interpreted independently of the anatomic and hemodynamic context of the examination.

Emerging Technology Approaches to Plaque Characterization

Emerging carotid ultrasound techniques extend plaque assessment beyond measurement of luminal stenosis and conventional grayscale morphology. Their common purpose is to provide additional information about the biologic activity and mechanical behavior of atherosclerotic plaque, particularly characteristics associated with vulnerability. The three emerging approaches discussed in this paper are contrast-enhanced ultrasound, microvascular flow imaging, and shear wave elastography. Together, these techniques evaluate plaque neovascularization, microvascular perfusion, and tissue stiffness—features that are not adequately characterized by conventional triplex imaging alone.

Contrast-Enhanced Ultrasound (CEUS)

Contrast-enhanced ultrasound uses intravenously administered microbubble contrast agents to improve visualization of vascular structures and perfusion. Because ultrasound contrast agents remain within the intravascular space, they function as blood-pool agents and can depict both macrocirculatory luminal detail and microvascular flow within the arterial wall and atherosclerotic plaque. This makes CEUS particularly useful for evaluating plaque surface abnormalities and intraplaque neovascularization.

Ultrasound contrast agents

Modern ultrasound contrast agents consist of inert, low-solubility gas microbubbles surrounded by a stabilizing shell. The gas component remains within the circulation until the microbubble is disrupted, after which the gas is eliminated through the lungs and shell components are metabolized. Their intravascular confinement allows the microbubbles to serve as strong acoustic reflectors within both larger vessels and small microvascular channels.

Improved delineation of luminal and plaque surface irregularities

CEUS can improve definition of the residual arterial lumen and provide clearer visualization of irregular plaque surfaces. This may be particularly useful when conventional grayscale or color Doppler imaging incompletely defines small surface defects or ulcerations. By enhancing the blood-tissue interface, contrast imaging can make subtle luminal and surface irregularities more conspicuous.

Detection of plaque neovascularization

One of the most important carotid applications of CEUS is visualization of small neovessels within atherosclerotic plaque. These vessels may arise from the vasa vasorum and extend into the plaque itself. Because plaque neovascularization is associated with intraplaque hemorrhage and structural instability, its detection provides information about plaque vulnerability that conventional grayscale imaging cannot reliably provide.^{9 10}

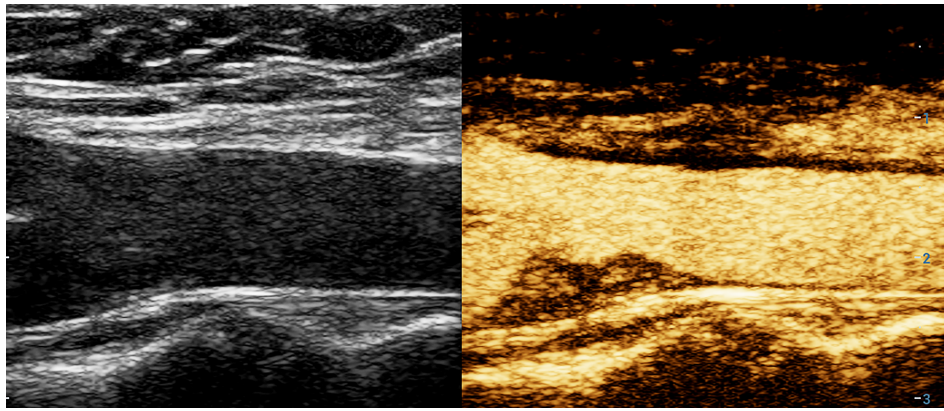


Figure 6. Conventional ultrasound and contrast-enhanced ultrasound demonstration of carotid plaque.

The left image shows conventional grayscale/color Doppler imaging, in which the soft plaque is not clearly delineated. The right CEUS image demonstrates improved lumen definition and visible intraplaque microbubble enhancement, revealing plaque neovascularization not apparent with grayscale imaging alone.

Quantitative CEUS

CEUS may also be analyzed quantitatively by measuring contrast signal intensity within defined regions of interest. Quantitative CEUS provides data on microbubble intensity within a plaque by comparing values obtained from three related regions of interest (ROIs): within the atherosclerotic plaque, normal arterial wall (a virtually non-perfused reference region), and carotid lumen (region of maximum contrast enhancement¹¹). Intensity values in a neovascularized plaque fall between those obtained from the carotid lumen and those obtained from the normal arterial wall. Increased microbubble intensity within the plaque, as compared to normal carotid wall, has been correlated histologically with plaque neovascularity and confirms the grayscale findings.^{12 13}

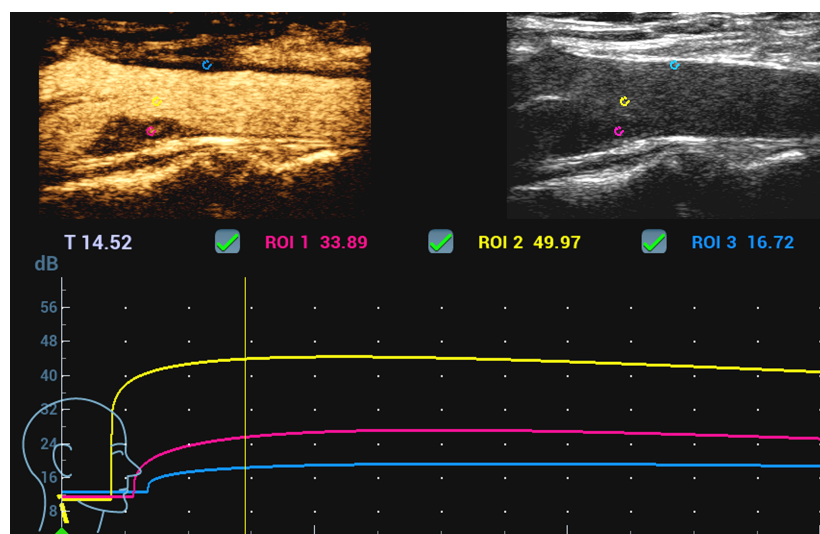


Figure 7. Quantitative contrast-enhanced ultrasound (CEUS).

(A) CEUS and corresponding grayscale reference image demonstrate placement of regions of interest within the carotid plaque (magenta), normal arterial wall (cyan), and vessel lumen (yellow). (B) Time-intensity curves demonstrate greater microbubble enhancement within the plaque than in the normal arterial wall, consistent with intraplaque neovascularization, while luminal enhancement remains highest.

Microvascular Flow Imaging (MFI)

Microvascular flow imaging is a Doppler-based technique designed to improve visualization of very slow, low-amplitude blood-flow signals. Conventional Doppler clutter filters may suppress these signals along with tissue motion, whereas MFI uses adaptive filtering methods intended to separate true slow flow from background clutter. In carotid plaque imaging, this allows depiction of small intraplaque vessels without the need for intravenous contrast administration.

Adaptive filtering and slow-flow sensitivity

The principal technical advantage of MFI is improved preservation of low-velocity Doppler signals. Adaptive filtering reduces acoustic noise and tissue clutter while retaining signals produced by slowly moving blood. This increases sensitivity to microvascular flow that may be too weak to display with conventional color or power Doppler methods.

Color-coded microvascular display

The detected microvascular signals are displayed as a color-coded map superimposed on the grayscale image. This allows the examiner to relate small-vessel flow directly to plaque anatomy and may produce perfusion patterns resembling those seen with contrast-enhanced imaging.

Visualization of plaque neovascularization

In carotid applications, MFI can demonstrate small vessels within or adjacent to atherosclerotic plaque. Detection of this microvascular activity provides another means of identifying plaque neovascularization, an important structural feature associated with plaque instability. Few peer-reviewed studies focused on the use and efficacy of MFI in histologically characterizing vulnerable plaques have been published to date. However, there are several studies that do demonstrate MFI as equivalent to CEUS in correlating plaque neovascularization and in predicting CIE-related patient outcomes.¹⁴¹⁵ The singular microvascular ultrasound finding associated with plaque neovascularization is the demonstration of blood flow into the body of the lesion.

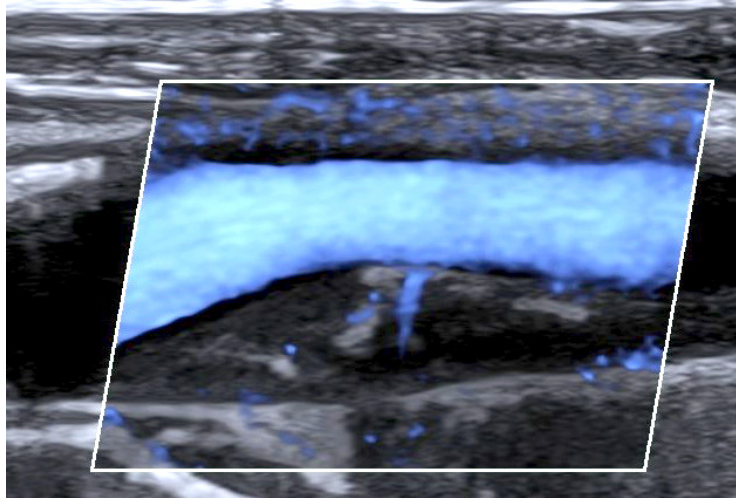


Figure 8. Microvascular flow imaging (MFI) of carotid plaque.

Color-coded low-velocity microvascular flow is superimposed on the grayscale image, demonstrating intraplaque neovascularization that may not be apparent with conventional Doppler imaging.

Workflow advantages

Unlike CEUS, MFI does not require intravenous contrast administration or a separate post-injection imaging sequence. Images can be obtained during the routine carotid examination, allowing plaque perfusion information to be added without substantially altering the standard scanning workflow

Comparison with CEUS

CEUS and MFI differ substantially in their workflow and operator requirements. CEUS requires contrast injection, additional examination time, and specific acquisition skills, whereas MFI can be incorporated into the initial scanning pass without contrast administration. Reported diagnostic performance suggests that both techniques can improve detection of plaque neovascularization, while MFI may offer practical workflow advantages.

Plaque Elastography and Shear Wave Elastography (SWE)

Elastography adds a mechanical dimension to plaque characterization by estimating tissue stiffness. Rather than assessing plaque solely by echogenicity or perfusion, elastography evaluates how rigid or compliant the tissue is. Quantitative shear wave techniques are particularly useful because softer plaque has been associated with symptomatic disease and with structural characteristics that may indicate greater susceptibility to rupture.

Overview of elastographic approaches

Several forms of ultrasound elastography are available. Strain elastography provides a primarily qualitative or semiquantitative assessment of tissue deformation, while shear wave techniques provide quantitative stiffness measurements. Point shear wave elastography, two-dimensional shear wave elastography, and acoustic radiation force impulse–based methods represent quantitative approaches that can be applied to carotid plaque evaluation.

Physical principle of shear wave elastography

Shear wave elastography uses an acoustic push pulse to generate transverse shear waves within tissue. Ultrafast imaging is then used to track the propagation of these waves. Because shear waves travel more rapidly through stiffer tissue and more slowly through softer tissue, measured shear-wave velocity can be converted into a quantitative estimate of tissue stiffness, commonly expressed in kilopascals.

Point shear wave elastography (pSWE)

Point shear wave elastography measures stiffness at a small, targeted region within the plaque. The grayscale image is used to guide placement of the sampling cursor, and a quantitative stiffness value is obtained from that selected location. Unlike two-dimensional elastography, pSWE does not generate a full color stiffness map, but its small sampling region permits focused measurement of specific plaque components.



Figure 9. Point shear wave elastography (pSWE) of complex carotid plaque.

The targeted sampling cursor is positioned within the plaque to obtain a quantitative stiffness measurement, with an average value of 27.45 kPa.

Two-dimensional shear wave elastography (2D-SWE)

Two-dimensional SWE acquires multiple stiffness measurements across a user-defined region of interest and displays the information as a real-time elastographic map superimposed on the grayscale image. This provides a global view of relative stiffness within the plaque while also allowing quantitative reporting of minimum, maximum, and mean stiffness values.

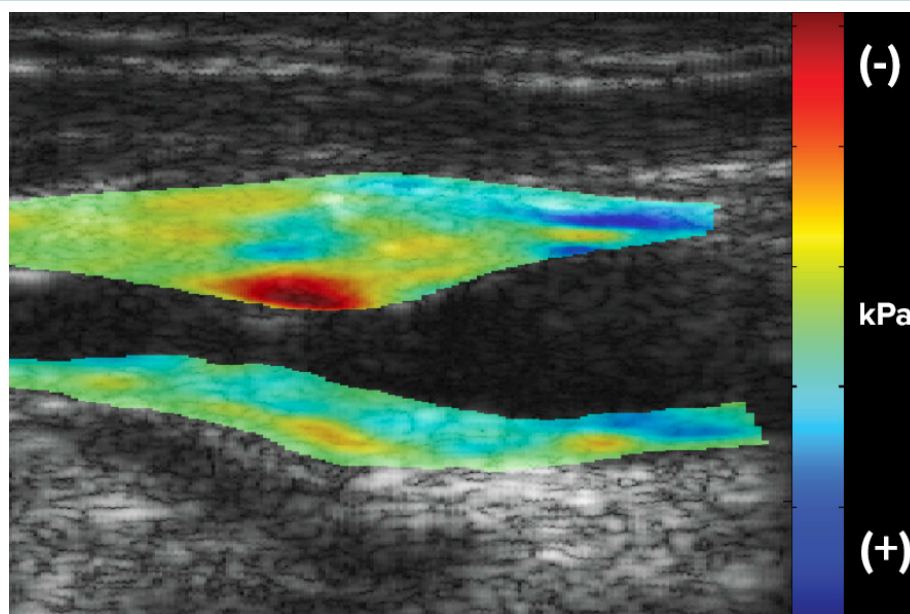


Figure 10. Two-dimensional shear wave elastography (2D-SWE) of carotid plaque.

The regional elastographic map is superimposed on the grayscale image, displaying relative variations in plaque stiffness across the sampled area. Lower kilopascal (kPa) values represent softer tissue, whereas higher kPa values indicate greater tissue stiffness.

Potential clinical value

The clinical rationale for plaque elastography is that mechanically softer plaques may be more vulnerable than stiffer lesions. Typically, plaques in symptomatic patients demonstrate lower stiffness values than plaques in asymptomatic patients, and softer plaques were associated with greater concern for rupture. There is also a demonstrated correlation between shear wave findings and both histologic and CT-based plaque characterization, supporting the potential value of elastography as an adjunct to morphology and stenosis severity.^{16 17 18}

The practical appeal of these emerging approaches is that they assess different aspects of plaque biology. CEUS and MFI emphasize microvascular perfusion and neovascularization, whereas SWE evaluates mechanical stiffness. Used alongside conventional grayscale, color Doppler, and spectral Doppler imaging, they move carotid ultrasound toward a more comprehensive assessment of plaque behavior rather than relying on luminal stenosis alone.¹⁹

Conclusion

Carotid ultrasound is evolving from a primarily stenosis-centered examination toward a more comprehensive assessment of atherosclerotic disease and vascular risk. Conventional triplex imaging remains the foundation of the examination, providing essential information about vascular anatomy, plaque burden, global hemodynamics, and the severity of internal carotid artery stenosis. Its limitations are most apparent in plaque characterization, where grayscale morphology alone cannot reliably distinguish vulnerable from nonvulnerable lesions.

Emerging techniques extend the clinical reach of carotid ultrasound rather than replace conventional methods. Contrast-enhanced ultrasound and microvascular flow imaging provide information about plaque neovascularization and microvascular activity, while shear wave elastography adds quantitative assessment of plaque stiffness. Additional emerging modalities such as automated carotid intima-media thickness, arterial wall stiffness, and wall shear stress broaden the examination further by providing structural, mechanical, and hemodynamic markers related to overall vascular health and cardiovascular risk.

The future direction of carotid ultrasound is therefore increasingly multiparametric. By integrating conventional stenosis assessment with information about plaque biology, tissue mechanics, arterial wall properties, and local flow dynamics, ultrasound may provide a more complete characterization of carotid atherosclerotic disease than stenosis severity alone.

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