Over the past decade, advances in vascular surgery and imaging of the vasculature have paralleled each other. For instance, in vascular surgery, a transition to more minimally invasive procedures has not only changed the treatment of isolated arterial stenoses, but impacted the treatment of aortic aneurysm repair and venous disorders as well. Numerous vascular operations are now performed either percutaneously or via small cutdown incisions, thus minimizing patient discomfort. As such, the categorized discipline of endovascular surgery has emerged. Similarly, through developments in arterial imaging, acquisition of arterial pathology requires less invasive procedures with fewer side effects from contrast agents, also decreasing potential patient risks. More frequently, diagnoses and treatment plans are formulated based on information acquired from computerized tomography (CT) scans, magnetic resonance imaging (MRI), and duplex scans, obviating the requirement of contrast angiography. This article reviews the recent advances in vascular imaging and discusses the role these innovations have in the management of patients with vascular disease.

Historic background

Contrast angiography

Successful intravascular contrast injection was initially reported in 1929 [1,2], and since that time radiopaque contrast angiography has become the “gold standard” for diagnostic vascular anatomic imaging. In fact, the breakthroughs in open vascular surgery and the birth and growth of
endovascular surgery can be directly attributed to the refinement and ongoing development of this form of diagnostic imaging.

One such technologic advancement was the development of digital subtraction angiography (DSA). DSA is a technique where the X-ray signals are electronically detected and digitized before display. Computer subtraction of less relevant background data from the image of interest is performed with the goal of enhancing the structure of interest. Logarithmic amplification of the X-ray signal can then be employed to further supplement the image or amplify small differences in density.

For contrast angiography to take place, access to the arterial tree must be established. Although several routes are available, the femoral approach, with infrainguinal femoral artery puncture, is the most commonly used technique. If the femoral vessels cannot be punctured or cannulated, alternative access vessels include the axillary or proximal brachial artery. It must be noted that axillary puncture may be more problematic due to the comparatively smaller vessel size surrounded by significant neurovascular structures; therefore, the potential for complications such as nerve trauma and hematoma may be increased. Although sparingly employed, direct translumbar abdominal aortic puncture is another alternative access vessel. Contraindications to translumbar puncture include the presence of a co-existing aortic aneurysm and periprocedural use of anticoagulation.

Minimally invasive modalities

Although radiopaque contrast angiography is the standard for diagnostic and interventional imaging, it is an invasive procedure that carries contrast-related risks, primarily anaphylaxis, and dose-related induction of renal toxicity. Although careful patient selection, hydration, and use of other renal protective techniques may decrease the risk of contrast related renal dysfunction, the risk is never nonexistent [3]. These risks are what have promoted the effort to develop less toxic contrast agents and search for alternate less invasive but effective imaging modalities.

Since 1990, the search for alternate, less invasive but effective modalities has led to more widespread use of CT and magnetic resonance (MR) technology to image the vascular system [4–6]. Although conventional CT has been in use for over 2 decades, the development and use of helical (spiral) CT coupled with computer-assisted three-dimensional reconstruction (CT angiography) has dramatically improved and expanded the utility of CT for vascular imaging, particularly for the abdominal aorta and visceral vessels [5,6]. Magnetic resonance angiography (MRA) has gained popularity in recent years for cerebrovascular and infrainguinal arterial imaging. Although he utility of MRA has previously been limited, the addition of three-dimensional reconstructive capability and gadolinium for contrast enhancement have helped to improve image resolution [4].
CT angiography

Multiplanar reconstruction of helical CT images, also termed CT angiography (Fig. 1), is a minimally invasive procedure performed with venous injection of radiopaque contrast and scanning through the anatomic region of interest as the contrast medium makes its initial pass through into the arterial bed of the desired region. The entire anatomic area of interest must be scanned while the contrast is in the arteries, before draining into the venous system. Although this technique requires the use of a contrast agent, the amount needed is less than for a conventional angiogram [5].

CT angiography has several advantages over conventional CT. Specifically, by decreasing the slice thickness (collimation) to 1 mm or less, the axial reconstruction format can be reduced, and reconstruction of the image can be accomplished in multiple planes [7,8]. Initially, CT images were represented as a two-dimensional image of three-dimensional structures. With CT angiography, reconstructions are now being recreated in three dimensions. The images can also be viewed in any plane to rapidly delineate anatomic and pathologic conditions [5,7]. Acquired images can be viewed in the following ways: maximum intensity projection, shaded surface display, and volume rendering. Also, the addition of color to the image may help to further delineate the anatomic details. The data can be manipulated on a computer workstation to electronically subtract structures, such as bones and overlapping anatomy, which may interfere with accurate image depiction and quality. Advancements in the software used for reconstruction and of the scanners have resulted in improved visual accuracy of

Fig. 1. CT angiogram of the abdominal aorta.
acquired images. In addition, there is ongoing research being performed to develop imaging systems that will display thrombus and calcified plaque as separate entities.

Currently, CT angiography occupies a very important place in endovascular surgery. This modality has positively impacted the treatment of abdominal aortic aneurysms (AAA) [5]. In fact, at many centers it has become the primary imaging tool used for the preoperative evaluation and planning of endovascular aneurysm repair (EVAR). CT has also been the primary postoperative surveillance tool for AAAs repaired with an endograft [5,7,8]. Recently, improvements in computer software and graphic workstations have allowed transformation of two-dimensional CT and MRI images into patient specific three-dimensional computer models. The leader in this innovative proprietary software has been Medical Media Systems (MMS) (West Lebanon, New Hampshire). MMS-generated images are able to not only distinguish thrombus from blood flow, but also delineate calcifications and provide accurate measurements of aneurysm volume, angles, and distances between specific anatomic structures (Figs. 2 and 3). Aziz et al compared the accuracy of the Preview MMS software to intravascular ultrasound (IVUS) and axial CT scans in the assessment of preoperative and postoperative anatomic characteristics in AAA [9]. No significant difference between measurements of aneurysms using Preview MMS software and axial CT scan was observed. Similar accuracy was noted when Preview MMS software was compared with IVUS for proximal aneurysm neck measurements, leading to the adoption of Preview MMS

Fig. 2. Anterior–posterior view of abdominal aortic aneurysm generated with Preview MMS software.
software for preoperative sizing of aortic endografts at the authors institution. Through collaboration with endovascular graft manufacturers, MMS has now created a stent-graft sizing component. Manufacturer Specific Virtual Graft (MSVG) allows physicians to construct virtual aortic grafts based on real-time measurements and determine product sizes, landing zones, and entry points.

The utility of CT angiography has also expanded into evaluation of infrainguinal arterial occlusive disease. With improvements in the resolution of the images, this modality may prove to be as effective as conventional angiography in the evaluation of lower extremity arterial occlusive disease [5,8].

In the past 5 years, improvement in CT scanners has resulted in quicker image acquisition times. A potential problem with improved scanning speed is that the scanners may scan faster than the contrast can travel. Also, although the dose of required contrast has lessened with the newer scanners, contrast enhancement continues to be necessary. However, the adverse effects of contrast use should be mitigated with development of less toxic agents and decreased dosing requirements of newer agents.

**Magnetic resonance angiography**

MRI is a noninvasive diagnostic technique that creates differential atomic signals in soft tissues via use of electromagnetic field energy. The use of MRI techniques to acquire arterial images results in MRA. MRA can detect blood flow without contrast enhancement. Herein lies a major advantage of
MRA: arterial image acquisition without arterial puncture or use of nephrotoxic contrast enhancement. Thus, MRA is potentially associated with reduced patient morbidity and decreased risk of complications usually associated with conventional contrast angiography [7,10].

The use of a paramagnetic contrast agent has added even greater value to MRA imaging. The most common currently used agent is gadolinium. Gadolinium is a nonnephrotoxic heavy metal analog that is administered intravenously as a bolus injection at a rate of 1.5 to 2 mL/s over 30 seconds. Gadolinium enhanced MRA results in reduction of flow artifacts and defects and enhanced image resolution [4,7]. When compared with contrast angiography, overall accuracy is improved with gadolinium enhancement. For instance, when compared with conventional angiography, MRA has a reported sensitivity that ranges from 75% to 100% for assessment of carotid artery stenosis [4]. However, Cosottini et al have shown that with contrast enhanced MRA, sensitivity for detection of carotid stenosis can be improved [11].

MRA is typically used for preoperative and postoperative imaging [4,7]. There is, however, ongoing research into other uses of MR technology for vascular imaging such as MRA for intraprocedural imaging, with real-time image acquisition. Another potential use of MR is transvenous evaluation of arterial wall lesions [12]. Through placement of an intravenous MR coil/guidewire, observers were able to detect architectural differences in arterial pathology in swine. Documentation of successful translation to human atherosclerotic lesions is in progress.

MRA is not commonly used for preoperative evaluation in patients undergoing EVAR. Limiting factors include poor imaging of calcified plaque, insufficient contrast between aortic lumen and thrombus or plaque, large extent of anatomy to be viewed, and poorer image resolution when compared with CT [7]. The potential for use of MRA in this setting may be realized in the not too distant future as more information is revealed with the use of gadolinium enhancement and improvements in imaging hardware and software.

More importantly, MRA has been used to image the visceral aortic, branches, especially the renal arteries (Fig. 4) [4,13–15]. With the introduction of gadolinium, MRA is rapidly supplanting the gold standard of contrast arteriography as the imaging modality of choice for examination of the renal arteries with a reported sensitivity of 91% or greater [14–16].

MRA has also been used for imaging the vessels of the lower extremity. MRA for preoperative evaluation in the planning of peripheral interventions, particularly in patients with renal insufficiency, has been a very significant use of this modality. In a prospective study, Cambria et al found that MRA compared favorably to contrast angiography in demonstration of infrainguinal anatomy. However, MRA did not assess inflow disease or tibial/pedal vessel anatomic detail as well as angiography [10]. Widespread usage of MRA is dependent on factors that need to be carefully evaluated.
These factors include institutional equipment and staff experience, diffuse multisegment disease, extensive infrapopliteal disease, and presence of artifacts. These limitations dictate that the choice of MRA to image the lower extremity vessels be made on a selective basis. As with MR in general, gadolinium enhancement may prove to expand the role of MRA for evaluation of lower extremity occlusive disease [4].

Use of MRA for the evaluation of occlusive disease in the extracranial carotid arteries has increased in the past decade, thus decreasing the reliance on conventional contrast angiography. However, in carotid disease, MRA is susceptible to flow artifacts with resultant inaccuracy of the acquired image, that is, tendency to overestimate stenoses [4,11]. For this reason, the exact role of MRA in the management of carotid disease, including carotid stenting, remains inconclusive. MRA is therefore usually combined with duplex ultrasonography to improve diagnostic accuracy in both symptomatic and asymptomatic carotid disease.

**Duplex ultrasonography**

Duplex ultrasonography combines two separate diagnostic modalities: a pulsed Doppler detector, and a real-time B-mode ultrasound image. This system was initially developed at the University of Washington in the 1970s, and since then, has become an integral tool in noninvasive imaging of arterial and venous systems. In the past decade application of duplex ultrasound has become the test of choice for evaluation of postprocedural success. For example, duplex ultrasound began replacing arteriograms for completion studies after vascular reconstructions. Similarly, duplex imaging has been effective for preoperative planning of lower extremity revascularization [17]. Use of duplex imaging has also extended into the realm endovascular surgery as an immediate postintervention evaluation tool to document areas of residual stenosis after angioplasty and for surveillance of aortic endografts to evaluate for endoleak (Fig. 5) [18–22]. The Endovascular Aneurysm Clinical Trial reviewed a number of the duplex studies and found that most did not meet the criteria to be considered
complete evaluation for endoleaks. Nonetheless, duplex scanning holds promise as a postoperative EVAR surveillance imaging modality particularly given that ultrasound contrast agents are being developed for image enhancement.

**Intravascular ultrasound**

Beginning in the 1990s, the clinical role of IVUS began to expand as technologic advancements in catheter design and image quality were achieved. The use of IVUS by endovascular specialists has been increasing rapidly as experience with this modality continues to grow. Application of IVUS to endovascular surgery has proven useful. IVUS images can outline the lumen of normal arterial segments, and can frequently differentiate normal from diseased vessel walls. Although IVUS can be used as an adjunct to preoperative imaging, it is particularly useful in the evaluation of endovascular interventions. After stent placement for occlusive disease, IVUS can be used to evaluate the vessel for areas of residual stenosis or inadequately deployed stents. Similarly, IVUS can demonstrate adequacy of stent to vessel wall approximation, the length of the seal zone proximally and distally, and evaluate the native vessels for intimal flaps and dissections [23,24]. Limitations to the widespread use of this technology include expense, problems with accurate measurement of vessel wall dimensions with currently available three-dimensional image reconstructions and successful application is operator dependent [7,24]. Hopefully, the role of IVUS will be enhanced by the development and incorporation of ultrasound contrast agents.
Venous imaging

For many years venous imaging has been practically limited to contrast venography, duplex ultrasonography, and CT, the principles of which are similar to those described for arterial imaging. However, MR represents a new modality for diagnostic imaging of venous disease, mainly lower extremity thromboembolic disease. Studies reported in the 1990s compared MR to contrast phlebography for the evaluation of deep venous thrombosis (DVT) found that there is a high sensitivity and specificity for the detection of DVT and that the addition of gadolinium helps to differentiate acute from chronic thrombus based on the decreased signal intensity of the venous wall with time [25]. Given the higher cost of this modality versus currently used techniques, it remains to be seen how the role of MR will be defined in the future.

Contrast agents

The role of contrast agents for imaging of the vascular tree is no longer limited to traditional radiopaque contrast angiography. The commonly used iodinated contrast agents of the past were associated with increased risk of renal dysfunction (up to 11% of patients with peripheral arterial disease) [26] and of hypersensitivity reactions (up to 25% of patients with contrast allergy history) [27]. Although careful planning, preparation and adjunctive techniques could decrease the risk, this risk is never completely nullified. To this end, other more benign agents have been sought for contrast enhancement. Current options for conventional angiography and CT scanning include high-osmolar ionic agents, low-osmolar ionic agents, low-osmolar ionic hybrids, and carbon dioxide gas (CO2) [28]. The preexisting medical condition of the patient is usually a strong determinant of which agent is used. Other factors include cost (nonionic agents are about 20 times more expensive than ionic agents) and the expected total volume to be used for the procedure.

CO2 gas as a contrast agent was initially described in 1982 by Hawkins [29]. Various technologic advancements have made CO2 a viable alternative for arterial imaging (Figs. 6 and 7) [30]. CO2 gas displaces intraluminal flowing blood thus producing an image by detection of the small existing difference in radiographic density between the gas and the surrounding soft tissue. Adverse reactions are rare when used with caution and only for visualization of abdominal and lower extremity arterial segments. Use of CO2 gas is contraindicated for carotid or upper extremity imaging due to concerns of uncertain neurotoxicity [28].

The introduction of gadolinium as a contrast agent has expanded the utility of MR for imaging of the vascular system. It is hoped that the introduction of ultrasound contrast agents will do the same for duplex imaging and IVUS. Currently, ultrasound contrast agents are being used
primarily for echocardiography, but it is expected to impact sonographic vascular imaging as well [31–34].

**Endovascular suite**

As endovascular therapy for vascular disorders becomes more integrated in the treatment plans of vascular surgeons, establishment of a facility for performance of both open and endovascular procedures would be essential.
As such, more hospitals are outfitting operating rooms with equipment capable of providing high-quality arterial imaging for performing endovascular procedures, while still retaining the requirements for open vascular operations.

Arterial imaging within the operating room can be obtained by two methods: portable C-arm units and fixed ceiling-mounted C-arm units. Inherent advantages and disadvantages are present with each system and issues such as cost, image quality, radiation exposure, and space should be considered when deciding which system to use.

Although portable C-arm units have the advantage of being able to be transported between multiple operating rooms and requiring no structural changes to the facility, portable units are deficient in image resolution, reliability, and dispense a higher amount of radiation exposure when compared with ceiling-mounted units [35]. Inferior image quality with portable units is due to the fact that they use smaller diameter image intensifiers than ceiling-mounted units. Also, because the distance between the image intensifier is fixed, the intensifier is unable to be positioned in close proximity to the patient; therefore, increasing radiation scatter and decreasing tissue penetration [36].

Because of the larger size image intensifier in the ceiling mounted units, image quality is superior when compared with portable units and by adjustment of the intensifier distance to the patient, tissue penetration can be improved with minimal radiation scatter [35]. Other advantages of the ceiling-mounted units include better reliability, more generator power, and less overheating with prolonged imaging [36]. One disadvantage to the ceiling-mounted unit is the cost. Although a portable C-arm unit can be purchased for close to $200,000, ceiling-mounted units can range up to 5 to 10 times that amount depending on the manufacturer and desired model options [35]. That does not include the cost of construction, protective shields, lighting units, monitors, and fluoroscopic tables.

Whether the unit is portable or ceiling mounted, fluoroscopic tables are a required article of the endovascular suite. The tables are available in movable or fixed configurations. Movable tables are completely controlled by the operator by having the control knobs attached to the table. As such, the operator is able to change the position of the table when desired. Movable tables are frequently outfitted in cardiology and interventional radiology suites. Fixed tables are attached to the ground at one end, allowing the C-arm unit to travel the length of the table to image the patient (Figs. 8 and 9). Although visualization of the imaging field is improved compared with movable tables, because of the structural support design, a patient weight limit is applied.

Besides the essential equipment of catheters, balloons, guidewires, and sheaths, a whole array stents, both covered and uncovered, are involved in furnishing an endovascular suite. Also, special consideration should also be given to the method and capacity of data storage.
Fig. 8. An endovascular operating room with a ceiling-mounted C-arm and a movable operating table.

Fig. 9. A modern endovascular operating room showing a floor-mounted operating table and a ceiling-mounted C-arm.
Summary

The improvement of vascular imaging has allowed the acquisition of vascular images with higher resolution while minimizing the risks and discomfort to patients. As imaging developments continue to progress, establishment of valid clinical-based evidence, before the application of each innovation, will assure maintenance of the current trend. Also, as the vascular surgeon adopts a more comprehensive approach in the care of vascular patients, a high-quality endovascular suite will provide an environment for integration of both traditional open and evolving endovascular procedures.

References


