Diagn Interv Radiol 2026; DOI: 10.4274/dir.2025.253448

CARDIOVASCULAR IMAGING

INVITED REVIEW

Recent advances in vascular ultrasound imaging technology and their clinical implications

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ABSTRACT

A multiparametric ultrasound (US) approach, which is defined as the use of existing and new ultrasonographic technologies to enhance diagnostic accuracy, can be applied in vascular imaging. By incorporating techniques such as stiffness evaluation, elastography modalities, vector flow imaging, slow flow imaging, contrast-enhanced US, and three-dimensional imaging, this approach offers deeper insights into various vascular conditions, including vascular aging. Advancements in technology now make it possible to quickly obtain numerical values for various vessel properties on a screen or worksheet, simplifying and streamlining the multiparametric approach. Thus, recent advances in vascular US imaging technology allow for detailed investigation of many complex physiological and pathophysiological vascular phenomena.

KEYWORDS

Arterial, carotid artery, contrast agent, microvascular imaging, ultrasonography, vascular aging

Vascular ultrasound (US) has evolved as a cornerstone in the diagnosis and management of vascular diseases, offering a safe, non-invasive, and highly accessible imaging modality. It has traditionally been widely recognized as the first-line, and sometimes the only imaging modality for the screening, diagnosis, and monitoring of vascular diseases. The role of US is particularly important given the need for accurate and non-invasive methods for the early detection of vascular degenerative changes, which is crucial as cardiovascular disease remains the leading cause of mortality worldwide.[1-3] Doppler US, including color Doppler, spectral Doppler, and power Doppler modes, has been an essential component of vascular imaging for over 40 years, with its advantages and limitations extensively documented in the literature.[4] However, several challenges persist in the US imaging of vascular conditions. For example, in patients with carotid artery disease, there is a need for improved methods to characterize atheromatous plaques and enhance risk stratification, enabling more effective treatments.

Improvements in US image quality and the development of high-frequency transducers have enhanced the spatial resolution of images, enabling detailed visualization of small vessels and vascular pathologies, such as atherosclerotic plaques. In addition to improved B-mode tissue characterization, advancements in US technology and image analysis now enable the assessment of various physiological and pathophysiological conditions in vessels. The role of vascular US in diagnosing and managing vascular diseases has grown considerably, with recent innovative advances in US techniques enhancing its diagnostic capability, accuracy, and clinical utility.

This review covers recent and relatively new advancements in vascular US, with a focus on quantitative arterial stiffness for assessing vascular aging, microvascular US, tissue elastography, three-dimensional (3D) US and contrast-enhanced ultrasound (CEUS). The availability of these technologies facilitates the adoption of multiparametric US, integrating advanced imaging capabilities with existing techniques to deliver more comprehensive information and improve diagnostic accuracy in vascular imaging.

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Received 09 May 2025; revision requested 16 June 2025; accepted 27 July 2025

Epub: 27.08.2025

Publication date: 02.01.2026

DOI: 10.4274/dir.2025.253448

You may cite this article as: Özhan Oktar S, Cerit MN, Şendur HN, Karabörk Kılıç AC. Recent advances in vascular ultrasound imaging technology and their clinical implications. *Diagn Interv Radiol.* 2026;32(1):47-56.

Vascular aging and arterial stiffness

The notion that "A man is as old as his arteries," attributed to the English physician, Thomas Sydenham, in the 17th century, reflects the long-standing awareness of vascular aging. While this concept has been recognized for centuries, research into its underlying mechanisms has emerged only fairly recently.[5] Vascular aging refers to the cumulative structural and functional changes that occur in the vasculature with normal aging, independent of other diseases, beginning as early as in utero. It is recognized as a substantial risk factor for the development of cardiovascular diseases.

With aging, arteries undergo notable structural and functional alterations, including vessel wall thickening caused by the proliferation and migration of vascular smooth muscle cells, fragmentation of elastin fibers, and increased collagen deposition, all contributing to vascular stiffness. These changes contribute to reduced arterial compliance and its capacity to resist stress. Endothelial cell dysfunction, chronic low-grade inflammation, oxidative stress, and traditional cardiovascular risk factors further exacerbate the progression. In more advanced stages–as in atherosclerosis–plaque accumulation, macrophage infiltration, and foam cell formation are observed.[6-8]

The hallmark of vascular aging is this increased "vascular stiffness," which broadly refers to the reduced ability of the arteries to expand and recoil in response to changes in blood pressure with cardiac pulsations. Increased arterial stiffness by itself is a strong risk factor for a broad spectrum of cardiovascular diseases, including hypertension, heart failure, myocardial infarction, and stroke, independent of traditional risk factors. Vascular aging can be quantified by measuring vascular stiffness. Classical indirect methods for assessing arterial stiffness, such as arterial distensibility, compliance, elastic modulus, beta (β)-stiffness index, and pulse wave velocity (PWV) rely on the evaluation of changes in arterial diameter or volume during the cardiac cycle in response to corresponding changes in arterial pressure (Table 1). While these parameters are interrelated, each provides unique insights into the biomechanical properties of the vessel wall. These approaches remain central to understanding vascular biomechanics and age-related vascular changes. Among these, PWV is the most commonly used technique and is considered the gold standard for assessing arterial stiffness. The PWV increases with age due to reduced arterial elasticity, reflecting greater cardiovascular risk.[9-11]

During each ventricular contraction, a "pulse wave" is generated, causing the aorta to expand and the pressure wave to propagate along the arterial tree. The speed of this pressure wave is proportional to the stiffness of the artery. In young individuals, the arteries are more elastic, causing the reflected wave to travel more slowly and return to the heart during diastole. This phenomenon enhances diastolic pressure, improving coronary perfusion, and dissipates part of the pulsatile energy in the central aorta, thereby protecting the microcirculation from damage. With vascular aging, arterial stiffness increases, leading to a higher PWV (Figure 1). Given its strong association with vascular damage, PWV serves as a critical biomarker for evaluating cardiovascular risk and facilitates early detection of vascular dysfunction.[8,6,12-15] Increased arterial stiffness has been shown to predict cardiovascular events even in asymptomatic individuals without overt cardiovascular disease.[16]

New sonographic techniques focus on detecting wave propagation. Several manufacturers have provided wall motion detection capability with different techniques. The radiofrequency data-based quantification technique used in arterial stiffness evaluation automatically identifies the intimal surface of the near- and far-field vessel walls under investigation, tracks movements over several cardiac cycles, and measures vessel diameter and displacement in micrometers. Vessel distensibility, an indicator of vascular stiffness, is calculated from the difference between systolic and diastolic measurements and is displayed on the screen (Figure 2). Ultrasonographic strain imaging using the speckle tracking method is another technique for assessing carotid stiffness. Using this technique, circumferential, longitudinal, and radial movements of the carotid artery can be analyzed, and displacement of the carotid wall can be represented graphically. Combined with diastolic and systolic blood pressure data, this technique allows for automatically calculating arterial stiffness parameters, such as elastic modulus, arterial distensibility, compliance, and β-stiffness index, via a special software program. Additionally, strain, strain rate, and peak circumferential and radial displacements can be measured (Figure 3). These techniques show promise as a valuable non-invasive tool for identifying early subclinical carotid artery disease.[6,10,12,13]

Main points

- Increased arterial stiffness by itself is a strong risk factor for a broad spectrum of cardiovascular diseases, including hypertension, heart failure, myocardial infarction, and stroke, independent of traditional risk factors.
- The term "vulnerable plaque" refers to atherosclerotic plaques that are prone to rupture, potentially leading to thrombosis and embolism. The current challenge is to distinguish stable plaques from vulnerable ones, enabling identification of high-risk patients for acute cardiovascular and cerebrovascular events before clinical symptoms arise.
- Microvessel imaging also has potential for evaluating intraplaque neovascularization, a key factor in carotid plaque instability.
- Using microbubble-based contrast agents, contrast-enhanced ultrasound has significantly improved the ability to assess vascular perfusion and microvascular flow. This innovation has clinical implications for detecting tumor vascularity, characterizing plaques, and evaluating organ perfusion in both arterial and venous systems.

Table 1. Indirect methods for evaluating arterial stiffness

Parameter	Definition	Formula
Arterial compliance	Absolute change in vessel diameter for a given change in pressure	[diastolic diameter–systolic diameter (ΔD)]/[systolic pressure–diastolic pressure (ΔP)]
Arterial distensibility	The relative change in vessel diameter for a given change in pressure	ΔD/[ΔP × vessel diameter in the diastolic phase (D)] in mmHg
Elastic modulus index	Pressure change required for theoretical stretch from resting arterial diameter	(ΔP × D)/ΔD in mmHg
Beta-stiffness index	The ratio of the natural logarithm of systolic/diastolic pressure to relative change in diameter	log (SBP/DBP)/(ΔD/D)
Pulse wave velocity	The speed with which the pulse wave travels along the length of the artery	Stiffness index × diastolic blood pressure/(2 × blood density) while assuming the blood density to be 1.050 g/cm^3

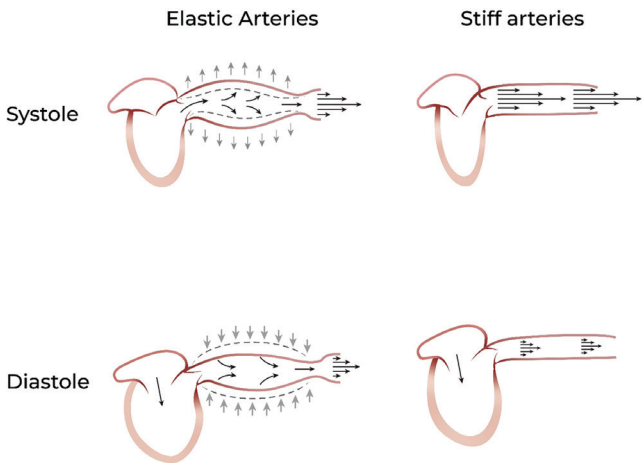

Figure 1. In a healthy artery, compliance allows the vessel to expand as blood is pumped from the heart and to recoil during diastole, propelling the accumulated blood forward into the peripheral tissues, providing continuous flow to the end organs. With vascular aging and increased arterial stiffness, the arterial walls become more rigid, reducing compliance and leading to higher pressure within the vessels, as demonstrated in the right column. In younger vessels, propagation velocity is slower than in aged vessels in which the walls move less.

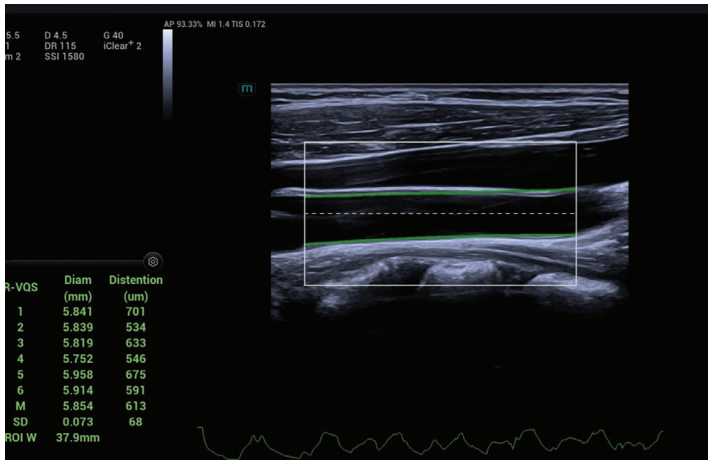

Figure 2. Radiofrequency data-based quantification on arterial stiffness tracks movements of vessel walls during consecutive cardiac cycles, with automatic detection of both near-and far-field vessel walls. Vessel distensibility is calculated from the difference between systolic and diastolic diameter measurements and shown on the screen. The motion curve of the vessel wall is displayed under the image in real time.

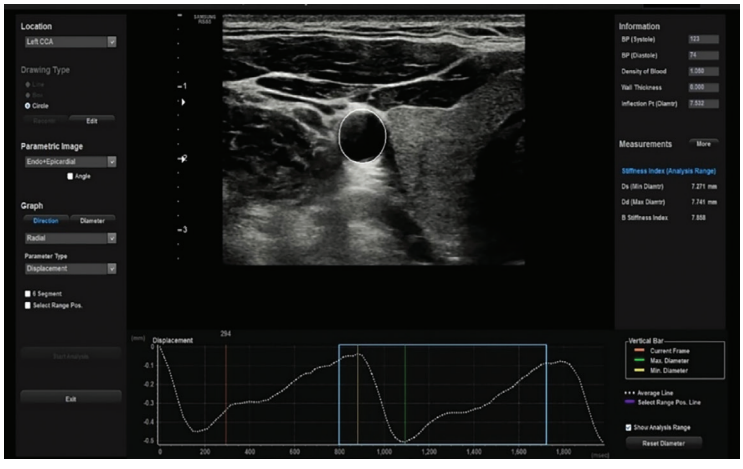

Figure 3. In the speckle tracking method, movements of the carotid artery can be analyzed and displacement of the carotid wall can be represented graphically.

Tissue elastography

US elastography is a method for assessing the elasticity of tissue, based on the cellular composition of the extracellular matrix. Several methods are available for elasticity evaluation, including real-time strain elastography or shear wave elastography (SWE), which have demonstrated efficacy in many clinical applications. The velocity of the shear wave created is directly linked to the elasticity of the arterial wall. Multiple factors influence arterial wall elasticity, such as personal factors (age, genetics, blood pressure, heart rate, different diseases), lifestyle factors (exercise, diet), and extrinsic factors (timing during cardiac cycle, acquisition characteristics, medical treatment). Unlike PWV, shear wave velocity is less dependent on other parameters, such as blood density and intra-arterial pressure. Local elasticity of the arterial wall or plaque can be calculated using SWE techniques.[17,18]

In the evaluation of atherosclerotic plaques, the paradigm has shifted from solely focusing on the hemodynamic effects of luminal stenosis to a more comprehensive assessment of plaque structure and composition. The term "vulnerable plaque" refers to atherosclerotic plaques that are prone to rupture, potentially leading to thrombosis and embolism. The current challenge is to distinguish stable plaques from vulnerable ones, enabling identification of high-risk patients for acute cardiovascular and cerebrovascular events before clinical symptoms arise. Distinct morphological features of vulnerable plaques, including intraplaque hemorrhage, lipid-rich necrotic cores, thin fibrous caps, plaque ulceration, inflammation, and neovascularization, allow for their identification and characterization through a range of invasive and non-invasive imaging tools (Figure 4).[19] The plaque elasticity quantification obtained via SWE is an indirect reflection of the major component of plaques, including dense fibrous tissue, calcifications, and lipid-rich necrotic core. Softer tissues such as lipid or hemorrhage, typically associated with vulnerable plaque, deform more easily and produce higher strains, whereas stiffer tissues such as those containing fibrous tissue deform less and result in lower strains (Figure 5). Preliminary investigations suggested that US elastography may be a clinically useful tool assessing plaque vulnerability. In some studies, it has been stated that SWE can identify statistically significant differences in elasticity and effectively distinguish different plaque types with good reproducibility in assessing rupture risk. Based on these results,

tissue elastography appears to be a promising method for risk stratification of carotid plaques. However, vascular elastography is challenging because of the relatively small heterogeneous tissue size, the dynamic environment resulting from pulsatile blood flow, thin vessel walls, anisotropy, and non-linear tissue elasticity. Therefore, in the European Federation of Societies for Ultrasound in Medicine and Biology guidelines and recommendations for the clinical practice of elastography, vascular US elastography has been considered as an area of active research, although it is currently not recommended for routine clinical decision-making.[20-24] While US elastography shows promise in vascular applications, especially for the assessment of carotid plaque, larger, multicenter studies are needed to validate findings, define cut-off values, and optimize techniques.

Vector flow imaging

Doppler techniques are angle dependent, providing correct information only when the US beam is aligned parallel to the flow direction. A major limitation of this approach is that tortuous vessels or unusual anatomy can produce complex flow patterns, leading to a mixed or unclear color display. Vector flow imaging (VFI) is an angle-independent technique that enables real-time visualization of complex blood flow patterns with extremely high frame rates. In conventional spectral Doppler imaging, the angle cursor must be manually aligned by the operator to estimate blood velocity based on the Doppler frequency, and only the velocity component along the direction of the beam is measured. In reality, a velocity vector representing blood flow consists of three components along the x, y, and z axes. The multibeam approach used in VFI enables the measurement of two or more velocity components. Using this technique, blood flow characteristics can be evaluated visually to assess the flow pattern. Each vector representing flow is displayed as a small color-coded arrow indicating the magnitude and the direction of a true velocity in real time at every point of the vessel (Figure 6).[25,26]

Wall shear stress (WSS) measurement is another capability of VFI. There are two major types of hemodynamic forces that act on blood vessels: tensile pressure (ρ), the outward force that acts perpendicular to the arterial wall, which is greater in systole; and shear stress (τ), the tangential frictional force per unit area of the vessel wall that is exerted in the direction of blood flow (Figure 7). As a local mechanical force, WSS heavily affects the biofunction of vascular endothelial and smooth muscle cells with diverse mechanisms.[27,28] The VFI technique enables automated WSS measurements by aligning the reference line to coincide with the vascular wall (Figure 8).

Endothelial cells have the ability to sense and transduce the shear stress from blood flow into biochemical signals that cause initiation and progression of the atherosclerotic process depending on the type and the magnitude of shear stresses through specific mechanisms. In straight regions of arteries, flow has a normal laminar pattern and is always in the same direction. Endothelial cells in these areas exposed to sustained laminar flow and high WSS have an anti-inflammatory phenotype characterized by alignment in the direction of flow, downregulation of atherogenic genes, low levels of oxidative stress, cell turnover, and permeability, which help protect against atherosclerosis. However, in regions where arteries divide or curve sharply, such as carotid bifurcation, disturbed or "atherogenic" flow patterns are observed, including flow separation, gradients, flow reversal, and turbulence. Endothelial cells in regions of disturbed flow or low shear have an activated, pro-inflammatory phenotype characterized by poor alignment, oxidative stress, expression of inflammatory genes, and high turnover, which is associated with high susceptibility to atherosclerosis.

Briefly, disturbed and laminar flow patterns may induce different molecular responses in endothelial cells, leading to the preferential development of atherosclerotic lesions at arterial branches and curvatures while sparing the straight sections of the arterial tree. The VFI technique may be useful for evaluating turbulent or disturbed blood flow, such as in stenotic arteries or aneurysmal regions, while simultaneously enabling measurements of WSS (Figure 9).

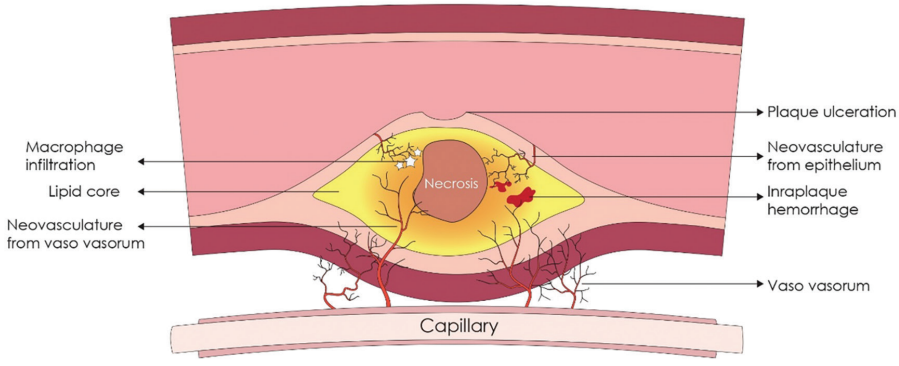

Figure 4. Schematic presentation of vulnerable plaque with remodeling.

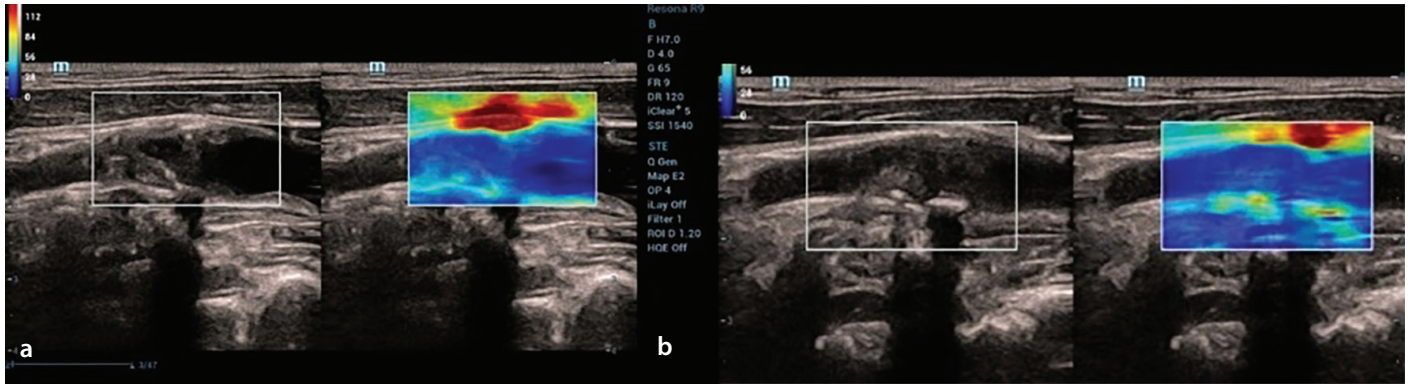

Figure 5. Shear wave elastography (SWE) imaging of plaques with different elastic properties: **(a)** SWE image displays a blue color at a hypoechoic plaque suggesting a soft texture; **(b)** B-mode image shows a mixed echogenicity of the plaque with hyperechoic areas suggesting calcifications. The SWE image shows a mixture of blue, red, and yellow colors, suggesting that the plaque contains stiff areas.

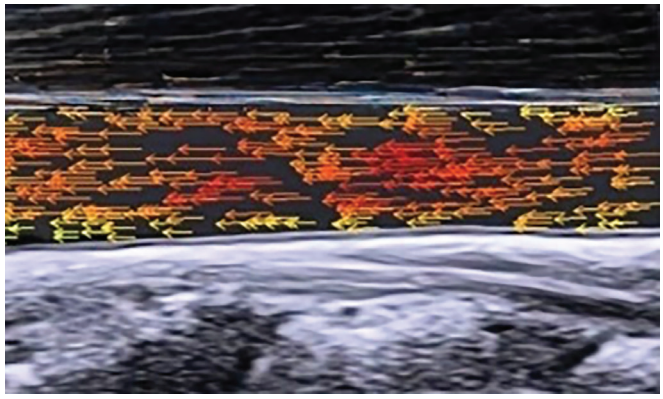

Figure 6. Vector flow imaging displays all velocity vectors in a selected region of interest. Each vector representing flow is shown as a small color-coded arrow indicating the magnitude and the direction of a true velocity in real time. The length and color of the arrows indicate the flow speed.

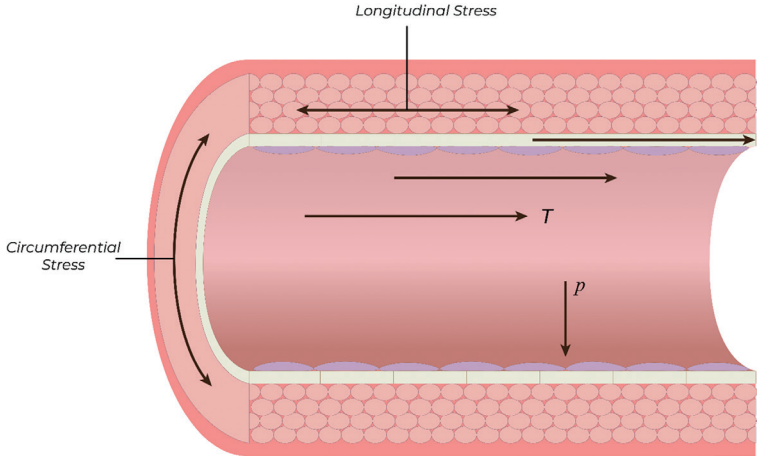

Figure 7. Schematic presentation of major hemodynamic forces that act on blood vessels. The tensile pressure (ρ) is the outward force acting perpendicular to the arterial wall, which is greater in systole. Shear stress (τ) is the tangential frictional force per unit area of the vessel wall, exerted in the direction of blood flow.

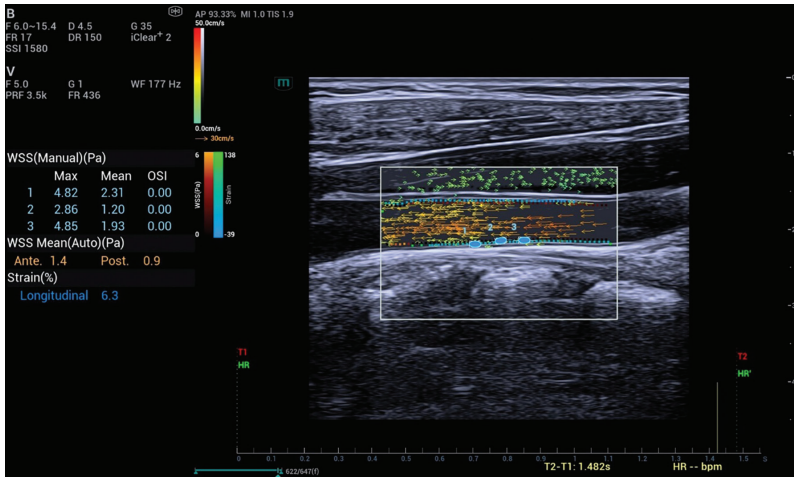

Figure 8. Wall shear stress measurements at a straight segment of a carotid artery by aligning the reference line to coincide with the vascular wall.

Non-physiological WSS also promotes plaque progression and the transformation of stable plaques into an unstable or vulnerable state.[27,29,30] Obtaining the WSS value may be valuable in stratifying patients at risk and for further clinical decision-making in carotid stenosis.

The reference values for WSS have been established in previous studies, with the normal maximum WSS in arteries considered to range between 1 and 7 Pa. It is suggested that a local mean WSS below 0.4 Pa could change vessel wall morphology and contribute to the development of arteriosclerosis. Moreover, other studies have indicated that excessively high WSS values in stenotic arteries may promote the rupture of high-risk plaques, with a rupture risk threshold identified as 7 Pa. It is suggested that high WSS values may lead to thinning of the fibrous plaque cap, increasing the risk of plaque rupture through elevated mechanical stress within the wall.[31-33]

In brief, analyzing carotid flow patterns and measuring WSS via VFI can offer valuable insights into the development of atherosclerosis. However, due to the relative novelty of the technique, there remains a lack of strong clinical evidence regarding its use. Further research is required to explore the pathophysiological significance of various complex flow patterns, which may indicate plaque progression and thrombus formation.[31]

Microvessel imaging

Traditionally, color and power Doppler imaging have been the main tools for non-contrast microvascular flow visualization.[34] However, conventional Doppler techniques have limited sensitivity for the detection of slow vascular flow. Recently, a number of tools have been developed for assessing small-diameter vessels with low-velocity flow without the need for intravenous (IV) contrast agents, collectively referred to as microvascular flow imaging.

Doppler technologies employ single-dimensional wall filters for suppressing clutter artifacts resulting from vessel wall motion, which results in loss of slow flow signals from smaller vessels. Microvascular flow techniques, on the other hand, use multidimensional adaptive wall filters to selectively remove overlapping tissue movement artifacts, maintaining low flow signals otherwise lost in conventional Doppler imaging methods. This approach preserves slow flow signals originating from microvasculature, providing more sensitive and higher resolution blood flow evaluations with exquisite vascular details (Figure 10). Additionally, microflow imaging uses high-frequency sampling techniques and a high frame rate, enabling the display of high-resolution images. In certain cases, it can also rapidly confirm the presence or absence of blood flow without the need for IV contrast administration. Multiple vendors offer microvascular techniques on different ultrasonography devices, such as Superb Microvascular Imaging in Canon Medical Systems, ultra-micro angiography in Mindray Bio-Medical, Micro-vascular Imaging in GE Healthcare, Micro-vascular-flow in Samsung, Slow Flow in Siemens Healthineers, and MicroFlow Imaging in Philips systems. Display modes vary by manufacturer,

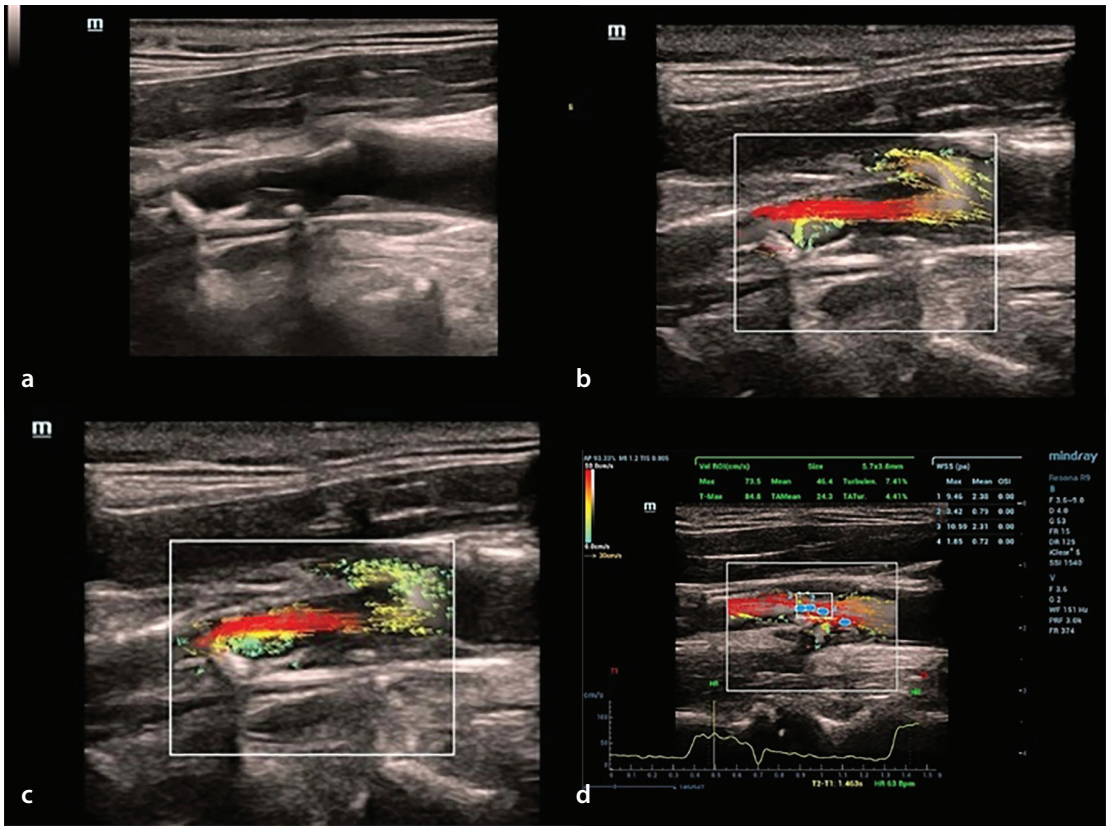

Figure 9. Vector flow imaging (VFI) of the carotid stenosis: **(a)** Grayscale image reveals calcified atherosclerotic plaque with irregular surface, causing severe stenosis of the right internal carotid artery; **(b, c)** VFI demonstrates complex flow patterns at different stages of cardiac cycle, with the vector arrows at the stenosis site becoming longer and the red color of the arrow indicating fast flow. Vortex flow is represented with short green or yellow vectors; **(d)** wall shear stress measurements at the level of stenosis.

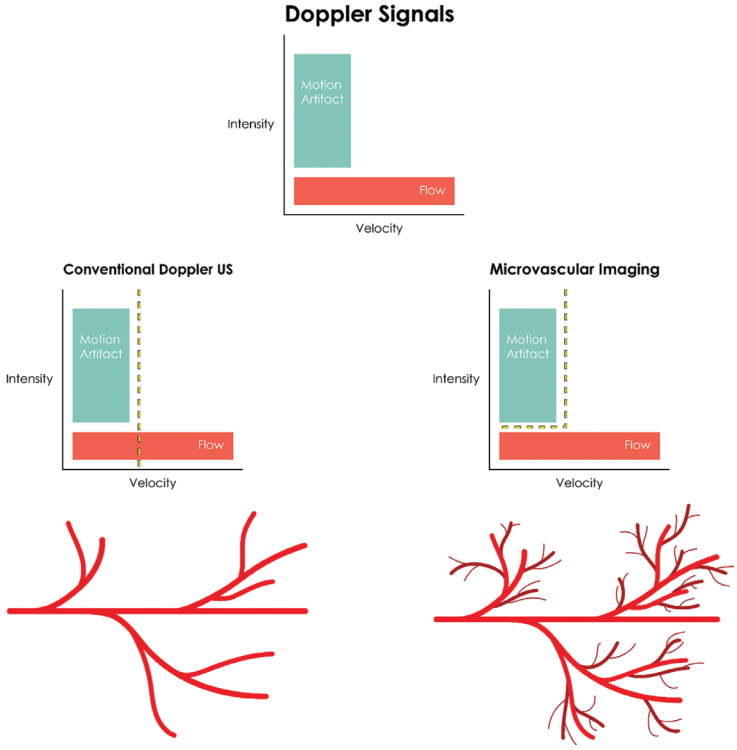

Figure 10. Imaging principles of microvascular ultrasound. The graph on the left shows that conventional Doppler techniques apply a single-dimensional wall filter (yellow dotted line) to remove clutter artifacts from wall motion, resulting in loss of signals from slow flow areas. In contrast, microvascular imaging techniques apply a multidimensional filter to remove only the clutter, preserving the slow flow signals, as shown on right. Exquisite detail of microvasculature can be detected via microvascular imaging.

but generally mimic the presentation of color or power Doppler modes, providing flow information overlayed on B-mode data using a variety of color hues.[20,35-37]

Existing research suggests that microflow imaging enhances the diagnosis and monitoring of a range of medical conditions. Possible clinical applications include assessment of the vascularity of breast masses and thyroid nodules, characterization of focal and diffuse liver lesions, detection of increased vascularity in tendons, joint capsules, and peripheral nerves in musculoskeletal US, depiction of mass lesions, and pre- and post-transplant kidney evaluations. It has also potential neurosonological applications, including in the eye.[35,38-41]

Microvessel imaging also has potential for evaluating intraplaque neovascularization, a key factor in carotid plaque instability, as illustrated schematically in Figure 4. The presence or progression of this neovascularization significantly affects the outcomes of vulnerable plaques, making its detection clinically important (Figure 11). The results of previous studies showed that blood flow detected by microvascular imaging frequently correlated with plaque enhancement signals

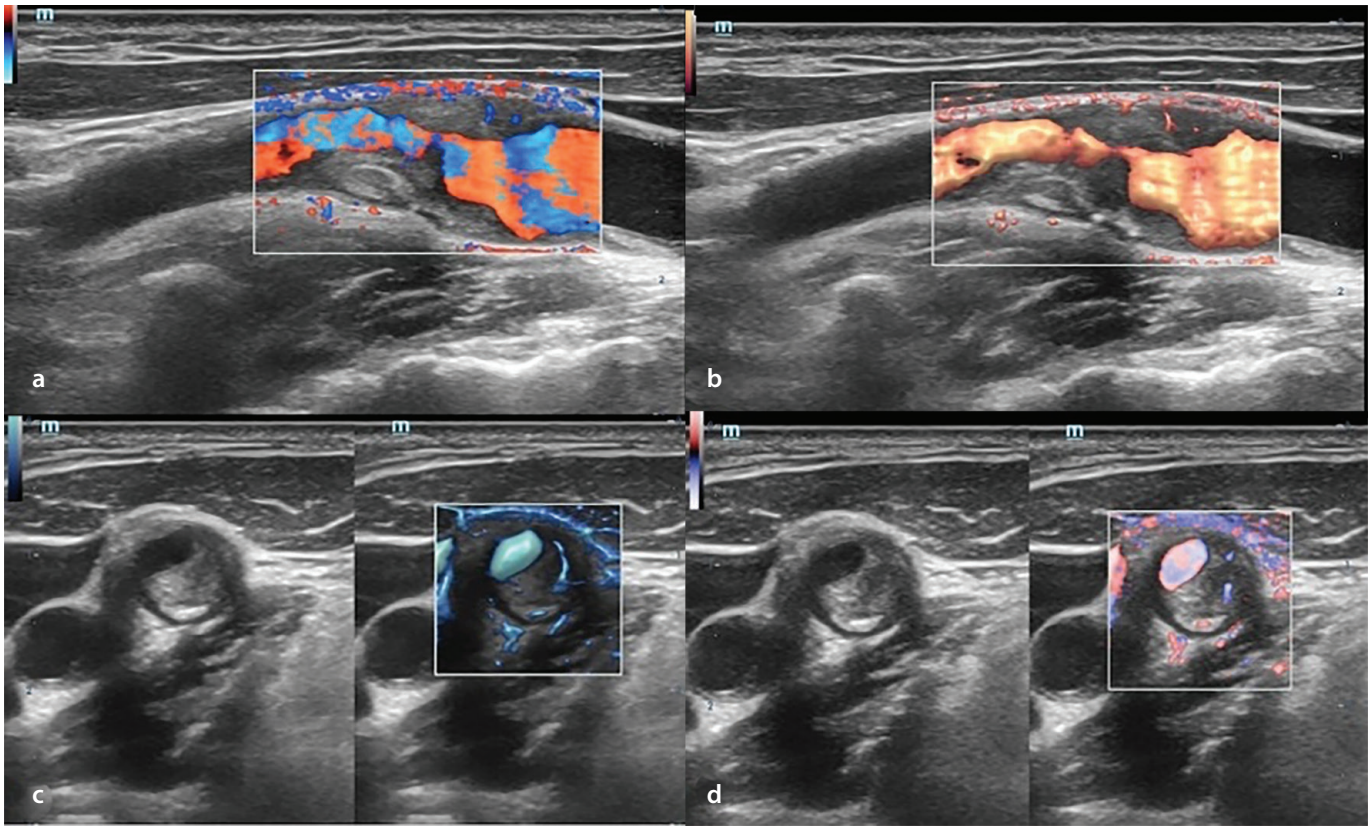

Figure 11. Microvascular ultrasound (US) imaging findings in complex plaques in the carotid bulb and proximal internal carotid artery causing high-grade carotid stenosis. Microvessel US imaging with different hues in longitudinal **(a, b)** and axial views **(c, d)** reveal tiny vessels at the anteriorly located plaque, representing neoangiogenesis.

observed in CEUS, demonstrating reliable consistency in assessing neovascularization in carotid plaques. The correlation between microvessel imaging and histology in detecting the neovascularization in atherosclerotic plaque has also been verified in corresponding studies.[42-46] While microvessel imaging techniques are not as accurate as CEUS or computed tomography (CT) in detecting endoleaks following endovascular aneurysm repair (EVAR), they offer a valuable improvement over standard color Doppler imaging and can serve as a useful alternative in the follow-up period, especially for patients who are unsuitable for contrast-enhanced imaging modalities.[47]

The development of increasingly sensitive microvascular flow imaging US techniques enhances the capability of non-contrast US to accurately diagnose or exclude pathologies, and may obviate the need for further contrast imaging methods, such as CEUS, CT, or magnetic resonance imaging, in selected cases. However, non-contrast US flow-detection methods have not achieved the same level of sensitivity as CEUS for detecting slow flow and perfusion. Additionally, they are unable to evaluate dynamic contrast kinetics. Moreover, microvascular US imaging has limited ability for deeper organs, making it clinically challenging to decide whether the absence of flow detection is due to depth limitations or reduced perfusion. This technique is also susceptible to motion artifacts, especially those caused by breathing and cardiac pulsations.

Three-dimensional ultrasound

3D US imaging is gaining popularity because of its superiority over conventional two-dimensional (2D) US by providing more accurate and reproducible assessment for anatomical structures and disease entities. This technique combines a series of 2D US cross-sectional slices, collected in a computer and reconstructed into a 3D volume. 3D US imaging provides volumetric reconstructions and dynamic imaging of vessel anatomy and blood flow. One of the most widely accepted advantages of 3D US is the reduction of operator dependency compared with 2D US imaging. Moreover, its potential for shortening the examination time makes it cost effective, and it is safe for serial testing. Further advantages of 3D US over 2D versions include its higher accuracy in evaluating the relationship between anatomical structures, evaluating treatment effects, estimating quantitative volume, and providing access to an unlimited number of imaging planes.[48,49]

The use of 3D US in obstetric imaging offers a new viewpoint on fetal anatomy, facilitates the identification of abnormalities, improves maternal–fetal bonding, and provides a better understanding of fetal abnormalities. In angiographic applications, viewing several 3D power Doppler US pictures in a fast cine loop has proven beneficial. Moreover, 3D US can help distinguish benign masses from malignant ones in breast imaging by exhibiting lesion borders and topography.[50-52]

There are three different methods for acquiring 3D US imaging. Mechanical 3D US consists of a motorized linear array transducer that moves within a housing to capture 2D image frames to be reconstructed into a 3D volume. Matrix 3D US has a larger imaging volume and acquires images more quickly compared with mechanical 3D US. However, the resolution of images decreases slightly. Lastly, in the freehand 3D US method, an external tracking system accompanies the transducer, and the operator can perform several maneuvers to avoid gas or artifacts.[49,53]

These 3D US techniques are increasingly utilized in clinical practice. Atherosclerotic plaque burden may be helpful in predicting individual risk for cardiovascular diseases,

and 3D US can allow for more accurate estimation of plaque burden.[54] Furthermore, carotid artery plaque assessment can be performed reliably and effectively using 3D US. According to a study conducted by Landry et al.[55], the inter- and intra-observer reliability was 93.2% and 94%, respectively. This study also reported that the higher the amount of plaque volume is, the lower the variability of measurements. However, a recent study revealed that with the advancements in 3D US technology, a new commercially available 3D transducer may provide more accurate plaque volume measurements in carotid and femoral arteries independent of plaque size.[56] In addition, 3D US may be feasible for the assessment of the effects of statin treatment on carotid artery plaques.[57]

The technique is also useful for preoperative planning and monitoring post-surgical outcomes, such as bypass grafts or endovascular repairs. Post-EVAR volume estimation of the aortic sac using 3D US can be both feasible and accurate. In a study conducted by Bredahl et al.[58], volume estimation in 93 consecutive patients undergoing EVAR was evaluated using 3D US, with CT angiography used as the reference standard. The authors reported that the mean difference between 3D US and CT angiography was 1 mm, and the limits of agreement ranged from -11% to 12%. Another study, which included 182 abdominal aortic aneurysms (AAAs) of patients under EVAR surveillance, reported no significant differences between 3D US and CT angiography in measuring the anteroposterior diameter of the residual sac, and underscored the potential benefit of 3D US in reducing the need for nephrotoxic contrast agents.[51]

Although 3D US has a promising role in clinical applications, a limited number of relevant studies are available. Therefore, future studies are required to better understand its clinical value.

Contrast-enhanced ultrasound

Using microbubble-based contrast agents, CEUS has notably improved the ability to assess vascular perfusion and microvascular flow. This innovation has clinical implications for detecting tumor vascularity, characterizing plaques, and evaluating organ perfusion in both arterial and venous systems. The method aims to address some of the drawbacks of traditional ultrasonography, such as the inability to clearly visualize slow flow, particularly in small vessels or in cases of substantial stenosis. US enables shell-encapsulated gas microbubbles, which have sizes <10 µm, to expand and contract, resonating at common medical US frequencies.[59] The energy of the transmitted pulse is scattered at harmonic and subharmonic frequencies as a result of this interaction. While the covering shell is metabolized, primarily in the liver, the patient's lungs exhale the interior gas. The contrast agent SonoVue (Bracco, Milan, Italy), which is made up of sulfur hexafluoride bubbles enclosed in a phospholipid membrane shell, is widely used in Europe and the United States under the brand name LumaSon®. CEUS enables continuous real-time scanning and can detect microvasculature in vessels as small as 40 µm with extremely low velocities, a capability that is frequently lacking in color and power Doppler US, which can image vessels as small as 100 µm.[49,60]

The CEUS method is used in the evaluation of extracranial carotid occlusive diseases. Regardless of the extent of stenosis, CEUS imaging can help determine whether a patient requires carotid endarterectomy by evaluating the shape and fragility of the plaque. The technique has a strong correlation with both conventional and magnetic resonance angiography, and it enables more precise evaluation of stenosis.[61] Additionally, when compared with color Doppler US imaging, CEUS improves measurements of the length of stenosis by reducing the visibility of intrastenotic flow aberrations.[62] Furthermore, abnormalities such as ulcers, hypoechoic plaques, and dissections that were previously missed by traditional US can be seen using CEUS imaging.[63] This imaging technique is a promising method for the diagnosis and treatment of pre-ruptured AAAs, ruptured AAAs, and endoleaks following EVAR, as well as the diagnosis of aortic dissections and peripheral arterial disease.[64] In summary, CEUS imaging is an important vascular imaging technology used to determine luminal perfusion, detect vascular irregularities, measure plaque vulnerability in various vascular pathologies, and measure neovascularization as a quantitative indicator of final muscle perfusion.

Footnotes

Conflict of interest disclosure

The authors declared no conflicts of interest.

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