Conferences and Reviews

Magnetic Resonance Imaging and Measurement of Blood Flow

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Blood flow can be shown as a negative image with magnetic resonance spin-echo techniques or as a positive image with gradient-echo techniques. Phase contrast refers to techniques where structures can be seen because of flow-induced phase shifts. These techniques can show the presence (slow flow) and also the direction of flow. Gradient-echo techniques—including phase-contrast versions—can be used with cardiac synchronization to obtain multiple images during the cardiac cycle. These images can be viewed in a movie or cine format to provide dynamic information about blood flow. Blood flow can be measured by using contrast media in boluses or even more elegantly with phase-contrast methods. Clinical applications of flow measurements are growing rapidly. Phase-contrast or gradient-echo techniques can be used to create magnetic resonance angiography, which was first used to study the carotid bifurcation and intracranial circulation and is now being used throughout the body.

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With magnetic resonance (MR) imaging, flow has inherently high contrast relative to static tissues. Magnetic resonance angiography allows the cardiovascular system to be visualized and allows the structure and patency of vessels to be evaluated. Furthermore, current techniques can delineate the direction and quantity of blood flow as well as flow patterns throughout the cardiac cycle.

We review the current clinical use of imaging and the measurement of blood flow with MR imaging.*

Spin-Echo Imaging

In simple terms, MR imaging produces images from protons (or hydrogen nuclei) within the body. These nuclei behave like small spinning magnets. The nuclei are excited by radio-frequency pulses, and signal is received as the excited state decays. Magnetic gradients allow for a single tomographic slice of tissue to be excited selectively and for an image to be taken at a given time.[1]

Magnetic resonance imaging has usually used spin-echo pulse sequences whereby each slice of tissue receives a 90-degree excitation pulse followed by a 180-degree refocusing pulse before a signal is received. Blood protons within that portion of blood vessel that is in the slice of tissue receiving the 90-degree excitation pulse continue to flow out of the tissue slice during the refocusing pulse and readout; therefore, the vessel lumen is represented by a lack of signal (a signal void) in contrast to surrounding soft tissue. Turbulence of the spinning protons also contributes to the loss of signal associated with blood flow in spin-echo imaging. Thus, blood vessels can be reliably evaluated for patency on traditional parenchymal images when a signal void is found. Other factors, such as slow flow, can lead to increased signal in the presence of flow on spin-echo imaging. In summary, on spin-echo images an intraluminal signal void indicates blood flow and vessel patency, but the presence of signal in the vessel does not exclude the presence of flow.[2]

Gradient-Echo Imaging

Faster MR imaging methods, referred to as gradient-echo techniques, have proved to be more valuable for obtaining images of blood flow. With gradient-echo techniques, there is only a single (lower-flip-angle) excitation pulse, followed by the signal readout. Magnetic gradients perform the refocusing function before a signal readout, making the image of blood flow bright, rather than using the 180-degree refocusing pulse seen in traditional spin-echo imaging, where the image of blood flow is black. With the gradient-echo techniques, this sequence of events is performed rapidly and repeatedly to produce an image representing a single slice of tissue. During these repeated excitations, protons within the static tissue in the slice of interest quickly reach a state of partial saturation or exci-

*See also the editorial by C. B. Higgins, MD, "Ebb and Flow of the Circulation," on pages 275-276.

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tation. Within a vessel lumen, blood protons from outside the slice are constantly flowing into the slice of interest. These flowing protons are fresh, or not partially saturated, and therefore produce more signal intensity than static tissues during a signal readout. With gradient-echo techniques, this flow-related enhancement effect is unopposed by the previously described factors that usually lead to signal loss for traditional spin-echo imaging.

Although gradient-echo techniques are sensitive to blood flow, they are subject to error. Very slow flow remains a limitation, and thrombosed blood passes through a subacute stage when it is bright on gradient-echo images. The combination of spin-echo and gradient-echo images will provide adequate evaluation for the presence of blood flow and vessel patency in most patients.

Phase-Contrast Imaging

Phase-contrast techniques, which are relatively new magnetic resonance techniques, are the most sensitive to flow and are the most useful for distinguishing between slow and absent flow. Phase-contrast methods exploit the fact that protons (spinning magnets) that move through magnetic field gradients obtain a different phase (or alignment of individual spins relative to one another) from static spins. With conventional MR imaging methods, these phase changes are not utilized. By keeping track of these phase changes, images with controlled sensitivity to flow can be produced. Furthermore, an additional set of images is obtained in which flow is encoded so that in one direction it is black and in the opposite direction it is white. The intensity of black or white is directly related to velocity. Thus, these imaging sets not only confirm flow (even slow flow) but also display its direction and magnitude.[3-5]

Cine Imaging

Both gradient-echo and phase-contrast techniques can be employed along with cardiac synchronization to provide images representative of several phases of the cardiac cycle. These can then be viewed in a movie, or cine, format.

Cine gradient-echo methods are useful for obtaining images of dynamic processes, such as a beating heart. They provide some information about the presence of flow due to inflow enhancement. This flow information is only qualitative, however, because the signal intensity of flowing fluid has a complicated dependence on multiple factors.

Phase-contrast cine magnetic resonance, which depicts motion and flow throughout the cardiac cycle, can be used to evaluate the presence, direction, and temporal dynamics of flow both qualitatively and quantitatively. The ability to characterize direction, pulsatility, and complexity of flow not only improves diagnostic accuracy but may provide unique insights into pathologic processes. Phase-contrast cine MR imaging is particularly useful in areas not easily accessible by Doppler methods or where the complex flow of a disease process may provide confusing data. For example, in a patient with aortic dissection, the velocity-dependent contrast, with the intrinsic suppression of static structures, improves sensitivity to measuring slow flow and its differentiation from thrombus from the pelvic great vessels (Figure 1).[6-10]

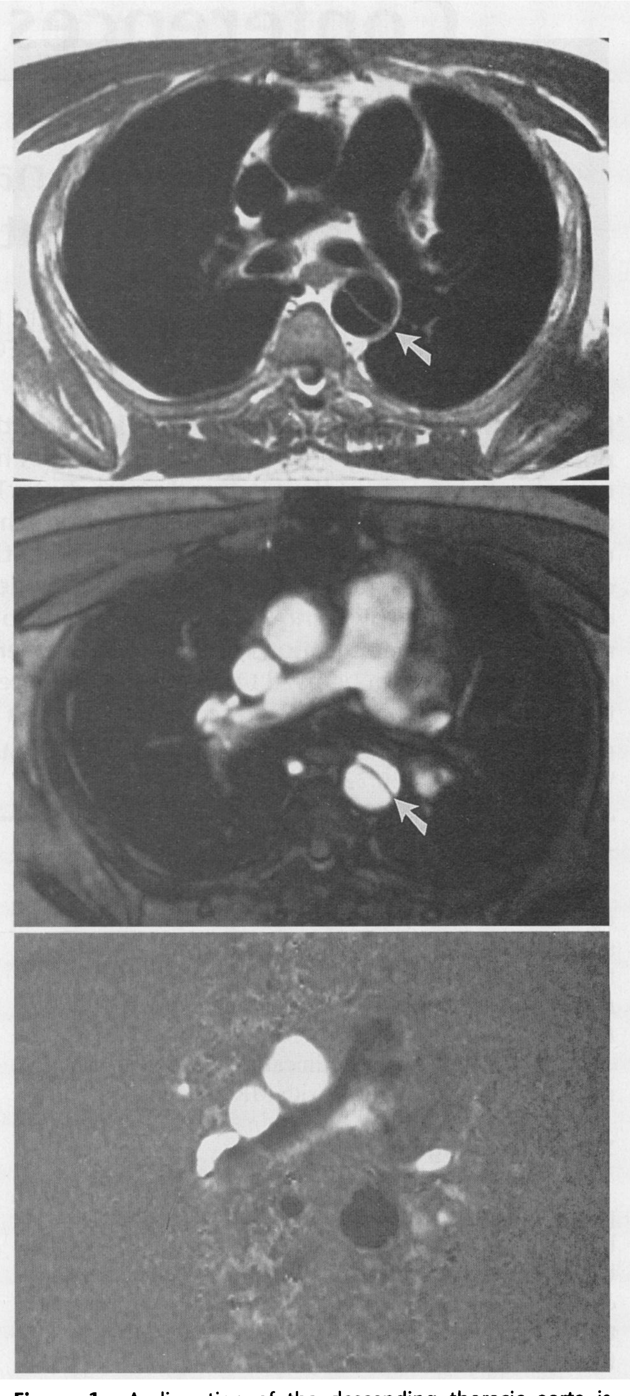

Figure 1.—A dissection of the descending thoracic aorta is shown by an axial gated T1-weighted spin-echo image **(top)**, an axial cine gradient-echo image **(middle)**, and a corresponding phase-contrast image with flow encoded superiorly to inferiorly **(bottom)**. Flow is seen in both lumens (on both sides of the intimal flap **[arrow]**). Note on the phase-contrast image that flow towards the head (ascending aorta) is black and flow towards the feet (descending aorta) is white.

Measuring Blood Flow

The ability to quantitate flow noninvasively is a poten-

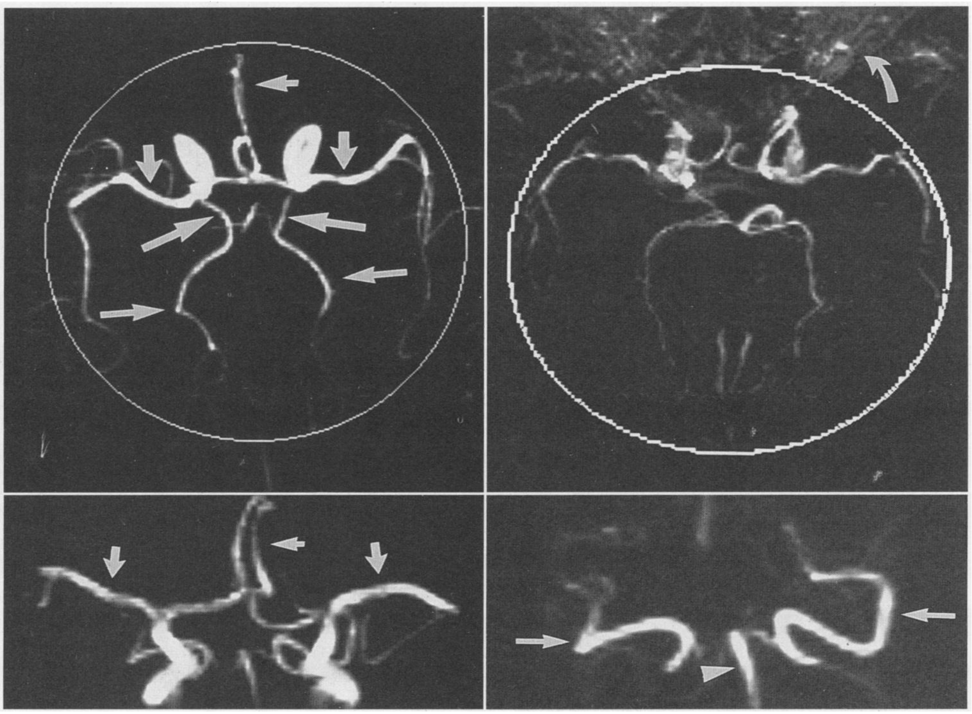

Figure 2.—A collapsed image allows a vantage point on the circle of Willis. A phase-contrast magnetic resonance (MR) angiogram **(upper left)** is compared with a time-of-flight MR angiogram **(upper right)**. The latter is distinguished by the presence of orbital fat **(curved arrow)** and subcutaneous fat signal. The large white circle depicts the chosen volume of interest for rotational views, such as the frontal **(lower left)** phase-contrast projection depicted or the selected frontal projection from a basilar **(lower right)** circulation volume of interest. Also shown are the anterior cerebral arteries **(short thin arrows)**, middle cerebral arteries **(short broad arrows)**, posterior communicating arteries **(long broad arrows)**, basilar artery **(arrowhead)**, and the posterior cerebral arteries **(long thin arrows)**.

tially powerful aspect of MR imaging. Magnetic resonance imaging does not need an appropriate acoustic window as required by ultrasonography. It provides excellent temporal data throughout the cardiac cycle with cine techniques, and it easily evaluates the edges of vessels.

Techniques used to measure blood flow take advantage of either time-of-flight effects or phase-shift effects. Time-of-flight effects refer to the bulk motion of protons, or spins, relative to the timing of a pulse sequence. Quantitative techniques based on time-of-flight effects are referred to as bolus tracking. In simple terms, a plug of blood within a blood vessel is tracked (by selective excitation or saturation) a measurable distance in a known amount of time. The average velocity of flow can then be calculated. Flow can then be calculated by multiplying the cross-sectional area of blood flow by the average velocity of flow through that area. The accuracy of these bolus tracking techniques can be limited by poor edge definition of the tagged (or saturated) plug of blood and by errors in measuring a cross-sectional area. With slow flow, small displacements of tagged blood are more difficult to measure accurately. Nevertheless, studies have shown close agreement between Doppler and bolus tracking measurements of peak flow velocity and velocity-integral measurements in the aorta.[11]

As described for phase-contrast imaging, the motion of protons in the presence of a magnetic field gradient produces a change in phase that is actually proportional to the velocity of the motion. By dividing up a bolus of blood into many small volumes and using phase changes to calculate the average velocity for each small volume, accurate peak and average flow velocities can be calculated. Flow can then be calculated after measuring the cross-sectional area of the blood vessel. Cine phase-contrast techniques allow pulsatile flow to be measured and flow patterns throughout the cardiac cycle to be delineated. Quantitative measurements based on phase shifts have been validated both in vitro and in vivo using implanted flow probes.[12,13]

Clinical Application

The highly accurate and noninvasive MR techniques for measuring blood flow are now widely available, but they have just begun to be used clinically. These tools have been used largely for research in a number of areas. Flow rate waveforms and average flow rates have been measured in the cerebral circulation of normal persons[14] and in patients with arteriovenous malformations.[15] Measuring flow within the aorta directly has been suggested as a method for evaluating cardiac output, aortic compliance, and coronary artery blood flow. Caudal flow in the ascending aorta in patients with normal aortic valve function may represent flow toward the coronary circulation. In patients with aortic insufficiency, this technique can be

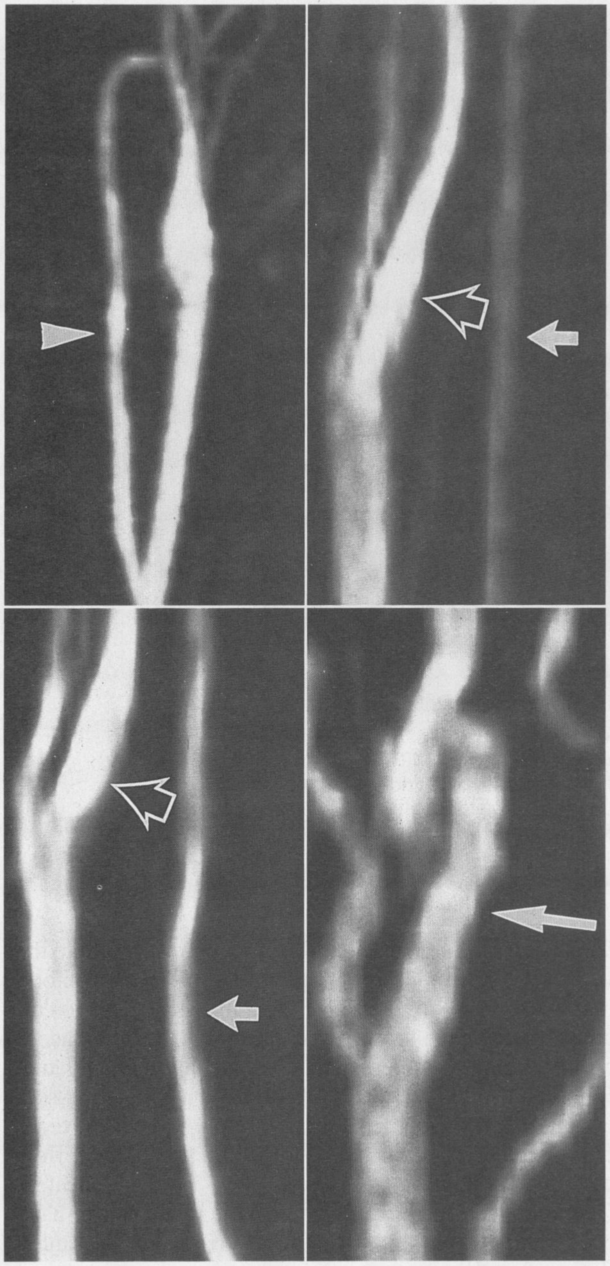

Figure 3.—A left dominant vertebral artery **(upper left, arrowhead)** is depicted in a frontal time-of-flight full-neck magnetic resonance angiography. Chosen lateral views of the volume of interest of the right **(upper right)** and left **(lower left)** common carotid bifurcations are compared with a right common carotid projection seen in a patient **(lower right)** with a folded right internal carotid artery **(long arrow)**. Also shown are the internal carotid artery **(open arrows)** and the vertebral artery **(short arrows)**.

used to directly measure the volumes of valvular regurgitation. Quantitative measurements may be useful for evaluating acquired and congenital lesions affecting pulmonary blood flow.[16] Cardiac output can be calculated easily by measuring the forward flow through the aorta. Cardiac shunts can also be evaluated by comparing left-sided cardiac output as measured at the aorta with the

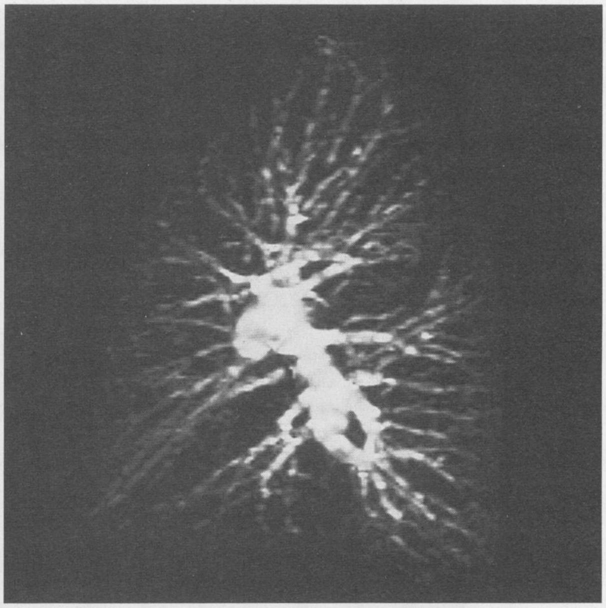

Figure 4.—A lateral view of a normal right lung from a magnetic resonance pulmonary angiogram was acquired with a time-of-flight technique in a healthy subject.

right-sided output as measured at the pulmonary artery.[17] These quantitative techniques (velocity-encoded cine MR) may prove useful in evaluating the severity of peripheral arterial stenoses because the normal triphasic flow pattern seen in peripheral arteries seems to become monophasic above and below hemodynamically important stenoses.[18]

Magnetic Resonance Angiography

A thorough evaluation of the cardiovascular system requires an evaluation of the blood vessels in addition to assessing patency and measuring flow. Conventional angiography has been the mainstay of such an evaluation. Over the past decade, however, MR angiographic techniques have been substantially improved, now allowing greater clinical use of this technique. Magnetic resonance angiography has several advantages over conventional angiography: noninvasiveness, no need for intravenous contrast (eliminating the risk of reactions), the potential of quantitative measurements, and the parenchymal information provided in addition to vascular anatomy.

Most published MR angiographic techniques use time-of-flight or phase-shift effects to produce signal from flowing blood within the blood vessels. Signal from surrounding static tissues is either suppressed or subtracted to increase the image of vascular detail. Vascular form and structure is then displayed in a projection format to simulate a conventional angiogram. With certain techniques, a rotating image is projected that can provide more information than a single or even two-plane conventional angiogram.[19]

Clinical Application

Magnetic resonance angiography was initially found to be useful in the head and neck because of technical advan-

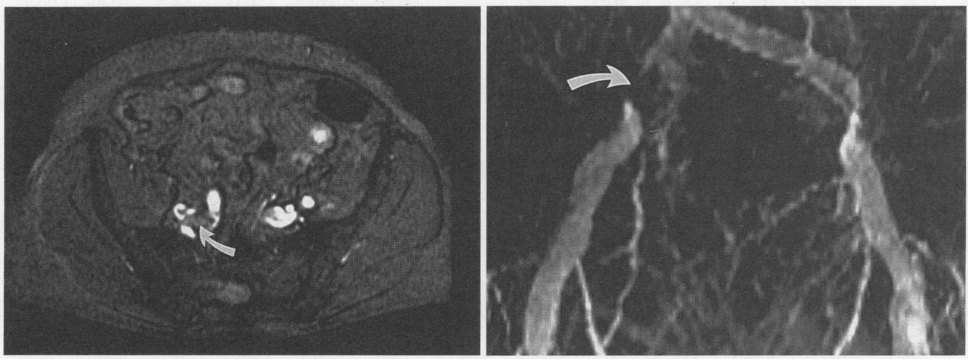

Figure 5.—An axial gradient-echo image **(left)** and a frontal view from a time-of-flight magnetic resonance venogram **(right)** show a focal thrombus **(arrows)** in the right iliac vein.

tages, including the lack of cardiac, respiratory, and peristaltic motion. The high incidence of atherosclerotic disease involving the surgically accessible carotid bifurcation has made the extracranial carotid circulation an area of concentrated research. Although the ability of MR angiography to quantitate carotid stenoses has steadily improved, the technique remains limited mainly due to signal loss from poststenotic turbulence and disturbed flow, such as that produced by intimal ulcerations. Magnetic resonance angiography, therefore, consistently overestimates the presence of stenoses, especially severe stenosis (Figure 2).[20-22]

The strengthened visualization of intracranial vascular anatomy has proved useful in searching for intracranial aneurysms. Of great value are selected "volumes of interest" that afford an interpreter several postprocessing image manipulations in three planes. Overlapping vessels may therefore be removed from the image, and the vascular tree may be positioned for optimal viewing of a specific portion of it. Magnetic resonance angiography may fail to detect the smallest aneurysms, but small aneurysms may not be at risk of rupture. This procedure, therefore, may be used predominantly as a screening tool in asymptomatic patients at risk for cerebral aneurysm. These may include patients with adult polycystic kidney disease, in whom a 10% to 15% incidence of berry aneurysms has been reported.[23,24] In a recent review, MR angiography was found to have a sensitivity of 95% and a specificity of 100%, compared with conventional angiography, for detecting intracranial aneurysms.[25] Patients with subarachnoid hemorrhage from possible aneurysmal rupture are primarily examined with conventional film angiography, which affords resolution currently unavailable with MR angiography (Figure 3).

Magnetic resonance angiography provides an evaluation for intracranial occlusive disease involving major arteries and veins. Such information is complementary to the sensitive evaluation for infarction provided by MR imaging.[26-29]

Intracranial MR angiography is of some value in characterizing the vascular supply of neoplasms and in observing arteriovenous malformations after surgical repair or embolization.[30]

Magnetic resonance angiography may also prove to be useful in planning for stereotactic biopsies and operations on the brain. The advantages of MR over other modalities include the ability to show both vasculature and soft tissue, its noninvasiveness, its high contrast with regard to delineating disease, and the potential of true three-dimensionality of data.[31]

The arteries in the thorax are pulsatile and are best evaluated with cardiac gated or cine techniques as described earlier. Magnetic resonance angiography can nevertheless be used to evaluate accurately the great vessels and veins of the thorax, including the superior vena cava. Magnetic resonance venography depicts central venous compression from adjacent masses as well as thrombosis with great accuracy.[32]

High-resolution images of the pulmonary arteries have also been obtained with MR angiography. Work is now going on to test these techniques in patients with pulmonary embolism (Figure 4).[33]

Magnetic resonance angiography and even conventional gradient-echo techniques are useful for evaluating abdominal vasculature. These techniques can confirm portal venous patency of the portal splenic and mesenteric circulation and determine the direction of flow. Portosystemic collaterals can be identified, and portosystemic shunts can be evaluated. Some centers now use MR angiography to evaluate patients before and after liver transplantation. Hepatic venous and caval patency can also be evaluated to exclude the Budd-Chiari syndrome. Magnetic resonance angiography can also document the relationship of liver tumors with the hepatic veins.[34]

Magnetic resonance angiography is sensitive to the presence of occlusive and nonocclusive thrombi in the renal veins and vena cava, making it of great value in the evaluation of renal cell carcinoma. It shows great promise for screening patients with hypertension for renal artery stenosis, with reported sensitivities as high as 100%. Limitations include an overestimation of the degree of stenosis, lessened sensitivity for the distal stenoses commonly seen with fibromuscular dysplasia, and the imperfect detection of small accessory renal arteries.[35-37]

So far, little work has been done on the use of MR angiography for evaluating peripheral arterial disease.[38,39] It has been used to evaluate runoff vessels in candidates for bypass operations. It was used to find all runoff vessels shown by conventional angiography, but found several that conventional angiography failed to detect.[40] Certainly, MR angiography can play a role as a noninvasive screening technique for peripheral arteries and as an alternative to conventional angiography for long-term postintervention follow-up.

Magnetic resonance angiographic and gradient-echo techniques can be used for peripheral venography to detect the presence of thrombosis or extrinsic compression. Although ultrasonography is accurate for evaluating the veins in the thighs, MR angiography can also evaluate the deep veins in the pelvis and calves (Figure 5).[41,42]

Summary

Magnetic resonance imaging is a valuable tool for the noninvasive assessment of the cardiovascular system. Traditional spin-echo and rapid gradient-echo techniques have proved useful for obtaining images of blood flow and vessel patency. The phase-contrast MR flow examinations also provide two-dimensional instantaneous velocity and flow profiles with high temporal resolution. Blood flow dynamics are delineated better than with any other invasive or noninvasive method for examining flow. Furthermore, many vessels that are not accessible by other noninvasive methods can be examined, such as those contained within the calvarium. As techniques continue to improve, MR angiography will become more reliable and clinically useful throughout the body. Although conventional angiography is in no immediate danger of becoming obsolete, many invasive and costly examinations may be avoided with the use of MR angiography.

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