Atherosclerotic Vascular Disease Conference

Writing Group IV: Imaging

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The goals of the imaging writing group were to define the role of imaging and to recommend important programmatic research and advocacy initiatives in atherosclerotic peripheral vascular disease for the American Heart Association. It should be noted that this is not a practice guideline initiative; therefore, the writing group purposely avoided recommending imaging modalities for specific circulatory beds.

This report discusses the following imaging modalities: duplex ultrasound, MRI and MR angiography (MRA), CT imaging and angiography (CTA), and digital intra-arterial angiography. The requirements for proficiency in all of these modalities include physician oversight, quality assurance programs, and standardization for acquisition of images, interpretation of the study, postprocessing procedures, workstations, and reporting. The roles of imaging for each modality such as screening for subclinical disease, diagnosis, and treatment planning as an adjunct to invasive therapies (interventional MR and CT) and follow-up and monitoring are reviewed.

Duplex Ultrasound

Ultrasound is the use of sound waves with frequencies above those heard by the human ear [typically >20 000 cycles per second (Hz)]. Commercially available ultrasound units generate frequencies of 2 to 10 million cycles per second (MHz). When electronic voltage is transmitted to an oscillator within an ultrasound transducer, a crystal vibrates and emits an ultrasound beam with a defined frequency ranging from 2 to 15 MHz. The ultrasound beam hits various targets in its path (ie, soft tissue, bone, and flowing blood) and is reflected back to the crystal.

The ultrasound units available today use B-mode ("brightness") technology to provide a real-time, gray-scale image. B-mode provides the operator with a "live" image of the blood vessel that is updated several times per second. High-frequency transducers (ie, 10 to 15 MHz) provide excellent image resolution in the superficial structures; however, the beam attenuates rapidly as depth increases. Such high-frequency transducers are used to image extracranial carotid arteries, in arterial and venous mapping studies, and to clearly delineate plaque morphology. Low-frequency transducers (ie, 2 to 4 MHz) are better able to visualize deeper structures while sacrificing image resolution. Low-frequency transducers are used for abdominal imaging such as the renal arteries, abdominal aorta, and mesenteric arteries and veins.

The term "duplex" ultrasound refers to B-mode real-time imaging and pulsed Doppler analysis of the velocity of flowing blood in arteries and veins. Christian Doppler described the physics of ultrasound by identifying the Doppler shift.[1] The velocity of blood in vessels can be measured using the variables of velocity of flowing blood, velocity of sound in tissue, the difference between frequency of transmitted and reflected sound, and the cosine of the angle of the ultrasound beam to the direction of flowing blood. This is the basis for all vascular ultrasonography, thus allowing quantification of degree of stenosis; as an artery narrows, blood flow velocity increases.

Screening for Subclinical Disease

There are 4 major areas in which screening for subclinical disease may have applications in the noninvasive vascular laboratory. Measuring the ankle-brachial index with a handheld continuous-wave Doppler instrument is an accurate way to diagnose patients with peripheral arterial disease (PAD). In the Peripheral Arterial Disease, Awareness, Risk and Treatment: New Resources for Survival (PARTNERS) study,[2] patients >70 years of age and those 50 to 69 years of age with

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a 10–pack-year history of smoking or diabetes mellitus were screened by ankle-brachial index. The study demonstrated that 29% of 6979 patients had PAD, and many of these did not have symptoms. It is important to identify patients with PAD because they have a high rate of morbidity and mortality from myocardial infarction and stroke[3] and can be placed in an appropriate risk factor modification program.

Duplex ultrasound may be used to screen the carotid arteries to measure the thickness of the intima and compare it with the thickness of the media (intima-media thickness). As intima-media thickness increases, cardiovascular event rates increase.[4]

Duplex ultrasound may also be used to measure brachial artery reactivity (an indicator of endothelial function or dysfunction). The diameter of the brachial artery is measured at rest, and a blood pressure cuff is then placed on the forearm or upper arm and inflated to suprasystolic pressures for 5 minutes to render the arm ischemic. When the cuff is released, reactive hyperemia should be present, as should an increase in brachial artery size and flow, indicating normal endothelial function.[5]

Finally, duplex ultrasound may be used to screen for the presence of abdominal aortic aneurysm (AAA) in first-degree relatives of patients with AAA. In the Multicenter Aneurysm Screening Study (MASS), 27 147 (80%) of 33 839 men 65 to 74 years of age underwent screening. During ultrasound screening, 1333 aneurysms were detected. Sixty-five aneurysm-related deaths (absolute risk, 0.19%) occurred in the screened group, and 113 aneurysm-related deaths (0.33%) occurred in the control group (risk reduction, 42%; $P=0.0002$).[6] Because up to 20% of first-degree relatives of persons with AAA have AAA themselves, ultrasound is a useful screening test in these persons, starting at 50 years of age.[6]

Duplex Ultrasound for Diagnosis, Treatment, and Follow-Up Monitoring

Arterial duplex ultrasonography provides an in-depth “road map” of the arteries of the upper and lower extremities. Vessels are classified into 1 of 5 categories: normal, 1% to 19% stenosis, 20% to 49% stenosis, 50% to 99% stenosis, and occlusion. The categories are determined by alterations in the Doppler waveform and increasing peak systolic velocities.[7] Identification of the location and extent of stenosis or occlusion allows the clinician to determine the best therapy (ie, percutaneous transluminal angioplasty, stent, or surgery).[8] The sensitivity of duplex ultrasonography in detecting occlusions and stenoses has been reported to be 95% and 92%, with specificities of 99% and 97%, respectively.[9] Duplex ultrasound has also been used after endovascular therapy to determine technical success[10] and durability of the procedure.[11]

A well-organized graft surveillance program is crucial for preserving patency of the bypass graft.[12] In 1 series of 170 saphenous vein bypass grafts, 110 stenoses were detected over a 39-month period. Four-year patency was 88% in those grafts that underwent surgical revision after a stenosis was detected. Four-year patency was 57% in grafts that did not undergo revision despite detection of stenosis.[13,14] Similar surveillance programs should be instituted after angioplasty or stenting of peripheral arteries.

Direct visualization of the extracranial carotid and vertebral arteries with duplex ultrasonography provides excellent accuracy and reproducibility. The carotid duplex examination identifies plaque,[15] stenoses, and occlusions in the common, internal, and external carotid arteries. The examination also identifies flow direction in the vertebral arteries.

Velocity measurements are used to determine categories of stenosis on the basis of many validation studies that compared duplex-derived velocity data with catheter angiography. Patients are placed in broad categories based on peak systolic velocity, end-diastolic velocity, and ratio of internal carotid artery to common carotid artery (0% to 19%, 20% to 39%, 40% to 59%, 60% to 79%, and 80% to 99%). Early comparative data demonstrated 97% accuracy of duplex scanning compared with arteriography.[16] Duplex ultrasonography is highly accurate in identifying carotid artery occlusion, with a positive predictive value of 92.5%,[17] and is very useful in documenting the results of revascularization.[18] Vascular laboratories must validate their own accuracy, however, to avoid potential errors in performing these exams.

Renal artery duplex ultrasonography has proved to be a useful diagnostic tool that can accurately diagnose renal artery stenosis and exclude it in patients without disease.[19,20] Peak systolic velocity is obtained in the aorta at the level of the superior mesenteric artery. The entire renal artery from the ostium to the hilum of the kidney must undergo Doppler interrogation. A renal-to-aortic ratio $\geq$3.5 and peak systolic velocity $>$200 cm/s correspond with a stenosis of 60% to 99%. In a prospective series of 102 consecutive patients who underwent both duplex ultrasonography and contrast arteriography within 1 month of each procedure, sensitivity of duplex ultrasonography was 98%, specificity was 99%, positive predictive value was 99%, and negative predictive value was 97%.[21]

Duplex ultrasonography of the renal arteries may also be useful for predicting which patients will demonstrate improved blood pressure control or renal function after surgical or endovascular revascularization. If resistance within the renal circulation (as measured by the resistive index) is $>$80, the chance of improvement is quite small.[22]

Duplex ultrasonography is ideal for determining the adequacy of renal artery stent revascularization. The entire renal artery can be imaged despite the presence of a metallic endoprosthesis. Patients who have undergone percutaneous renal revascularization should be placed in a surveillance program at 6 months, 1 year, and each year thereafter.

Duplex ultrasound of the renal arteries has limitations. The technique has a steep learning curve and requires expertise and patience; it is often difficult to perform in obese persons; and sensitivity and specificity of identifying accessory renal arteries is only $\approx$60%.[23]

Ultrasound is an ideal test for detection of abdominal and peripheral artery aneurysms.[6] After an overnight fast, the patient is studied in the supine position. The aorta is identified at the level of the diaphragm in the sagittal plane throughout its length. The ultrasound probe is then reoriented in the transverse view, and measurements are obtained in the suprarenal, juxtarenal, and infrarenal positions. The iliac arteries should also be evaluated during this examination.

Duplex ultrasound has proved to be useful for diagnosing vascular complications such as pseudoaneurysm, hematoma, and arterial venous fistula after arterial access (postcardiac or peripheral catheterization). A pseudoaneurysm represents a persistent defect in the walls of the artery, resulting in extravasation of blood outside the artery (contained rupture). The treatment of choice is ultrasound-guided thrombin injection. This procedure is highly effective, rapid, and safe. In a prospective series of 70 patients, complete obliteration of the pseudoaneurysm occurred in 66 of patients (94%) with no complications.[24]

MR Angiography

MRA of the aorta and peripheral vasculature can be performed rapidly with excellent image quality. MRA has 2 fundamental advantages: Contrast agents for MRA lack renal toxicity, and images are obtained without the use of ionizing radiation.

Noncontrast MRA can be performed with "time of flight" methods. In this method, background tissue is suppressed while the in-flowing blood signal is bright on MRA imaging. With this technique, either the arterial or venous signal can be selectively visualized by saturating blood in the unwanted vascular territory before it moves into the cross-sectional imaging slice. Time-of-flight MRA is a time-consuming technique that is susceptible to flow-related signal loss. The primary applications of time-of-flight MRA are venous imaging and as a supplement to other arterial sequences, as discussed in the next section.

Contrast-enhanced 3D MRA is a newer technique for acquiring noninvasive angiogram-like images.[25–27] In many practices, this method has become the standard because of improved speed of acquisition, excellent image quality, and robustness of the method. Contrast-enhanced 3D MRA uses an injected gadolinium-based contrast medium followed by rapid 3D MRI. Contrast-enhanced MRA is performed with fast 3D spoiled gradient-echo recalled pulse sequences. These pulse sequences are available primarily at higher magnetic field strengths (1.0 or 1.5 T). Imaging is usually performed in the coronal plane with a field of view of ≈40 cm. Images are obtained during breathholding and require ≈20 seconds. When multiple areas of the body are examined, multiple 20-second acquisitions are used. For example, for an aortogram and peripheral runoff, 3 MRA volumes are obtained: the abdomen, thighs, and calves. Because hundreds of images are acquired, 3D image processing is subsequently performed to project vessels in views of high diagnostic interest.

Advanced MR methods use techniques such as partial k-space sampling, rectangular field of view, and real-time fluoroscopic imaging to improve image quality. Additional slices can be acquired in the slice select direction by interpolating between adjacent acquired slices to improve the "smoothness" of the reconstructed 3D images.

MRA for Subclinical Disease

Currently, the only indication for screening for asymptomatic disease is to search for the presence of aneurysms, for example, in patients with a history of Marfan syndrome or inflammatory vascular diseases such as Takayasu's arteritis and giant cell arteritis. When techniques of identifying the vulnerable plaque improve, MR screening may become more widely applied.

MRA for Diagnosis, Treatment, and Follow-Up Monitoring

For the aorta, contrast-enhanced MRA images are readily reformatted to provide information about the cross-sectional size of aortic aneurysm, extent and origin of aortic dissection, and branch vessel involvement.

Patients with intramural hematoma of the thoracic aorta without intimal tear present similarly to those with typical aortic dissection.[28,29] However, T1-weighted images reveal a crescent-shaped area within the aortic wall instead of a distinct intimal flap. The signal intensity of the intramural hemorrhage is variable, presumably depending on its age. The signal intensity is often medium to low, which may make it difficult to distinguish intramural hematoma from mural thrombus or even slow flow on T1-weighted images. Cine images of the aorta offer rapid interrogation of multiple sites along the aorta, and cine images demonstrate an absence of cyclical changes in signal intensity within the intramural hematoma.

Abdominal MRA is increasingly being used to evaluate the abdominal aorta and its branches, particularly the renal arteries. MRA has a sensitivity of 91% to 100% and a specificity of 71% to 100%.[30–38] However, MRA is not useful for monitoring patients after renal artery angioplasty and stenting because of artifact produced by the stent.

The quality of MRA is so good that it has virtually replaced diagnostic angiography for evaluating patients with PAD to determine what type of intervention is most appropriate. The success of MRA in identifying small runoff vessels meets or exceeds that of traditional catheter-based angiography.[39]

MRA of the thigh and iliac vessels is commonly performed with the 3D contrast-enhanced method. A "bolus-chase" technique is used, which substantially reduces examination times relative to time-of-flight methods.[40] Bolus-chase MRA involves manual or automated translation of the patient after a moderate, sustained infusion of gadolinium contrast agent via peripheral vein. The success of MRA for demonstrating clinically significant stenoses of the iliac and femoral vessels is excellent.[41]

In addition to detecting stenosis or occlusion of an artery, MRI can be used to assess the vessel wall directly for early atherosclerotic changes.[42,43] In vivo studies have shown that MRI can distinguish among a variety of lipid mixtures typically found in human plaque.[44,45] T2-weighted MRI sequences offer good contrast for distinguishing plaque components and interrogating the vessel wall.[46] Serfaty et al[47] tested the ability of T2-weighted MRI alone for determining fibrous cap thickness and lipid core volume. Shinnar et al[48] reported very high sensitivities and specificities of MRI in detecting various plaque components.

The use of MRI for a variety of interventional procedures has been motivated by the superior soft tissue contrast it affords. Compared with x-ray imaging, MR guidance of devices is in its early stages, and the MR process of image acquisition itself is relatively slow. Potential reasons for using MRI are improved soft tissue visualization, novel vessel wall interventions (gene or other therapeutic methods related to the vessel wall), and lack of radiation exposure.

A wide variety of interventional cardiovascular applications have been carried out in animal models, including percutaneous angioplasty, transjugular intrahepatic portosystemic shunt procedures, stent placement, and embolization procedures.[49–54] One approach has been to combine 3D MRA techniques as road maps for catheter manipulation, particularly in the peripheral vessels and carotid arteries. Current intracoronary imaging may not be suitable for this approach, however, because of cardiac motion during the relatively long acquisition times for 3D MRA.

Few peer-reviewed studies of human intravascular MRI have been published to date. Manke et al[55] conducted a feasibility study to assess the potential application of vascular stent placement using MR guidance. Eleven of 12 stents were found to be correctly placed.

CT Angiography

CTA is a vascular imaging technique that can be performed rapidly and safely for assessment of many vascular diseases. With the advent of multidetector-row CTA, excellent image quality is now possible with higher resolution than could be obtained previously with single-detector-row technology. Current multidetector-row scanners acquire up to 16 simultaneous interweaving helices; 32-row and flat-panel scanners are in development. CTA has several advantages over conventional angiography, including volumetric acquisition, which permits visualization of the anatomy from multiple angles and in multiple planes after a single acquisition; improved visualization of soft tissues and other adjacent anatomic structures; less invasiveness and thus fewer complications; and lower cost.[56,57] CTA has several advantages over MRA, including wider availability of scanners, higher spatial resolution, absence of flow-related phenomena that may distort MRA images, and the capability to visualize calcification and metallic implants such as endovascular stents or stent grafts. The disadvantages of CTA compared with MRA are exposure to ionizing radiation and the need for potentially nephrotoxic iodinated contrast.

Current Techniques in CTA

Rapid CTA acquisition of images is critical because the images are obtained during the arterial phase of an intravenous contrast injection. The multidetector-row CTA has an increased speed of acquisition with concomitant faster table feed and shorter exposure times.[56] These features allow greater longitudinal coverage for a given scan duration and greater spatial resolution (ie, imaging the thoracoabdominal, aortoiliac, and lower extremities), which may require up to 1400 mm of coverage. More rapid acquisition also allows a reduction in the amount of iodinated contrast material needed without significantly affecting the degree of arterial enhancement. Moreover, rapid acquisition permits more uniform vascular enhancement, thin-section scans of large anatomic territories during a single breathhold, improved visualization of small branch vessels and calcified plaque, and decreased pulsation-related artifacts.[56–58]

Injection protocols and precise scanning parameters vary, depending on the clinical application. Generally speaking, however, nonionic iodinated contrast medium is used in concentrations of ≥300 mg iodine/mL, with the dose typically determined on the basis of the patient's weight (usually 2 mg iodine/kg).[56]

The initial image output from all CT scans consists of sets of contiguous or overlapping transverse cross sections. These are always formally interpreted in the same manner as any CT scan, with full attention given to all nonvascular structures, including bones, bowel, visceral organs, and lungs. To create angiographic representations, postprocessing of the volumetric data is necessary. The best postprocessed images are created from overlapping images, usually 50% to 80%. In the absence of overlap, the angiographic images may have a marked stair-step appearance.

Four techniques from the workstation postprocessing of CT data may be used: multiplanar reformation, maximum intensity projection, shaded surface display, and volumetric rendering. Each of these techniques has advantages and disadvantages, depending on clinical application, anatomic area of interest, and image acquisition technique used.[59,60] Used individually or in concert, these techniques allow manipulation of raw data to optimize visualization of relevant lesions or disease processes. An important common pitfall is the selective visualization of the maximally opacified vascular lumen. Both automated creation and manual creation of postprocessed images risk inadvertent rejection of critical vascular and nonvascular information. Postprocessed images alone should not be used for interpretation of CTAs.

Screening for Asymptomatic Disease

The same screening applications advocated for MRA can be used for CTA (see above). No studies to date support widespread use of "whole-body" CT scans to detect asymptomatic disease.

Clinical Applications

Occlusive Disease of the Extracranial Carotid Arteries

Multiple investigators have demonstrated the high degree of accuracy of CTA compared with the "gold standard" of conventional arteriography.[61–64] The accuracy of CTA compared with MRA has been studied extensively.[64–66] The relative inability of CTA to assess hemodynamics is a disadvantage of this technique compared with conventional angiography.[66]

Carotid artery CTA has a sensitivity of 65% to 100% and a specificity of 88% to 100% for atherosclerotic stenosis.[61–66] The percentage ranges represent differences in level of lesions, degree of stenosis, and postprocessing techniques used for image reconstruction.

CTA of the Thoracic Aorta

Indications for imaging of the thoracic aorta with CTA include aneurysm, dissection, penetrating aortic ulcers, intramural hematoma, and trauma. CTA has largely replaced conventional angiography in the initial evaluation of patients

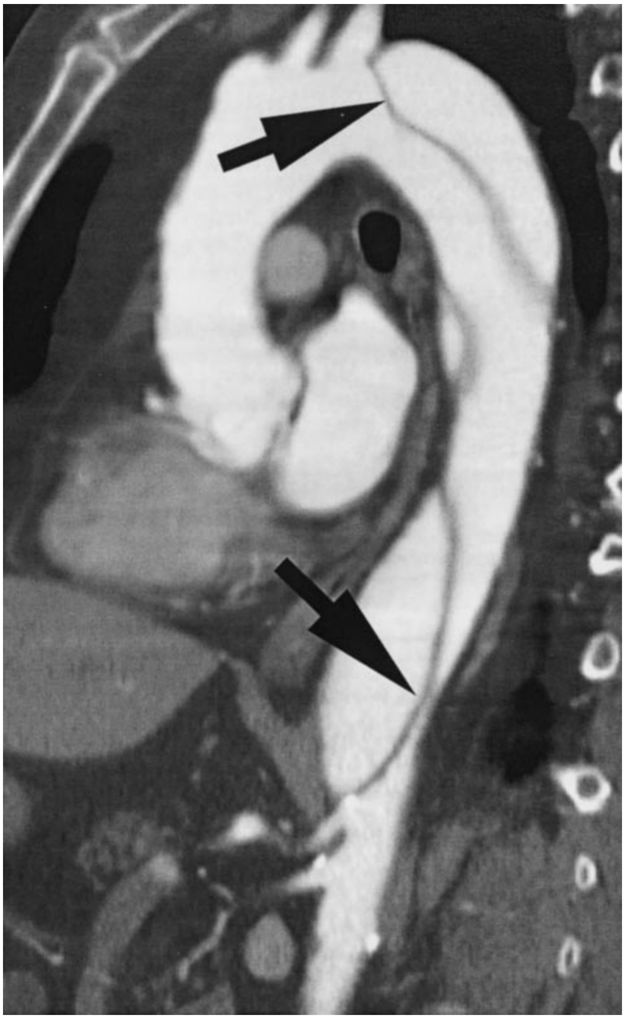

Figure 1. Reformatted oblique sagittal CTA of chest showing spiraling type B thoracic aortic dissection (arrows).

Figure 2. Volume rendering of abdominal CTA showing superior mesenteric artery (SMA) occlusion (arrow) with reconstitution of SMA via arc of Riolan (arrowhead).

with suspected acute thoracic aortic pathology.[67,68] One major advantage of CTA in this setting is the ability to accurately evaluate the surrounding structures within the thorax for pathology that may provide alternative explanations for the patient's symptoms, which is particularly important in evaluation of the patient with chest trauma.

Thoracic aortic dissection, intramural hematoma, and penetrating ulcer are often present with overlapping symptoms. In addition to diagnosis, localization and characterization of the abnormality are essential for management. CT in general has proved highly sensitive and specific for these aortic diseases because the involved vessel is large and the abnormality tends to be pronounced (Figure 1). The most common entity, aortic dissection, has been subject to only 1 investigation using single-row helical CT with sensitivity and specificity values of 100% in that study.[69]

CTA of the Abdominal Aorta and Its Branches

Vascular diseases of the aorta and its branch vessels are more common and varied than in the thoracic aorta. Indications for imaging of the abdominal aorta include AAA, occlusive disease, aortic dissection, and follow-up of interventions such as stent placement and surgical bypass. CTA is essential in evaluation of patients with AAA, particularly in planning stent-graft procedures, because of the high accuracy of this technique in measuring vessel lengths, diameters, and angles, as well as assessing for occlusive disease and calcification.[70–74] After placement of stent grafts for AAA, CT/CTA is the most widely used imaging modality for follow-up. Aneurysm size, volume, persistent perfusion, endograft patency, and status of adjacent aorta and branch vessels can be evaluated. Persistent sac perfusion, or endoleak, can be accurately identified, especially when a delayed (90 to 120 seconds after injection) scan is obtained in addition to the arterial phase acquisition.

Additionally, CTA evaluation of the abdominal aorta and its branches is increasingly accepted in place of conventional arteriography for other clinical applications such as imaging of the renal arteries for renal artery stenosis or prospective renal donors and evaluation of anatomic variants in conjunction with uretopelvic obstruction.[75–81] Sensitivity of CTA for renal artery stenosis ranges from 89% to 100%, and its specificity ranges from 82% to 100%.[75,78–81] MRA or duplex ultrasound may be the preferred imaging modality in patients with impaired renal function. Other accepted applications of CTA for visceral arteries are to evaluate hepatic arteries before transplantation and mesenteric arteries to exclude ischemia resulting from stenosis and to establish variant anatomy or collateral channels before organ resection (Figure 2).

Peripheral Arterial Disease

PAD is frequently multifocal; thus, lower-extremity arterial inflow and runoff should be imaged in their entirety. Before the advent of multidetector-row CT, limitations in scanning speed with single-detector row CT yielded insufficient spatial resolution of the lower-extremity inflow and runoff to adequately characterize occlusive and aneurysmal disease in arteries that may be only 2 to 3 mm in diameter and span a distance of >1 m.[82–87] Recently, however, the greater longitudinal coverage of multidetector-row CT has been successfully used in imaging the entirety of the lower-extremity inflow and runoff.[83,85] For arterial segments identified with conventional angiography, Rubin et al[83] found 100% concordance with CTA. Moreover, CT depicted 26 additional segments that could not be analyzed with conventional angiography because of improved arterial opacification distal to the occluded segments.[83] As 16-row (and greater) detector-row scanners become available, CTA will become generally accepted for evaluation of patients when visualization of distal calf and foot vessels is also critical.

Digital Subtraction Angiography

Vascular imaging with ultrasound, CTA, and MRA has or will soon replace catheter-based techniques in the initial diagnostic evaluation of patients in most circumstances. Angiography for diagnosis is reserved primarily for clarification of inadequate or conflicting results from physiological testing and cross-sectional vascular imaging. Despite a paradigm shift away from conventional angiography as a purely diagnostic technique, its importance in intervention has increased dramatically. Digital subtraction angiography (DSA) is a cornerstone technology in peripheral vascular intervention and will likely remain so for the foreseeable future.

In most institutions, DSA has replaced screen-film angiography for vascular applications. The resolution of DSA is less than that of screen film but can approach 3 to 4 line pairs per millimeter with current equipment. The standard imaging matrix is now 1024×1024, with image intensifiers that range up to 16 in. in diameter. Flat-panel image intensifiers will soon become available.

A number of major developments in DSA hardware and software contribute to greater diagnostic accuracy, faster procedures, and improved outcomes of interventions. Bolus chasing, rapid image acquisition, vessel diameter analysis, regional pixel shifting, image stacking, 3D reconstructions from rotational angiograms, and even angioscopic representations of DSA data are now routinely available.[87–91] Lower concentrations of iodinated contrast and nonephrotoxic and nonallergenic alternative contrast agents such as CO_2 and gadolinium chelates can be used with DSA.[92,93] The smaller diameter of catheters and devices, use of alternative access sites such as the radial artery, and access site management with closure devices and hemostatic agents have contributed greatly to the improved overall safety of angiographic procedures.[94–96]

The major attributes of DSA that contribute to its importance in vascular imaging are high resolution relative to current cross-sectional imaging techniques, the ability to selectively evaluate individual vessels, access to direct physiological information such as pressure gradients, and its use as a platform for intervention. Exposure to ionizing radiation, use of iodinated contrast agents, risks related to vascular access and catheterization, and cost restrict more general application. Nevertheless, until an alternative platform for intervention is developed or devices that are completely MR compatible become available, DSA will continue to have a central role in management of patients with vascular disease.

Recommendations

Research

The writing group identified several areas for future research:

- Plaque characteristics with cardiovascular outcomes.
- Use of contrast agents to speed time and increase accuracy of the study.
- Higher-resolution imaging and novel imaging techniques.
- Perfusion and function, along with general imaging, perhaps combining imaging with PET scanning to assess anatomic and functional aspects of disease.
- Application of better postprocessing technologies.
- Perhaps most importantly, appropriate use of screening for all of these modalities.

Specific research opportunities for a given imaging modality were also identified:

- Duplex ultrasound: More work in 3D ultrasound, use of hand-held ultrasound, and clinical applications of brachial artery reactivity or measurement of intima-media wall thickness.
- MR: Further study of metabolic and cellular imaging and the new field of interventional MR.
- CT scanning:
  - Flat-panel CT scanning, which will improve image quality even more and shorten time and contrast required to complete the study.
  - Interventional CT.
  - Use of whole-body CT to assess plaque distribution and type, calcium burden, and vascular road mapping.
  - Appropriate and cost-effective strategies for screening.

Advocacy Issues

A number of issues require a more comprehensive advocacy campaign in the field of imaging for atherosclerotic vascular disease. The National Institute of Biomedical Imaging and Bioengineering needs incremental funding to support investigation of noncardiac vascular disease. Reimbursement issues concern techniques that provide value to the overall care of the patient such as MRA of the renal arteries and aortoiliac arteries for occlusive disease. Industry should be encouraged to develop MRI-safe devices such as defibrillators, pacemakers, and stents.

References

1. Nelson TR, Pretorius DH. The Doppler signal: where does it come from and what does it mean? *AJR Am J Roentgenol*. 1988;151:439–447.
2. Hirsch AT, Criqui MH, Treat-Jacobson D, et al. Peripheral arterial disease detection, awareness, and treatment in primary care. *JAMA*. 2001;286:1317–1324.
3. Criqui MH, Langer RD, Fronek A, et al. Mortality over a period of 10 years in patients with peripheral arterial disease. *N Engl J Med*. 1992;326:381–386.
4. O'Leary DH, Polak JF, Kronmal RA, et al. Carotid-artery intima and media thickness as a risk factor for myocardial infarction and stroke in older adults: Cardiovascular Health Study Collaborative Research Group. *N Engl J Med*. 1999;340:14–22.
5. Corretti MC, Anderson TJ, Benjamin EJ, et al. Guidelines for the ultrasound assessment of endothelial-dependent flow-mediated vasodilation of the brachial artery: a report of the International Brachial Artery Reactivity Task Force [published correction appears in *J Am Coll Cardiol*. 2002;39:1082]. *J Am Coll Cardiol*. 2002;39:257–265.

6. Ashton HA, Buxton MJ, Day NE, et al. The Multicentre Aneurysm Screening Study (MASS) into the effect of abdominal aortic aneurysm screening on mortality in men: a randomised controlled trial. *Lancet*. 2002;360:1531–1539.
7. Kohler TR, Nance DR, Cramer MM, et al. Duplex scanning for diagnosis of aortoiliac and femoropopliteal disease: a prospective study. *Circulation*. 1987;76:1074–1080.
8. Elsman BH, Legemate DA, van der Heyden FW, et al. The use of color-coded duplex scanning in the selection of patients with lower extremity arterial disease for percutaneous transluminal angioplasty: a prospective study. *Cardiovasc Intervent Radiol*. 1996;19:313–316.
9. Whelan JF, Barry MH, Moir JD. Color flow Doppler ultrasonography: comparison with peripheral arteriography for the investigation of peripheral vascular disease. *J Clin Ultrasound*. 1992;20:369–374.
10. Silke CM, Grouden MC, Nicholls S, et al. Noninvasive follow-up of peripheral angioplasty: a prospective study. *J Vasc Technol*. 1997;21:23–25.
11. Mewissen MW, Kinney EV, Bandyk DF, et al. The role of duplex scanning versus angiography in predicting outcome after balloon angioplasty in the femoropopliteal artery. *J Vasc Surg*. 1992;15:860–865.
12. Bandyk DF. Ultrasonic duplex scanning in the evaluation of arterial grafts and dilatations. *Echocardiography*. 1987;4:251–264.
13. Mattos MA, van Bemmelen PS, Hodgson KJ, et al. Does correction of stenoses identified with color duplex scanning improve infrainguinal graft patency? *J Vasc Surg*. 1993;17:54–64.
14. Bandyk DF. Postoperative surveillance of infrainguinal bypass. *Surg Clin North Am*. 1990;70:71–85.
15. AbuRahma AF, Covelli MA, Robinson PA, et al. The role of carotid duplex ultrasound in evaluating plaque morphology: potential use in selecting patients for carotid stenting. *J Endovasc Surg*. 1999;6:59–65.
16. Fell G, Phillips DJ, Chikos PM, et al. Ultrasonic duplex scanning for disease of the carotid artery. *Circulation*. 1981;64:1191–1195.
17. Kirsch JD, Wagner LR, James EM, et al. Carotid artery occlusion: positive predictive value of duplex sonography compared with arteriography. *J Vasc Surg*. 1994;19:642–649.
18. Golledge J, Cuming R, Ellis M, et al. Duplex imaging findings predict stenosis after carotid endarterectomy. *J Vasc Surg*. 1997;26:43–48.
19. Taylor DC, Kettler MD, Moneta GL, et al. Duplex ultrasound scanning in the diagnosis of renal artery stenosis: a prospective evaluation. *J Vasc Surg*. 1988;7:363–369.
20. Strandness DE Jr. Duplex imaging for the detection of renal artery stenosis. *Am J Kidney Dis*. 1994;24:674–678.
21. Olin JW, Piedmonte MR, Young JR, et al. The utility of duplex ultrasound scanning of the renal arteries for diagnosing significant renal artery stenosis. *Ann Intern Med*. 1995;122:833–838.
22. Radermacher J, Chavan A, Bleck J, et al. Use of Doppler ultrasonography to predict the outcome of therapy for renal-artery stenosis. *N Engl J Med*. 2001;344:410–417.
23. Hansen KJ, Tribble RW, Reavis SW, et al. Renal duplex sonography: evaluation of clinical utility. *J Vasc Surg*. 1990;12:227–236.
24. LaPerna L, Olin JW, Goines D, et al. Ultrasound-guided thrombin injection for the treatment of postcatheterization pseudoaneurysms. *Circulation*. 2000;102:2391–2395.
25. Earls JP, Rofsky NM, DeCorato DR, et al. Breath-hold single-dose gadolinium-enhanced three-dimensional MR aortography: usefulness of a timing examination and MR power injector. *Radiology*. 1996;201:705–710.
26. Prince MR, Narasimham DL, Jacoby WT, et al. Three-dimensional gadolinium-enhanced MR angiography of the thoracic aorta. *AJR Am J Roentgenol*. 1996;166:1387–1397.
27. Prince MR. Body MR angiography with gadolinium contrast agents. *Magn Reson Imaging Clin N Am*. 1996;4:11–24.
28. Prince MR, Narasimham DL, Stanley JC, et al. Breath-hold gadolinium-enhanced MR angiography of the abdominal aorta and its major branches. *Radiology*. 1995;197:785–792.
29. Wolff KA, Herold CJ, Tempany CM, et al. Aortic dissection: atypical patterns seen at MR imaging. *Radiology*. 1991;181:489–495.
30. Snidow JJ, Johnson MS, Harris VJ, et al. Three-dimensional gadolinium-enhanced MR angiography for aortoiliac inflow assessment plus renal artery screening in a single breath hold. *Radiology*. 1996;198:725–732.
31. Steffens JC, Link J, Grassner J, et al. Contrast-enhanced, K-space-centered, breath-hold MR angiography of the renal arteries and the abdominal aorta. *J Magn Reson Imaging*. 1997;7:617–622.
32. Hany TF, Debatin JF, Leung DA, et al. Evaluation of the aortoiliac and renal arteries: comparison of breath-hold, contrast-enhanced, three-dimensional MR angiography with conventional catheter angiography. *Radiology*. 1997;204:357–362.
33. De Cobelli F, Vanzulli A, Sironi S, et al. Renal artery stenosis: evaluation with breath-hold, three-dimensional, dynamic, gadolinium-enhanced versus three-dimensional, phase-contrast MR angiography. *Radiology*. 1997;205:689–695.
34. Rieumont MJ, Kaufman JA, Geller SC, et al. Evaluation of renal artery stenosis with dynamic gadolinium-enhanced MR angiography. *AJR Am J Roentgenol*. 1997;169:39–44.
35. Bakker J, Beek FJ, Beutler JJ, et al. Renal artery stenosis and accessory renal arteries: accuracy of detection and visualization with gadolinium-enhanced breath-hold MR angiography. *Radiology*. 1998;207:497–504.
36. Schoenberg SO, Bock M, Knopp MV, et al. Renal arteries: optimization of three-dimensional gadolinium-enhanced MR angiography with bolus-timing-independent fast multiphase acquisition in a single breath hold. *Radiology*. 1999;211:667–679.
37. Hahn U, Miller S, Nagele T, et al. Renal MR angiography at 1.0 T: three-dimensional (3D) phase-contrast techniques versus gadolinium-enhanced 3D fast low-angle shot breath-hold imaging. *AJR Am J Roentgenol*. 1999;172:1501–1508.
38. Fain SB, King BF, Breen JF, et al. High-spatial-resolution contrast-enhanced MR angiography of the renal arteries: a prospective comparison with digital subtraction angiography. *Radiology*. 2001;218:481–490.
39. Grist TM. MRA of the abdominal aorta and lower extremities. *J Magn Reson Imaging*. 2000;11:32–43.
40. Earls JP, DeSena S, Bluemke DA. Gadolinium-enhanced three-dimensional MR angiography of the entire aorta and iliac arteries with dynamic manual table translation. *Radiology*. 1998;209:844–849.
41. Rofsky NM, Johnson G, Adelman MA, et al. Peripheral vascular disease evaluated with reduced-dose gadolinium-enhanced MR angiography. *Radiology*. 1997;205:163–169.
42. Wasserman BA, Smith WI, Trout HH 3rd, et al. Carotid artery atherosclerosis: in vivo morphologic characterization with gadolinium-enhanced double-oblique MR imaging initial results. *Radiology*. 2002;223:566–573.
43. Fernandez-Ortiz A, Badimon JJ, Falk E, et al. Characterization of the relative thrombogenicity of atherosclerotic plaque components: implications for consequences of plaque rupture. *J Am Coll Cardiol*. 1994;23:1562–1569.
44. Helft G, Worthley SG, Fuster V, et al. Atherosclerotic aortic component quantification by noninvasive magnetic resonance imaging: an in vivo study in rabbits. *J Am Coll Cardiol*. 2001;37:1149–1154.
45. Choudhury RP, Aguinaldo JG, Rong JX, et al. Atherosclerotic lesions in genetically modified mice quantified in vivo by non-invasive high-resolution magnetic resonance microscopy. *Atherosclerosis*. 2002;162:315–321.
46. Toussaint JF, Southern JF, Fuster V, et al. T2-weighted contrast for NMR characterization of human atherosclerosis. *Arterioscler Thromb Vasc Biol*. 1995;15:1533–1542.
47. Serfaty JM, Chaabane L, Tabib A, et al. Atherosclerotic plaques: classification and characterization with T2-weighted high-spatial-resolution MR imaging: an in vitro study. *Radiology*. 2001;219:403–410.
48. Shinnar M, Fallon JT, Wehrli S, et al. The diagnostic accuracy of ex vivo MRI for human atherosclerotic plaque characterization. *Arterioscler Thromb Vasc Biol*. 1999;19:2756–2761.
49. Adam G, Neuerburg J, Bucker A, et al. Interventional magnetic resonance: initial clinical experience with a 1.5-tesla magnetic resonance system combined with c-arm fluoroscopy. *Invest Radiol*. 1997;32:191–197.
50. Yang X, Bolster BD Jr, Kraitchman DL, et al. Intravascular MR-monitored balloon angioplasty: an in vivo feasibility study. *J Vasc Interv Radiol*. 1998;9:953–959.
51. Yang X, Atalar E, Li D, et al. Magnetic resonance imaging permits in vivo monitoring of catheter-based vascular gene delivery. *Circulation*. 2001;104:1588–1590.
52. Yang X, Atalar E. Intravascular MR imaging-guided balloon angioplasty with an MR imaging guide wire: feasibility study in rabbits. *Radiology*. 2000;217:501–506.
53. Buecker A, Neuerburg JM, Adam GB, et al. Real-time MR fluoroscopy for MR-guided iliac artery stent placement. *J Magn Reson Imaging*. 2000;12:616–622.
54. Kee ST, Rhee JS, Butts K, et al. 1999 Gary J. Becker Young Investigator Award: MR-guided transjugular portosystemic shunt placement in a swine model. *J Vasc Interv Radiol*. 1999;10:529–535.

55. Manke C, Nitz WR, Djavidani B, et al. MR imaging-guided stent placement in iliac arterial stenoses: a feasibility study. *Radiology*. 2001; 219:527–534.
56. Rubin GD. Techniques for performing multidetector-row computed tomographic angiography. *Tech Vasc Interv Radiol*. 2001;4:2–14.
57. Bluemke DA, Chambers TP. Spiral CT angiography: an alternative to conventional angiography. *Radiology*. 1995;195:317–319.
58. Rubin GD. Three-dimensional helical CT angiography. *Radiographics*. 1994;14:905–912.
59. Ibukuro K, Charnsangavej C, Chasen MH, et al. Helical CT angiography with multiplanar reformation: techniques and clinical applications. *Radiographics*. 1995;15:671–682.
60. Addis KA, Hopper KD, Iyriboz TA, et al. CT angiography: in vitro comparison of five reconstruction methods. *AJR Am J Roentgenol*. 2001; 177:1171–1176.
61. Marcus CD, Ladam-Marcus VJ, Bigot JL, et al. Carotid arterial stenosis: evaluation at CT angiography with the volume-rendering technique. *Radiology*. 1999;211:775–780.
62. Anderson GB, Ashforth R, Steinke DE, et al. CT angiography for the detection and characterization of carotid artery bifurcation disease. *Stroke*. 2000;31:2168–2174.
63. Randoux B, Marro B, Koskas F, et al. Carotid artery stenosis: prospective comparison of CT, three-dimensional gadolinium-enhanced MR, and conventional angiography. *Radiology*. 2001;220:179–185.
64. Patel SG, Collie DA, Wardlaw JM, et al. Outcome, observer reliability, and patient preferences if CTA, MRA, or Doppler ultrasound were used, individually or together, instead of digital subtraction angiography before carotid endarterectomy. *J Neurol Neurosurg Psychiatry*. 2002;73:21–28.
65. Magarelli N, Scarabino T, Simeone AL, et al. Carotid stenosis: a comparison between MR and spiral CT angiography. *Neuroradiology*. 1998; 40:367–373.
66. Sameshima T, Futami S, Morita Y, et al. Clinical usefulness of and problems with three-dimensional CT angiography for the evaluation of atherosclerotic stenosis of the carotid artery: comparison with conventional angiography, MRA, and ultrasound sonography. *Surg Neurol*. 1999;51:301–308.
67. Thorsen MK, San Dretto MA, Lawson TL, et al. Dissecting aortic aneurysms: accuracy of computed tomographic diagnosis. *Radiology*. 1983; 148:773–777.
68. Nienaber CA, von Kodolitsch Y, Nicolas V, et al. The diagnosis of thoracic aortic dissection by noninvasive imaging procedures. *N Engl J Med*. 1993;328:1–9.
69. Sommer T, Fehske W, Holzknecht N, et al. Aortic dissection: a comparative study of diagnosis with spiral CT, multiplanar transesophageal echocardiography, and MR imaging. *Radiology*. 1996;199:347–352.
70. Bromley PJ, Kaufman JA. Abdominal aortic aneurysms before and after endograft implantation: evaluation by computed tomography. *Tech Vasc Interv Radiol*. 2001;4:15–26.
71. Armerding MD, Rubin GD, Beaulieu CF, et al. Aortic aneurysmal disease: assessment of stent-graft treatment: CT versus conventional angiography. *Radiology*. 2000;215:138–146.
72. Qanadli SD, Mesurolle B, Coggia M, et al. Abdominal aortic aneurysm: pretherapy assessment with dual-slice helical CT angiography. *AJR Am J Roentgenol*. 2000;174:181–187.
73. Thurnher SA, Dorffner R, Thurnher MM, et al. Evaluation of abdominal aortic aneurysm for stent-graft placement: comparison of gadolinium-enhanced MR angiography versus helical CT angiography and digital subtraction angiography. *Radiology*. 1997;205:341–352.
74. Sawhney R, Kerlan RK, Wall SD, et al. Analysis of initial CT findings after endovascular repair of abdominal aortic aneurysm. *Radiology*. 2001; 220:157–160.
75. Rubin GD, Dake MD, Napel S, et al. Spiral CT of renal artery stenosis: comparison of three-dimensional rendering techniques. *Radiology*. 1994; 190:181–189.
76. Rubin GD, Alfrey EJ, Dake MD, et al. Assessment of living renal donors with spiral CT. *Radiology*. 1995;195:457–462.
77. Pozniak MA, Balison DJ, Lee FT Jr, et al. CT angiography of potential renal transplant donors. *Radiographics*. 1998;18:565–587.
78. Urban BA, Ratner LE, Fishman EK. Three-dimensional volume-rendered CT angiography of the renal arteries and veins: normal anatomy, variants, and clinical applications. *Radiographics*. 2001;21:373–386.
79. Beregi JP, Elkohen M, Deklunder G, et al. Helical CT angiography compared with arteriography in the detection of renal artery stenosis. *AJR Am J Roentgenol*. 1996;167:495–501.
80. Johnson PT, Halpern EJ, Kuszyk BS, et al. Renal artery stenosis: CT angiography: comparison of real-time volume-rendering and maximum intensity projection algorithms. *Radiology*. 1999;211:337–343.
81. Willmann JK, Wildermuth S, Pfammatter T, et al. Aortoiliac and renal arteries: prospective intraindividual comparison of contrast-enhanced three-dimensional MR angiography and multi-detector row CT angiography. *Radiology*. 2003;226:798–811.
82. Rubin GD, Shiau MC, Leung AN, et al. Aorta and iliac arteries: single versus multiple detector-row helical CT angiography. *Radiology*. 2000; 215:670–676.
83. Rubin GD, Schmidt AJ, Logan LJ, et al. Multi-detector row CT angiography of lower extremity arterial inflow and runoff: initial experience. *Radiology*. 2001;221:146–158.
84. Ofer A, Nitecki SS, Linn S, et al. Multidetector CT angiography of peripheral vascular disease: a prospective comparison with intraarterial digital subtraction angiography. *AJR Am J Roentgenol*. 2003;180: 719–724.
85. Katz DS, Hon M. CT angiography of the lower extremities and aortoiliac system with a multi-detector row helical CT scanner: promise of new opportunities fulfilled. *Radiology*. 2001;221:7–10.
86. Rieker O, Duber C, Neufang A, et al. CT angiography versus intraarterial digital subtraction angiography for assessment of aortoiliac occlusive disease. *AJR Am J Roentgenol*. 1997;169:1133–1138.
87. Bosanac Z, Miller RJ, Jain M. Rotational digital subtraction carotid angiography: technique and comparison with static digital subtraction angiography. *Clin Radiol*. 1998;53:682–687.
88. Seymour HR, Matson MB, Belli AM, et al. Rotational digital subtraction angiography of the renal arteries: technique and evaluation in the study of native and transplant renal arteries. *Br J Radiol*. 2001;74:134–141.
89. Unno N, Mitsuoka H, Takei Y, et al. Virtual angioscopy using 3-dimensional rotational digital subtraction angiography for endovascular assessment. *J Endovasc Ther*. 2002;9:529–534.
90. Meijering EH, Niessen WJ, Bakker J, et al. Reduction of patient motion artifacts in digital subtraction angiography: evaluation of a fast and fully automatic technique. *Radiology*. 2001;219:288–293.
91. Ashleigh RJ, Hufton AP, Razzaq R, et al. A comparison of bolus chasing and static digital subtraction arteriography in peripheral vascular disease. *Br J Radiol*. 2000;73:819–824.
92. Spinosa DJ, Kaufmann JA, Hartwell GD. Gadolinium chelates in angiography and interventional radiology: a useful alternative to iodinated contrast media for angiography. *Radiology*. 2002;223:319–325.
93. Oliva VL, Denbow N, Therasse E, et al. Digital subtraction angiography of the abdominal aorta and lower extremities: carbon dioxide versus iodinated contrast material. *J Vasc Interv Radiol*. 1999;10:723–731.
94. Iwasaki S, Yokoyama K, Takayama K, et al. The transradial approach for selective carotid and vertebral angiography. *Acta Radiol*. 2002;43: 549–555.
95. Leffers AM, Wagner A. Neurologic complications of cerebral angiography: a retrospective study of complication rate and patient risk factors. *Acta Radiol*. 2000;41:204–210.
96. Young N, Chi KK, Ajaka J, et al. Complications with outpatient angiography and interventional procedures. *Cardiovasc Intervent Radiol*. 2002;25:123–126.

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