Noninvasive Evaluation of Vascular Diseases

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In the early days of vascular surgery, angiography provided the only objective determination of a patient's pathology. Early experience with angiography demonstrated some of the limitations of this technique, including patient discomfort, risk of complications, and the high cost of the procedure. These limitations precluded the routine use of angiography as a screening tool and for postoperative follow-up.

When evaluating patients with vascular disease, a detailed history and complete physical examination remain the most important parts of the initial assessment. In the past decade, many noninvasive techniques have been developed and used to detect peripheral vascular disease, and noninvasive vascular laboratories are becoming common. These techniques may be useful in quantifying disability and localizing the site of the vascular obstruction. The use of these techniques is now essential in the evaluation of patients with vascular diseases, and physicians who intend to treat such patients should become familiar with these methods.[1]

This article describes the principal diagnostic techniques used in the noninvasive laboratory and discusses the clinical application of these techniques for patients with vascular disease. Of all the noninvasive methods that have been developed, techniques that employ the Doppler shift principle to measure blood flow through the use of modified ultrasound equipment represent an important step forward in the rapid development of noninvasive studies.[2]

SEGMENTAL PRESSURE MEASUREMENT

In the evaluation of patients with peripheral arterial disease, the noninvasive recording of pressure is the simplest method for assessing functional vascular impairment. This technique uses a pneumatic cuff and a Doppler ultrasonic velocity detector.

Information on the localization of occlusive disease can be obtained by measuring pressure at different levels of the legs. Segmental pressure measurements are usually obtained by applying cuffs to the thigh, upper calf, and immediately above the ankle. The cuff size applied to the limb is of paramount importance to achieve an accurate reading. A cuff that is too narrow gives an erroneously high pressure reading. In general, the cuff should be 20% wider than the diameter of the limb being studied. Gradients of more than 20 mm Hg between measuring sites are indicative of occlusive disease in the intervening segment (**Figure 1**).

Normally in the lower limb, peak systolic pressure increases as the pulse wave progresses distally. Systolic pressure in the lower extremity is normally higher than systolic pressure in the upper extremity. The ratio obtained by dividing systolic pressure measured in the ankle by systolic pressure measured in the arm is normally greater than 1 at rest; values below 0.95 are abnormal.[3] This ratio is termed the *ankle index* or *ankle pressure index*. Vessel walls are abnormally stiff in patients with calcification of the arterial wall and in patients with diabetes; therefore, the ankle index is not a good indicator of disease severity.

Stress Testing

In patients who have typical symptoms of claudication and normal or borderline leg pressure, segmental extremity pressure measurements may not be enough to determine the extent of the occlusive disease. In these patients, reducing the resistance of the peripheral vascular bed with exercise is an effective physiologic method for stressing the peripheral circulation.[4] When occlusive lesions are in the main arteries in the lower limbs, blood is diverted through high-resistance collateral pathways. Although the collateral vessels may provide adequate blood flow to the resting extremity with

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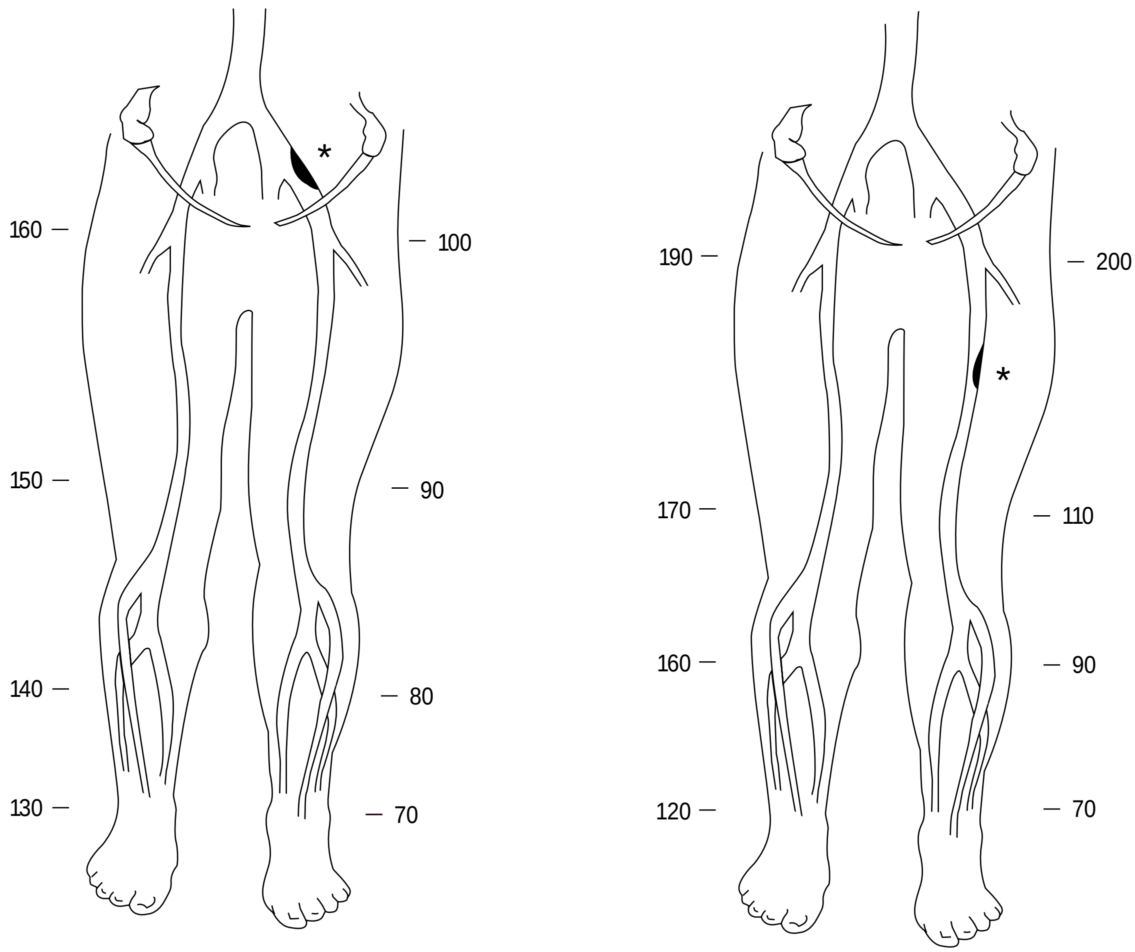

Figure 1. Segmental blood pressures noted in two different patients. The asterisks (*) indicate lesions. Values are noted in mm Hg.

only a modest reduction in ankle pressure, these pathways have a limited capacity for increasing blood flow during exercise. Pressure gradients that are minimal at rest are accentuated by the stress test, which is therefore a good method for detecting less severe arterial disease.[1]

The stress test is performed as the patient walks on a treadmill at 2 miles per hour on a 10% to 12% grade for 5 minutes or until symptoms occur and the patient is forced to stop. The examiner should always ask a patient why she or he stopped walking because the limiting factor in some cases may be angina or shortness of breath rather than claudication. Identification of these conditions is another important benefit of the stress test.

PLETHYSMOGRAPHIC METHODS

Plethysmography is one of the oldest methods used for measuring blood flow in the extremities.[5] During systole, the blood entering a limb normally causes an increase in the total volume of the extremity with a return to resting volume during diastole. The total effect of the volume changes is quite small and can only be detected with the aid of sensitive devices. Many plethysmographic recorders have been devised using a mercury strain gauge, water displacement, and an impedance system.

Pulse Volume Recording

Pulse volume recording was designed specifically for the diagnosis of peripheral arterial diseases. This system uses standard blood pressure cuffs applied at the thigh, calf, and ankle levels. The cuffs are inflated to 65 mm Hg to ensure optimal contact of the cuff around the extremity. A transducer detects small increases in pressure within the cuff that result from increased volume in the extremity during systole. The

$$V = C (Ft - Fr) / 2 \times Ft (\cos 8)$$

Figure 2. Doppler shift equation. C = Velocity of sound in the tissue (1540 m/s); cos 8 = cosine of the angle of the ultrasound beam to the direction of the moving object; Ft = transmitted frequency; Fr = reflected frequency; (Ft – Fr = frequency [Doppler] shift); V = velocity of the moving objects.

recorder provides a tracing of the pulse wave. A sharp rise to the systolic peak with a prominent dicrotic notch constitutes a normal tracing. As the occlusive disease becomes more severe, the dicrotic notch disappears, followed by the systolic peak becoming rounded until the wave is flattened.

Impedance Plethysmography

Impedance plethysmography (IPG) was developed to detect acute deep vein thrombosis. IPG measures volume changes in a limb by changes in electrical resistance. Two pairs of electrodes are placed on the calf to detect the volume changes in a 10-cm segment, and a blood pressure cuff is placed on the thigh. The thigh cuff is inflated to 35 to 40 mm Hg, occluding the venous outflow. During occlusion, calf volume increases until the venous system below the cuff is maximally filled. The cuff is then rapidly deflated, releasing the blood trapped in the calf veins, producing a decrease in calf volume to its baseline size.

In a normal extremity, an IPG tracing shows a steady rise and, after the cuff is deflated, a rapid decrease to baseline volume levels, usually within 3 to 4 seconds. In the presence of acute deep vein thrombosis, the venous system is maximally filled so no further increase in size occurs when the thigh cuff is inflated. In addition, the IPG curve remains flat and the volume requires more time to return to baseline levels.

VASCULAR ULTRASONOGRAPHY

Humans can hear sound waves that occur in a relatively narrow spectrum of frequencies, from 20 Hz to 20,000 Hz. Sounds above this range are termed ultrasonic. Ultrasonography devices used today generate frequencies of 2 to 10 MHz.[1] The transducer transmits a beam with a frequency of 2 to 10 MHz. The same transducer or a separate transducer receives the sound waves as they are reflected from material in the path of the ultrasound beam.

B-Mode Ultrasonography

B-mode ultrasonography provides a spatial image, and a real-time two-dimensional picture is produced. The various intensities of reflections are displayed by different shades of black and white. Highly reflective tissues become whiter, whereas areas devoid of reflective qualities become darker gray or black. This type of imagery is now widely used in two-dimensional echocardiography for imaging blood vessels and for assessing numerous other organ systems. A high-frequency transducer provides better resolution. Unfortunately, the penetration of high-frequency B-mode ultrasonography is very poor,[6] and this method is useful only for shallow structures. Lower frequency transducers penetrate to deeper tissues;[1] however, the resolution or sharpness of the picture is limited.

Doppler Ultrasonography

Doppler ultrasonography works on the basic principle that any moving object in the path of the sound beam shifts the frequency of the transmitted signal.[1] The difference between the frequency of transmission and the frequency of reflection is measured and represents the Doppler shift (**Figure 2**).

The importance of this equation is that the velocity of the object is directly proportional to the detected frequency shift. Blood flow is not constant but pulsatile (ie, the velocity varies with the cardiac cycle) and laminar (ie, fast in the middle of the lumen and slow near the vessel walls). The ultrasound device can present these frequency shifts as audible sounds or as waveforms on a screen (**Figure 3**). Characteristics of the audible sounds or the visualized waveforms indicate whether blood flow is smooth and laminar or is turbulent (**Figure 4**).

Pulsed wave Doppler ultrasonography. The pulsed wave Doppler apparatus has only one crystal that alternately sends and receives sound waves. Short transmissions occur at intervals of 0.5 to 1.0 ms, and reception occurs between these transmissions; reception is timed to a certain delay after transmission. The delay can be varied to facilitate sampling of blood flow at various distances or depths from the transducer. The pulsed wave Doppler technique allows evaluation of blood flow in a particular vessel and even at specific points within the lumen of the vessel.

Duplex Ultrasonography

Blood vessels are easily recognized on a B-mode ultrasound image by their characteristically prominent wall echoes and dark, sonolucent lumen. Calcified plaques produce bright intraluminal echoes.[1] Unfortunately, soft noncalcified plaques, recent thrombi, and flowing blood all have approximately the same

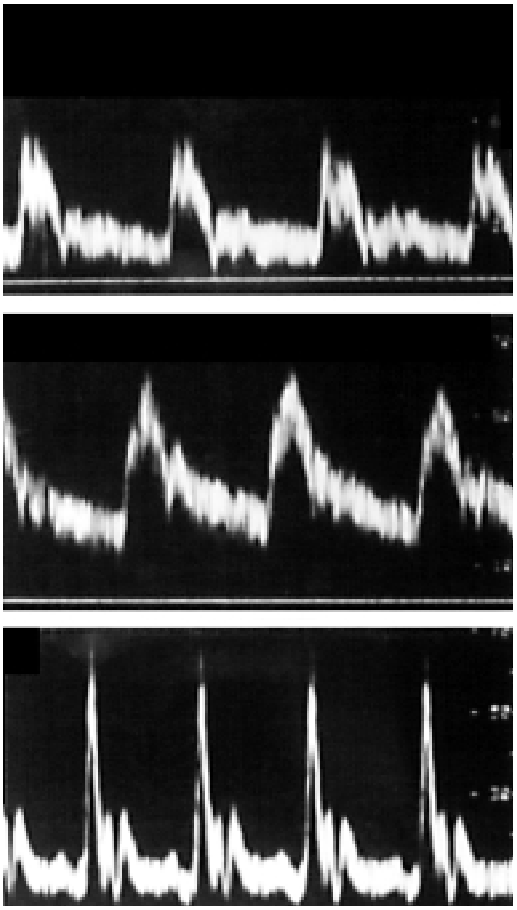

Figure 3. Doppler ultrasonography presents frequency shifts as waveforms.

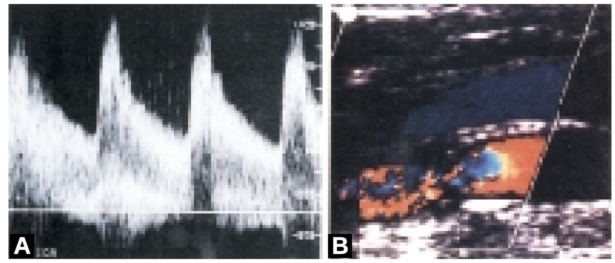

Figure 4. Characteristics of the waveforms visualized on Doppler ultrasonography indicate whether the blood flow is smooth and laminar or turbulent. A) Indicates a velocity waveform with color change; B) indicates severe stenosis.

acoustic echoes.[7] This similarity limits the grey-scale resolution of B-mode images and complicates the estimation of the percent of stenosis. Inadequacies of B-mode ultrasonography led to the duplex concept, which combines a pulsed wave Doppler technique with real-time B-mode scanning in one system.[1] The B-mode image is used to localize the artery, recognize anatomic variations, place the pulsed wave Doppler sample volume within the visualized vessel, and maintain a standard angle of incidence for the sound beam.[1]

Carotid duplex ultrasonography. The carotid bifurcation is a potential source of artery-to-artery embolization or of occlusion that can result in a transient ischemic attack or stroke. A stenosis or plaque in this region is safely and clearly visualized by duplex ultrasonography.

The normal arterial signal is triphasic, corresponding to 1) the rapid blood flow during systole, 2) the initial reversal of blood flow in diastole, and 3) the gradual return of forward flow during the late phase of diastole. In a vessel distal to a site of obstruction, the signal first becomes biphasic; then, as the degree of obstruction increases, the signal becomes monophasic with no or little variation between systole and diastole (**Figure 5**). This change in signal might be true for the external carotid artery where the blood flow is more pulsatile. The blood flow in the internal carotid artery is usually antegrade throughout the cardiac cycle because of low resistance in the cerebrovascular bed.

Accuracy studies of the use of carotid duplex ultrasonography for lesions of the common and internal carotid arteries show an overall 91% to 99% sensitivity and 84% to 90% specificity for this technique.[8]

Venous duplex ultrasonography. Venous duplex scanning has been shown to be considerably accurate in diagnosing deep venous thrombosis. Compared with venography performed in patients with suspected deep venous thrombosis, the sensitivity of venous duplex ultrasonography is 89% to 100%, and the specificity is 78% to 100% at experienced centers.[9] A normal vein has spontaneous blood flow and a phasic variation with respiration. Breath holding or a Valsalva maneuver decreases or abolishes blood flow, and a quick compression of the extremity distal to the probe produces a brisk augmentation. Examination of a thrombosed segment of vein shows no blood flow. The patent portion of the vein distal to an obstruction has continuous blood flow with no respiratory variation and limited augmentation on limb compression.

MAGNETIC RESONANCE IMAGING

In the growing field of noninvasive modalities, magnetic resonance imaging (MRI) is the newest technique used to evaluate patients with vascular diseases. This technique is based on the ability to induce and measure

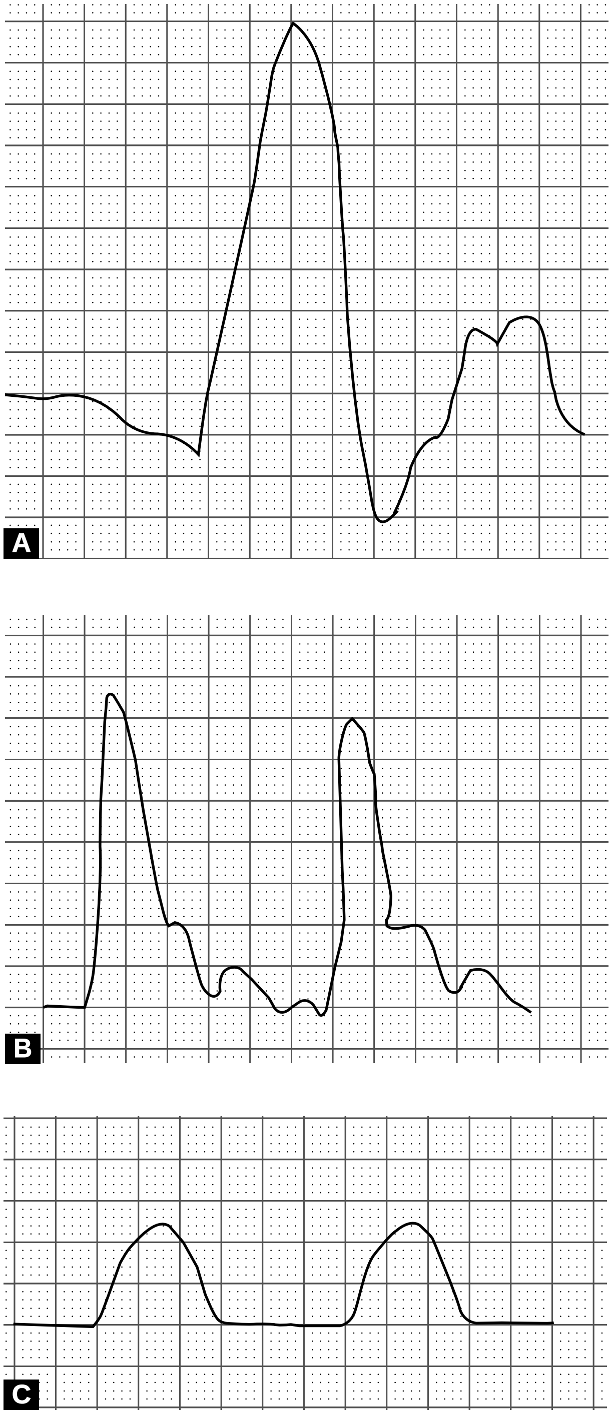

Figure 5. Waveforms seen on carotid duplex ultrasonography. A) A triphasic waveform is a normal arterial signal, B) a biphasic waveform is a signal from a vessel distal to the site of obstruction early in the development of a vascular disorder, and C) a monophasic waveform is a signal obtained as the degree of obstruction increases. Little or no variation is seen between systole and diastole.

radiofrequency energy emitted from atomic nuclei placed in a magnetic field.[10] MRI can visualize the anatomic detail of vessels because the contrast between flowing blood and vessel walls is precisely defined. Plaques are easily imaged because they project into the lumen. MRI does not require irradiation or contrast material, which eliminates the risk of nephrotoxicity and allergic reaction.[11]

Magnetic resonance angiography has a sufficiently high diagnostic accuracy to be considered an effective screening test for detecting significant carotid lesions.[12] Magnetic resonance angiography also can be used for evaluating the coronary arteries.[13] In the lower extremities, magnetic resonance angiography may be substituted for traditional arteriography.[14]

SUMMARY

In the past 10 years, many noninvasive studies have been developed. The findings of these studies are essential to the evaluation of a patient with vascular disease. The use of these studies not only decreases patients' discomfort but contributes to increased compliance when repeat examinations are required. All physicians who treat patients with vascular disease should familiarize themselves with these studies. **HP**

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(continued on page 58)

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