Multimodality Imaging of Carotid Stenosis

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Abstract

Four diagnostic modalities are used to image the following internal carotid artery: digital subtraction angiography (DSA), duplex ultrasound (DUS), computed tomography angiography (CTA), and magnetic resonance angiography (MRA). The aim of this article is to describe the potentials of these techniques and to discuss their advantages and disadvantages. Invasive DSA is still considered the gold standard and is an indivisible part of the carotid stenting procedure. DUS is an inexpensive but operator-dependent tool with limited visibility of the carotid artery course. Conversely, CTA and MRA allow assessment of the carotid artery from the aortic arch to intracranial parts. The disadvantages of CTA are radiation and iodine contrast medium administration. MRA is without radiation but contrast-enhanced MRA is more accurate than noncontrast MRA. The choice of methods depends on the clinical indications and the availability of methods in individual centers. However, the general approach to patient with suspected carotid artery stenosis is to first perform DUS and then other noninvasive methods such as CTA, MRA, or transcranial Doppler US.

Keywords
- carotid artery stenosis
- digital subtraction angiography
- duplex ultrasound
- computed tomography angiography
- magnetic resonance angiography

Four diagnostic modalities are used to image the internal carotid artery: digital subtraction angiography (DSA), duplex ultrasound (DUS), computed tomography angiography (CTA), and magnetic resonance angiography (MRA). Noninvasive methods have undergone significant development in the recent years, especially computed tomography and magnetic resonance. Despite this development, invasive DSA is still considered the gold standard. The aim of this article is to describe the potentials of these techniques and to discuss their advantages and disadvantages.

Digital Subtraction Angiography

Currently, conventional DSA is not the first-line method for assessment of carotid stenosis; however, it is still considered the gold standard and is an indivisible part of the carotid stenting procedure. The carotid artery is visualized in several projections, two at least, but three or more are recommended. DSA allows evaluation of the severity and morphology of stenosis, when an irregular margin suggests plaque ulceration and an intraluminal defect suggests thrombus. DSA of intracranial arteries allows visualization of collateral flow (►**Fig. 1**).

Several methods can be used to measure the severity of carotid stenosis based on angiographic images. Currently, three methods predominate worldwide (►**Fig. 2**). The North American Symptomatic Carotid Endarterectomy Trial (NASCET) method compares stenosis to the distal normal poststenotic internal carotid artery (ICA) diameter.[1] The European Carotid Surgery Trial (ECST) method compares stenosis to estimate the normal diameter of the carotid bulb.[2] The common carotid (CC) method measures the residual lumen diameter at the most stenotic portion of the vessel and compares this to the lumen diameter in the proximal CC artery.[3] Different measurement techniques lead to different estimations of the degree of stenosis. The relations between

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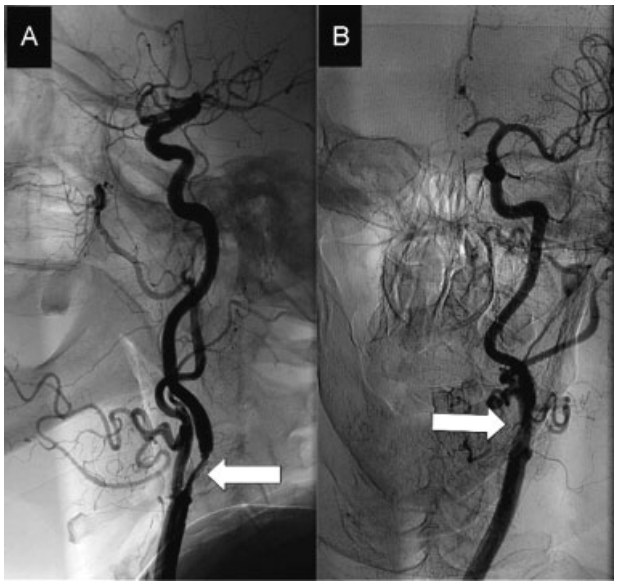

Fig. 1 Digital subtraction angiography of the carotid artery with stenosis more than 70% (arrow) in (A) lateral and (B) anteroposterior view. Stenosis is clearly visible in lateral view bud obscured by external carotid artery in anteroposterior view.

measurements are approximately linear. The ECST and CC methods indicate that twice as many stenoses are severe, as did the NASCET method, and classified less than one-third of the number of stenoses as mild.[4]

Advantages

DSA evaluates the entire carotid artery system, providing information about tandem atherosclerotic disease, plaque morphology, collateral circulation, and the presence of associated intracranial atherosclerotic disease.

Disadvantages

DSA is an invasive method. The most feared complication is embolization with consequent stroke; however, the incidence of permanent stroke is less than 1%.[5] The quality of the angiogram depends on selective catheterization of the carotid artery with at least two views. A limited number of projections could lead to an underestimation of the degree of stenosis in arteries that have asymmetrical eccentric stenosis.

Rotational angiography is based on scanning during rotation of the X-ray tube and detector around patient and allows depiction of stenosis from multiple angles during one administration of contrast media. Rotational angiography compared with conventional DSA frequently shows more severe ICA stenosis.[6] Moreover, rotational angiography correlates best with contrast-enhanced MRA.[7] Cone beam CT (reconstruction of CT-like images from rotational angiography) is useful for depiction of intracranial structures, but also shows the possibility for further plaque characterization in the extracranial portion of the carotid aterery.[8,9]

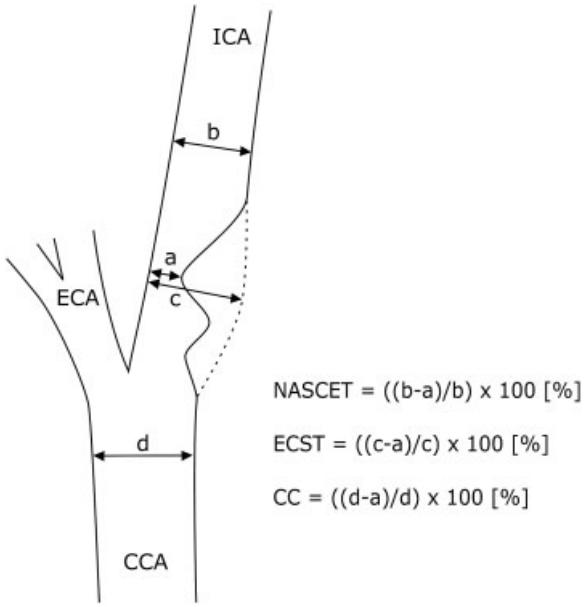

Fig. 2 Methods of the measurement of the carotid artery stenosis severity: The North American Symptomatic Carotid Endarterectomy Trial (NASCET), European Carotid Surgery Trial (ESCT), and common carotid (CC) method. CCA, common carotid artery; ECA, external carotid artery; ICA, internal carotid artery.

Duplex Ultrasound

Grayscale and Doppler ultrasound are used for assessment of extracranial segments of carotid arteries. The combination of these two ultrasound methods is called DUS.

Grayscale US allows evaluation of morphology with assessment of vessel wall atherosclerotic changes. Calcified (hyperechoic) and noncalcified (hypoechoic) parts of atherosclerotic plaques can be differentiated (►**Fig. 3**). Hypoechoic plaques are an independent risk factor for stroke.[10] Grayscale US also allows measurement of intima-media complex thickness, which helps detect preclinical atherosclerosis and assess risk stratification.[11]

Doppler US is based on the Doppler effect that allows measuring of flow based on the reflection of mechanical waves. Pulse and color Doppler US are both used. Color Doppler US visualizes flow in color-coded information about direction and velocity interposed on grayscale images, and high-grade stenosis can be more easily detected with color Doppler than with pulse Doppler US. However, pulse Doppler US allows direct measurement of flow velocity (►**Fig. 3**). Peak systolic velocity (PSV) is used for quantifying stenosis, but other parameters including end-diastolic velocity, carotid index, and spectral analysis of waveforms are also used for evaluation of stenosis. Standard criteria for stenosis assessment based on the study by Grant et al[12] are in shown in ►**Table 1**. Sensitivity and specificity for 70 to 90% stenosis are 0.89 and 0.84, for 50 to 69% stenosis they are, respectively, 0.36 and 0.91.[13]

Advantages

Carotid DUS is a noninvasive, safe, and inexpensive technique. DUS allows direct visualization of morphology and flow measurement.

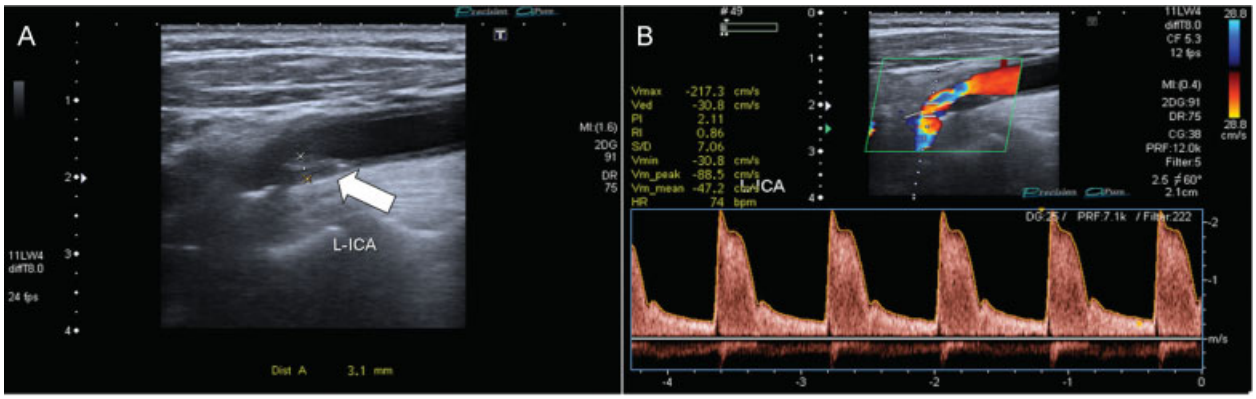

Fig. 3 (A) Grayscale ultrasound (US) with mixed plaque in the internal carotid artery (arrow). (B) Color and pulse Doppler US with peak systolic velocity 217 cm/s in the internal carotid artery (stenosis 50–69%). L-ICA, left internal carotid artery.

Disadvantages

The accuracy of DUS depends on the experience and expertise of the sonographer. The measurement may vary widely between laboratories. Patient habitus, atypical anatomical situation, or the tortuous course of carotid arteries might cause difficulties in detection and flow measurement. Imaging may be limited by features such as calcific carotid lesions. The absence of flow in the internal carotid artery may be because of the occlusion, but hairline residual lumens can be missed on DUS. Results of DUS must be interpreted carefully in patients with contralateral carotid occlusion to avoid overestimation of an ipsilateral carotid stenosis, because the PSV is often increased in the presence of contralateral internal carotid occlusion. Another limitation is that only the cervical portion of the internal carotid artery can be evaluated; however, transcranial Doppler may provide some information about intracranial vessels.

Transcranial Doppler US through transtemporal, transorbital, and transforaminal windows could be helpful in cases of extracranial carotid stenosis and allows evaluation of intracranial flow changes including diminished flow acceleration in the ipsilateral middle cerebral artery above stenosis and collateral reversed flow in ipsilateral anterior cerebral artery and ophthalmic arteries.[14]

Contrast-enhanced ultrasound seems to be a promising method for further evaluation of carotid stenosis morphology, plaque structure, and also possibly neovascularization of plaque. But this method is not widely used and has to be standardized and proven in prospective studies.[15]

Computed Tomography Angiography

CTA with intravenously administered iodine contrast medium shows the whole course of the carotid artery from the aortic arch to intracranial segments and allows assessment of the severity of stenosis at all levels (►**Fig. 4**). Evaluation is done in multiple view and different types of reconstructions with the possibility of plaque composition evaluation (►**Fig. 5**). Stenosis measurement can be done based on luminal area, but usually diameter measurement using NASCET or ESCT criteria is used in clinical practice. CT technology development with increasing the number of detector rows from 4 to 320 has influenced accuracy. A meta-analysis from 2006 by Wardlaw et al shows relatively low accuracy for CTA

Table 1 Gray-scale and Doppler US criteria for diagnosis of ICA stenosis

Stenosis (%)	Parameters
Normal	ICA PSV < 125 cm/s and none visible plaque, additionally ICA/CCA PSV ratio < 2.0 and ICA EDV < 40 cm/s
< 50	ICA PSV < 125 cm/s and estimate plaque < 50%, additionally ICA/CCA PSV ratio < 2.0 and ICA EDV < 40 cm/s
50–69	ICA PSV 125–230 cm/s and estimate plaque 50% and more, additionally ICA/CCA PSV ratio 2.0–4.0 and ICA EDV 40–100 cm/s
≥ 70 but less than near occlusion	ICA PSV > 230 cm/s and estimate plaque 50% and more, additionally ICA/CCA PSV ratio > 4.0 and ICA EDV > 100 cm/s
Near occlusion	ICA PSV high, low, or undetectable, estimate plaque visible, additionally variable ICA/CCA ratio and ICA EDV
Total occlusion	Undetectable flow, visible plaque, no detectable lumen

Abbreviations: CCA, common carotid artery; EDV, end-diastolic velocity; ICA, internal carotid artery; PSV, peak systolic velocity; US, ultrasound.
Note: Adapted from Grant et al.[12]

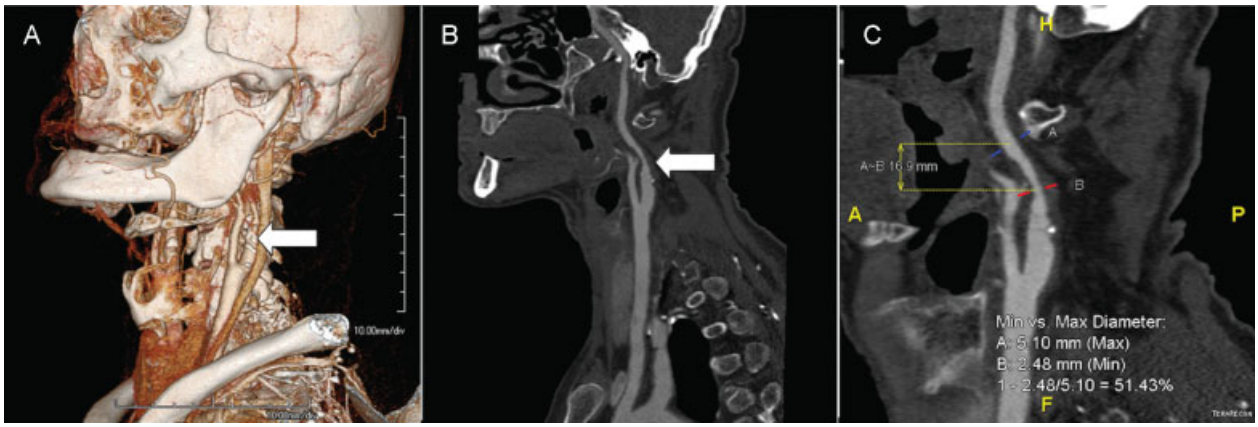

Fig. 4 Computed tomography angiography with mixed plaque in the internal carotid artery and stenosis (arrows). (A) Volume rendering technique, (B) curved multiplanar reconstruction, and (C) curved multiplanar reconstruction with stenosis measurement using North American Symptomatic Carotid Endarterectomy Trial method.

with sensitivity 0.77 and specificity 0.94 for 70 to 99% stenosis and sensitivity of 0.67 and specificity of 0.79 for 50 to 69% stenosis.[13] On the contrary, a recent study with dual source CT showed a sensitivity of 0.93 and a specificity of 0.94.[16]

Advantages

Wide availability of CT with the possibility of performing brain CT and CTA of carotid arteries anytime of the day. Acquisition of CT images is also faster than other methods and examination is relatively operator independent.

Disadvantages

Main disadvantages are the use of iodine contrast medium intravenously and radiation. Therefore, impaired renal function is a relative contraindication for its use. CT can detect small, calcified changes better than DSA or magnetic resonance imaging can; however, extensive calcification can reduce accuracy. Also, artifacts from dental amalgam and from highly concentrated contrast in the brachiocephalic vein can hinder assessment of the lumen. CTA can show intraluminal thrombus and also allows assessment of the plaque ulceration.

Although noncontrast-enhanced CT (NECT) can detect calcified plaques in carotid arteries, it is not routinely used for this purpose. On the contrary, NECT is routinely used for evaluation of ischemic changes in the brain and in an emergency setting also to distinguish between ischemic and hemorrhagic stroke. Thrombus in intracranial arteries may be visible in cases of acute ischemic stroke. CT brain perfusion is not usually used for extracranial internal carotid stenosis evaluation but can be used for detection of reversible ischemia in the case of acute stroke.[17]

Magnetic Resonance Angiography

MRA is used for direct visualization of stenosis with magnetic resonance imaging. This could be done as time-of-flight MRA

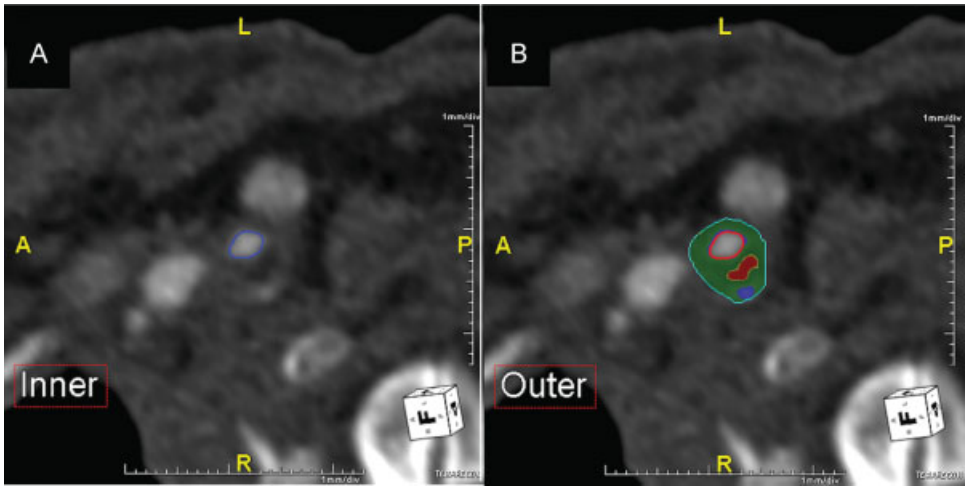

Fig. 5 Computed tomography angiography cross-sectional images perpendicular to the longitudinal axis of the internal carotid artery with plaque analysis. (A) Source image. (B) Same image with superimposed color map based on density; red represents lipid core, green fibrous tissue, and blue calcifications.

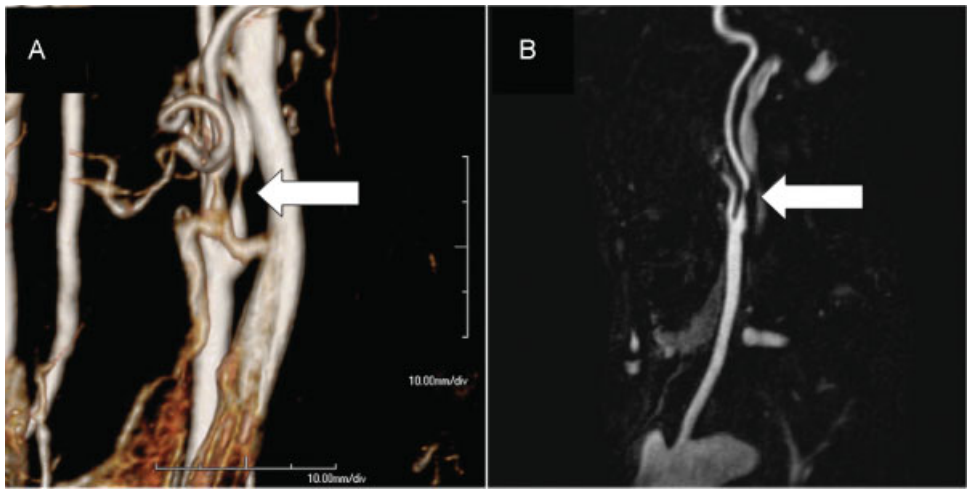

Fig. 6 Contrast-enhanced magnetic resonance angiography with the internal carotid artery stenosis more than 70% (arrow). (A) Volume rendering technique, and (B) maximum intensity projection reconstructions.

(TOF–MRA) without contrast and using physical features of flowing blood or as contrast-enhanced MRA (CE–MRA) using intravenously administered gadolinium contrast agent. Stenosis is measured using the NACSET or ESCT method. MRA is not sensitive to calcification and contrary to that in CTA even extensive calcifications do not cause difficulties in stenosis evaluation (►**Fig. 6**). CE–MRA is superior to TOF–MRA, because TOF–MRA is more sensitive to artifacts and could overestimate stenosis. According to the meta-analysis from 2006, the sensitivity of CE–MRA is 0.94 and specificity is 0.93 for stenosis of 70 to 90%, and 0.77 and 0.97, respectively, for stenosis of 50 to 69%. Sensitivity and specificity of TOF–MRA are lower than that for CE–MRA.[13] Despite MR technology development in the recent years, CE–MRA seems to still be superior to TOF–MRA.[18]

Advantages

MRA produces a reproducible three-dimensional image of the carotid bifurcation with good sensitivity for detecting high-grade carotid stenosis. Compared with carotid DUS, MRA is less operator dependent and does produce an image of the whole artery. There is no radiation in comparison to DSA and CT.

Disadvantages

MRA is more expensive than carotid DUS and CTA and is also less readily available. MRA may not be performed if the patient is unable to lie supine, or has claustrophobia, or has a pacemaker or ferromagnetic implants.

Other MRI sequences could be used for depiction of the vessel wall. Fat-saturated T1-weighted images are used for dissection detection. Velocity-encoded sequences can be used for flow measurement in carotid arteries.

MRI is very sensitive for detection of changes in the brain parenchyma. Diffusion-weighted imaging sequences detect hyperacute ischemia with a low number of false-negative investigations.[19] Mismatch between MRI brain diffusion and perfusion is a good approximation of the penumbra (ischemic but still viable tissue).[20] Perfusion MRI of the brain shows changes also in carotid stenosis but the clinical implication is not clear.[21,22]

Table 2 Comparison of methods for stenosis evaluation

	DSA	CE-MRA	CTA	DUS
Stenosis assessment accuracy	Gold standard	Sensitivity 0.94 Specificity 0.93	Sensitivity 0.77 Specificity 0.94	Sensitivity 0.89 Specificity 0.84
Stenosis morphology	Excellent	Good	Good	Limited
Plaque composition	Limited	Additional sequences needed	Good	Good
Aortic arch visibility	Good	Good	Good	Limited
Intracranial circulation	Good	Good	Good	Additional transcranial Doppler US needed
Invasiveness	Yes	Minimal	Minimal	No
Radiation	Yes	No	Yes	No
Contrast agent	Yes	Yes	Yes	No

Abbreviations: CTA, computed tomography angiography; DSA, digital subtraction angiography; DUS, duplex ultrasound.
Note: Sensitivity and specificity is for 70 to 90% stenosis and based on the meta-analysis from Wardlaw et al.[13]

Choice of Imaging Method

The choice among the carotid artery imaging methods depends mainly on the clinical indications for imaging and the availability and expertise at individual centers. To improve the accuracy of the diagnosis, the use of two-imaging modalities before revascularization is suggested.[23] Comparison of methods is in ►**Table 2**. The general approach to patients with suspected carotid stenosis is to first perform DUS. Patients with stenosis $<$ 50% are followed with serial examinations to determine whether disease progression has occurred. Patients with stenosis $\geq$ 50% should be evaluated with transcranial Doppler, MRA, or CTA.[24,25] Patients with a high pretest probability of disease may be studied initially by MRA or CTA to more completely evaluate intrathoracic or intracranial lesions. The advantage of CTA and MRA include the simultaneous imaging of the aortic arch, the common and internal carotid arteries in their totality, the intracranial circulation, as well as the brain parenchyma. Patients poorly suited to MRA, because of claustrophobia, implanted device, or other factors, may be evaluated by CTA, whereas those with extensive calcification should undergo MRA.[26] Conventional angiography is usually reserved for patients when noninvasive imaging studies have yielded discordant results or in the case of poor quality of the noninvasive imaging.[23]

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