

# Segmental Pressure Measurement and Plethysmography

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## Introduction

The current status and rapidly evolving capabilities of duplex ultrasonography are hard to overlook. Investigators are presented with a myriad of transducers, image and Doppler formats, and system configurations. However, ultrasound technology has only widely impacted vascular laboratories for the past two decades. Before the 1980s, indirect techniques were used to noninvasively detect arterial disease. These techniques include segmental pressure measurements and plethysmographic waveforms. Although the technology involved is not as complex as duplex ultrasonography, these modalities yield information on the status of the peripheral arterial system, and the presence or absence of disease can be rapidly ascertained. The degree of severity of the occlusive process can be determined and ranked into appropriate categories using qualitative terms such as mild, moderate, or severe. Last, anatomic details pertaining to the level of disease can be interpreted from pressure measurements and waveforms. These types of noninvasive tests are used as primary screening tools when assessing patients with suspected peripheral arterial disease. The results of these tests can help the clinician select patients for further testing, intervention, or other courses of treatment.

## Segmental Pressure Measurement

The measurement of pressure within a limb is done by placing a cuff around the part of limb to be investigated. The cuff is inflated with enough pressure to occlude the artery and stop blood flow. The cuff is then slowly deflated while using some method to detect the pressure at which blood flow resumes distal to the cuff. The methods available to detect the return of blood flow are varied and include strain-gauge plethysmography,<sup>1</sup> photoplethysmography,<sup>2</sup> and Doppler instrumentation. The most common device used to detect blood flow is a continuous wave (CW) Doppler. The frequency selected is typically between 4-8 MHz,

which allows for the insonation of both deep and superficial vessels.

## Cuff Size

The measurement of limb pressure is significantly affected by the size of the pressure cuff used. Accurate readings can only be achieved by using the appropriate sized cuff. The cuff itself surrounds an inflatable bladder. It is the width of this bladder that is critically important. If the cuff bladder is too narrow, the blood pressure reading will be falsely high. If the cuff bladder is too wide, the pressure measurement will be falsely low. Inappropriate cuff use during the measurement of brachial artery blood pressures has been shown to produce an average error of 8.5 mmHg.<sup>3</sup> The American Heart Association recommends that the bladder width be 40% of the circumference of the limb or 20% wider than the limb diameter.<sup>4</sup> Table 1 lists recommended cuff bladder sizes for lower limb pressure determinations.<sup>5-7</sup> For extremely obese patients or patients with unusually small limbs, the cuff selected should be appropriately sized.

## Examination Technique

The technique for obtaining segmental pressure measurements begins with placing the patient in a supine position. The feet should be elevated on a small cushion so that the ankles are at approximately the same level as the heart. This position will reduce the effects of added hydrostatic pressure. Brachial blood pressure should be measured bilaterally. By doing so, any latent subclavian artery disease will be revealed, and the most accurate calculation of an ankle-brachial index (ABI) can be determined. Pneumatic cuffs are then placed around the legs at the ankle, calf, and thigh levels. The ankle cuff should be placed just above the malleolus. The calf cuff should be around the widest portion of the calf, just below the tibial tuberosity. One singular contoured thigh cuff may be used, or two cuffs may be placed around the upper and lower thigh. The high thigh cuff should be positioned such that the upper edge of the cuff is at the highest level of the inner thigh. The low thigh cuff should be positioned such that the lowest edge of the cuff is just above the patella.

The measurement of systolic pressure begins at the ankle. The Doppler stethoscope is used to detect flow

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Table 1

*Recommended Cuff Bladder Width for Lower Limb Pressures in the Average Adult*

| Cuff Level                  | Cuff Width (in cm) |
|-----------------------------|--------------------|
| Upper thigh                 | 11                 |
| Lower thigh                 | 19                 |
| Single contoured thigh cuff | 22                 |
| Calf                        | 12                 |
| Ankle                       | 10–12              |
| Transmetatarsal             | 7–8                |
| Toe                         | 2.5–3              |

within either the posterior tibial artery or the dorsalis pedis artery. While listening to the flow signal, the ankle cuff is inflated above the brachial systolic pressure until the flow signal is no longer heard. The cuffs should continue to be inflated 20–30 mmHg beyond the pressure at which the last audible signal was obtained.<sup>8</sup> This is done to ensure complete closure of the artery. The cuff is then slowly deflated until the Doppler signal returns. The rate of deflation should be approximately 2–4 mmHg per sec. This will allow for a precise measurement of the systolic pressure. After measurement of the ankle pressure, the calf and then the thigh pressures are recorded.

If the Doppler signal is absent at the ankle level, the ankle cuff can be removed, and the mid to distal tibial arteries can be examined with the Doppler stethoscope. If a flow signal is obtained within the mid-calf, this can be used to determine the calf and thigh pressures. If no signal can be appreciated from the tibial level, the popliteal artery is then examined. A Doppler signal from the popliteal fossa can be used to determine the thigh pressure.

#### *Interpretation*

Because ankle systolic pressures are compared with the brachial artery pressures, it is important to have accurate measurements of brachial artery pressure. The right and left brachial pressures should be equal. If these pressures differ by more than 20 mmHg, an abnormality exists.<sup>9</sup> The arm with the lower pressure likely contains a hemodynamically significant obstruction within the subclavian artery. However, further testing would be needed to determine the exact location of such an obstruction. Thus, the higher of the two brachial artery pressures should be used for calculations of the ABI.

As stated earlier, both the posterior tibial and dorsalis pedis arteries can be used to determine ankle pressure. The pressure measured at these two arteries should not differ by more than 10 mmHg, and variations greater than 15 mmHg suggest a proximal obstruction in the artery with the lower pressure.<sup>10</sup> The higher pressure reading is the value used in the calculation of the ABI. The ankle systolic pressure normally is greater than the brachial systolic pressure by 12–24 mmHg.<sup>11,12</sup> This occurs as a result of an augmentation in the pulse pressure as blood travels to the

periphery. This augmentation is due to less elastic distal arterial walls and reflections of the pressure wave from distal branch points and the peripheral vascular bed.

One of the most common technical errors that can occur in the measurement of ankle pressures is due to the presence of medial calcification.<sup>13,14</sup> Calcification can result in falsely elevated pressure measurements or the inability to completely occlude the arterial flow signal. Medial calcification is frequently encountered in diabetic patients or patients with chronic renal failure. Calcific vessels are suspected when the ankle pressures exceed 300 mmHg. Although the medial calcification has a pronounced affect on ankle pressure measurements, it does not have an impact on plethysmographic or Doppler waveforms.

#### *Ankle Brachial Index*

Pressure measured at any point along the vascular system is going to vary, because the dynamic pressure supplied by the heart varies. Because of this, calculating the ABI can normalize the ankle pressure. The ABI is simply the ankle systolic pressure divided by the brachial systolic pressure. The range for normal ABI is between 1.0 and 1.1.<sup>15–18</sup> In the presence of significant arterial disease, the ABI is typically less than 1.0.<sup>15,18</sup> However, it is possible for a patient to have arterial disease yet have a resting ABI of 1.0 or greater.<sup>18,19</sup> Other studies have shown that only rarely does an individual without arterial disease have an ABI of less than 0.92.<sup>20</sup> If a patient has “normal” resting ABIs but describes symptoms associated with exercise, this patient should undergo exercise testing to detect the presence of a subcritical stenosis.

In early work by Yao,<sup>21</sup> the degree of functional impairment within subjects was compared with the measured ABI. He identified the following groups: no symptoms, ABI  $\geq 1.0$ ; claudication, ABI = 0.5–1.0; rest pain, ABI = 0.25–0.50; impeding tissue loss ABI  $\leq 0.25$ . Even though some overlap occurred, it is clear that with increasing severity of symptoms, there is a progressive decrease in the ABI. It has also been observed that differences in the ABI occur with increasing number of diseased segments of the arterial tree.<sup>22</sup> An ABI of  $\geq 0.5$  is found in patients with only a single level obstruction, whereas an ABI of  $< 0.5$  is often associated with multilevel disease. Within an individual, the measurement of the ABI is fairly stable between examinations, providing there is no significant change in the degree of disease. A change in the ABI of  $\geq 0.15$  from one examination to the next has been shown to be a good indicator of increasing severity of disease.<sup>23</sup>

#### *Segmental Pressures*

Although an ABI will identify those patients with significant arterial disease, it does not specify the segments involved. By measuring the pressure gradients down the limb, additional information can be obtained. The systolic pressure measured with a high thigh cuff is normally 30–50 mmHg greater than the brachial systolic pressure.<sup>24</sup> There is a great deal of

Table 2

*Original Criteria for the Pulse Volume Recorder (PVR)*

| Anatomic Level  | Bladder Size      | Inflation Pressure | Inflation Volume | Gain |
|-----------------|-------------------|--------------------|------------------|------|
| Thigh           | 36 × 18 cm        | 65 mmHg            | 400 ± 75 cc      | 1    |
| Calf and ankle  | 22 × 12 cm        | 65 mmHg            | 75 ± 25 cc       | 1    |
| Transmetatarsal | 12 × 7 cm         | 65 mmHg            | 50 ± 10 cc       | 2.5  |
| Digits          | 9 × 3 or 7 × 2 cm | 40 mmHg            | 5 ± 3 cc         | 5    |

inaccuracy with pressure measurements at this level. The pressure within the common femoral artery is almost always equal to the brachial artery pressure when measured by invasive techniques.<sup>25</sup> The difference between the thigh diameter and cuff size results in a higher thigh pressures in patients with larger thighs and lower, more accurate pressures in patients with smaller thighs. The presence of hemodynamically significant disease will result in thigh pressures equal to or lower than the brachial pressure.<sup>24</sup>

The normal variation in pressure measurement between limb segments should be no more than 20–30 mmHg.<sup>26</sup> A gradient of greater than 30 mmHg is suggestive of significant arterial obstruction between the segments measured.<sup>27</sup> If an artery is completely occluded, a gradient of greater than 40 mmHg is observed.<sup>26</sup> In addition to measuring differences within the same limb, it is also beneficial to compare pressures between limbs. The limb pressures recorded in the right and left lower extremity should be similar at the same level. A difference of greater than 20 mmHg is considered hemodynamically significant.<sup>16</sup> It is possible for normal pressure gradients to be obtained within limbs with arterial obstructions if large collateral vessels are present. This does not reflect an error in the measurement. Pressure measurements are reflective of the functional status of the arterial circulation rather than the anatomic condition of the vessels.

### Plethysmography

A plethysmograph is a device that records variations in volume or blood flow through an extremity. The volume of an extremity changes between systole and diastole as a result of the pulsatile blood flow into that region. There are a number of different types of plethysmographs that use various means to measure these changes. These include water, air, electrical impedance, mercury in rubber strain gauge, and photoelectric plethysmography. Segmental air plethysmography is an important part of the noninvasive assessment of arterial disease. In the 1970s, the pulse volume recorder (PVR) was developed and tested at the Massachusetts Institute of Technology and Massachusetts General Hospital.<sup>28,29</sup> The PVR measures pressure changes in the bladder of the cuff wrapped around the limb. The cuff pressure changes actually reflect changes in the cuff volume, which is a direct reflection of changes within the limb volume. PVR units are calibrated so that a 1 mmHg pressure change in the cuff produces a 20-mm deflection (amplitude) on the chart recorder. In normal patients, these noninvasive ple-

thysmographic waveforms strongly resemble direct intraarterial pressure pulse contours.<sup>29</sup>

### Examination Technique

The operation of a PVR is straightforward, but care needs to be taken to ensure reproducible results. Blood pressure cuffs are placed around the limb and attached to the plethysmograph. The same cuffs used to measure segmental pressures are used for the recording of the PVRs. The appropriate size should be selected as previously described for the pressure measurements (see Table 1). A measured quantity of air is injected until a preset pressure is achieved. The pressure within the cuff must be sufficient enough to produce adequate contact between the limb and the cuff bladder. Once the appropriate pressure is reached within the cuff, the plethysmographic tracings are recorded over three to four complete cardiac cycles. The original criteria developed with the PVR are listed in Table 2.<sup>30</sup> Although slight variations occur between laboratories, it is important to develop standardized criteria for obtaining PVRs, so that results may be comparable between visits.

### Interpretation

The PVR amplitude is highly reproducible in the same patient when care is taken to maintain consistent cuff volumes and pressures.<sup>29</sup> The PVR amplitude will vary between patients and is affected by ventricular stroke volume, blood pressure, vasomotor tone, blood volume, and the size and position of the limb. In very obese patients or those with extensive edema, the PVR waveforms can be attenuated. With increasing severity of disease, the pulse amplitude decreases. PVR recordings have been classified into five categories based on pulse amplitude and contour, which are defined in Table 3. Other grading systems may use terms

Table 3

*Definition of Pulse Volume Recorder (PVR) Categories*

| PVR Category | Chart Deflection (in mm) |      |
|--------------|--------------------------|------|
|              | Thigh and Ankle          | Calf |
| 1            | >15*                     | >20* |
| 2            | >15†                     | >20† |
| 3            | 5–15                     | 5–20 |
| 4            | <5                       | <5   |
| 5            | Flat                     | Flat |

\*With reflected wave.

†No reflected wave.

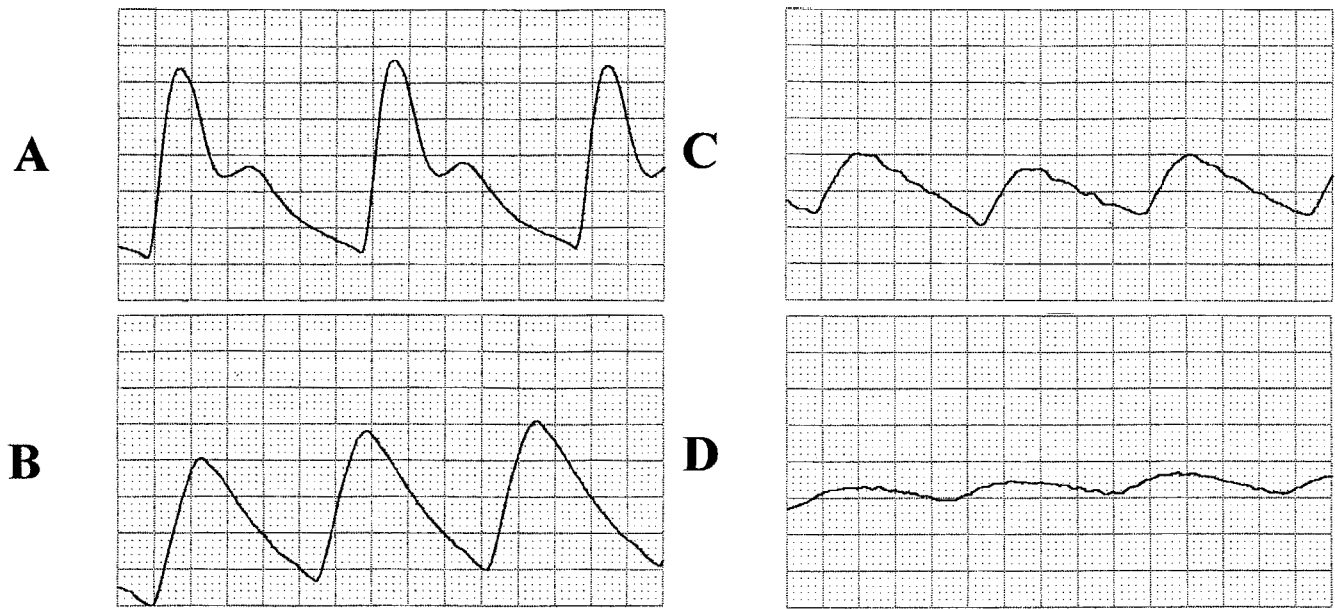


Figure 1

Pulse volume recordings demonstrating normal characteristics (A) and progressive changes with disease: (B) mild obstruction, (C) moderate obstruction, (D) severe obstruction or occlusion.

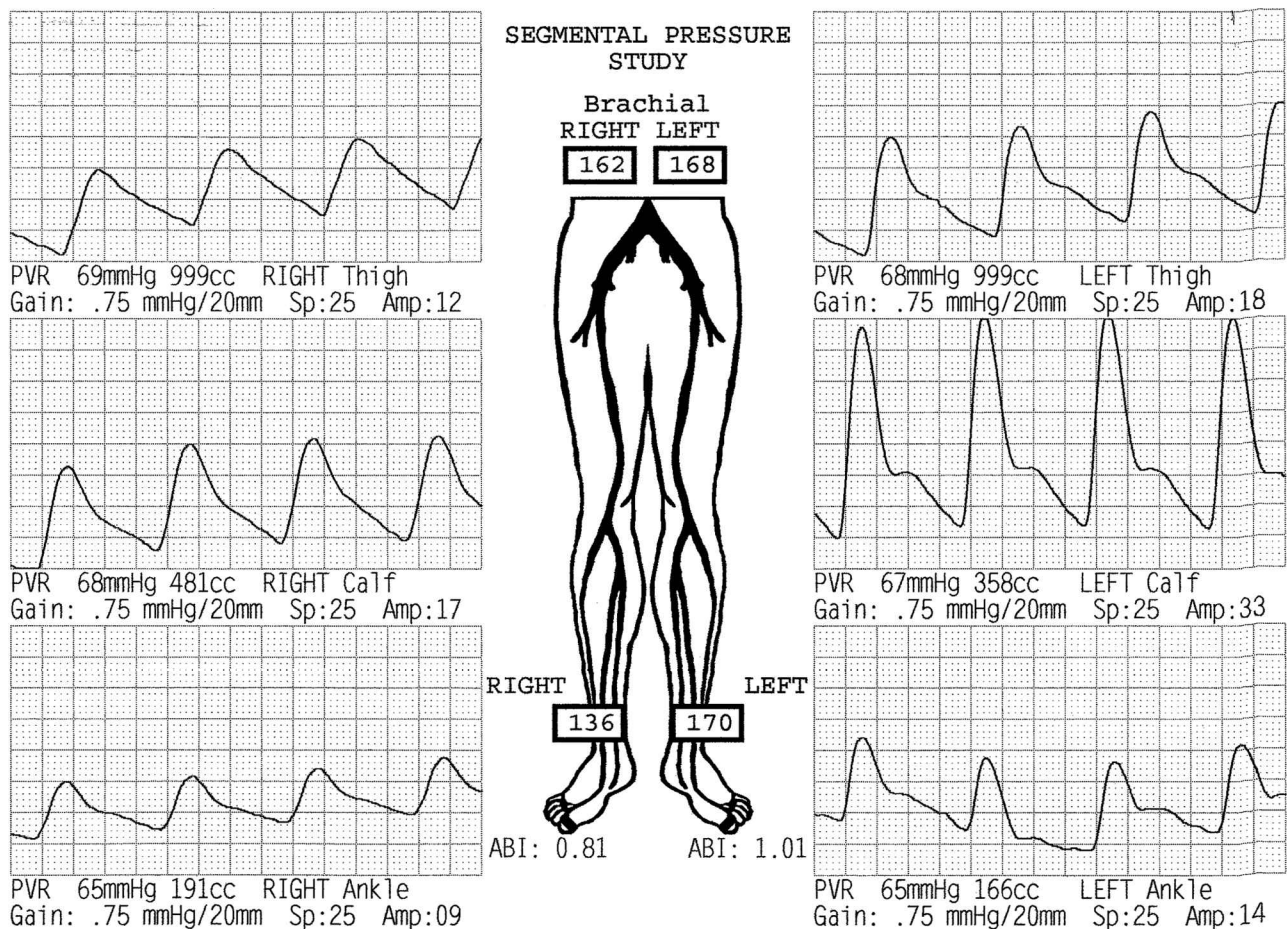


Figure 2

A PVR study demonstrating abnormal inflow to the right leg. These waveforms are consistent with iliofemoral disease. The left leg is within normal limits.

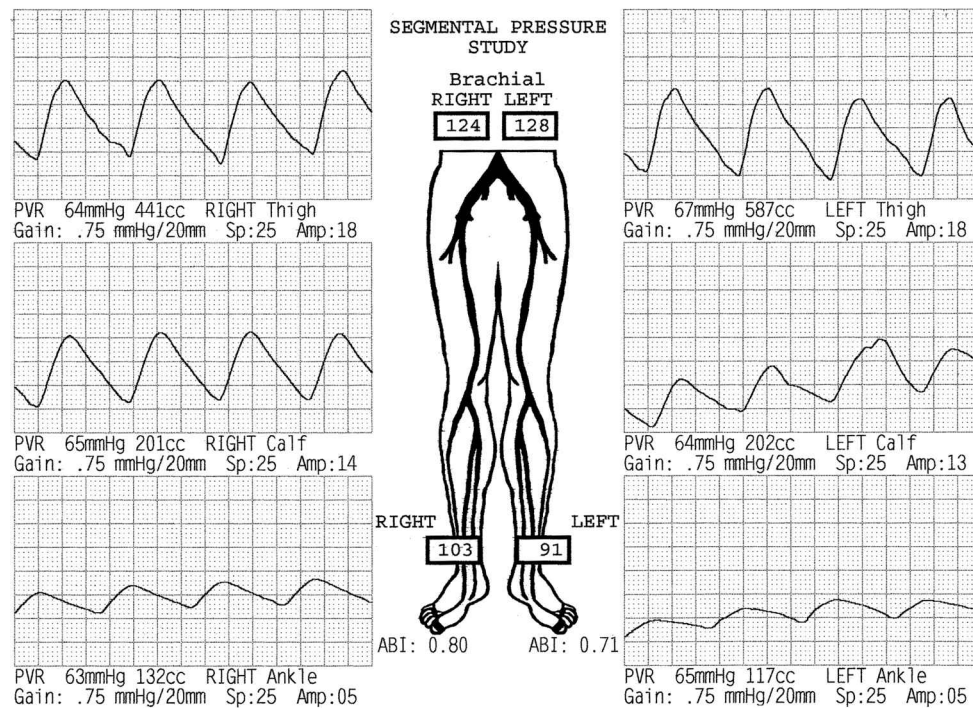


Figure 3

These PVRs waveforms demonstrate mild inflow disease. Because the thigh tracings are abnormal bilaterally, this likely represents aortoiliac disease. There is also outflow disease present bilaterally as the waveform contour and amplitude worsen distally.

such as "normal," "mildly abnormal or mild disease," "moderately abnormal or moderate disease," or "severely abnormal or severe disease" rather than original grading system proposed in Table 3. Normally, the

amplitude at the calf exceeds that at the thigh. This calf augmentation occurs because of the differences in muscle mass and cuff volumes between the thigh and the calf. Essentially, although the actual volume

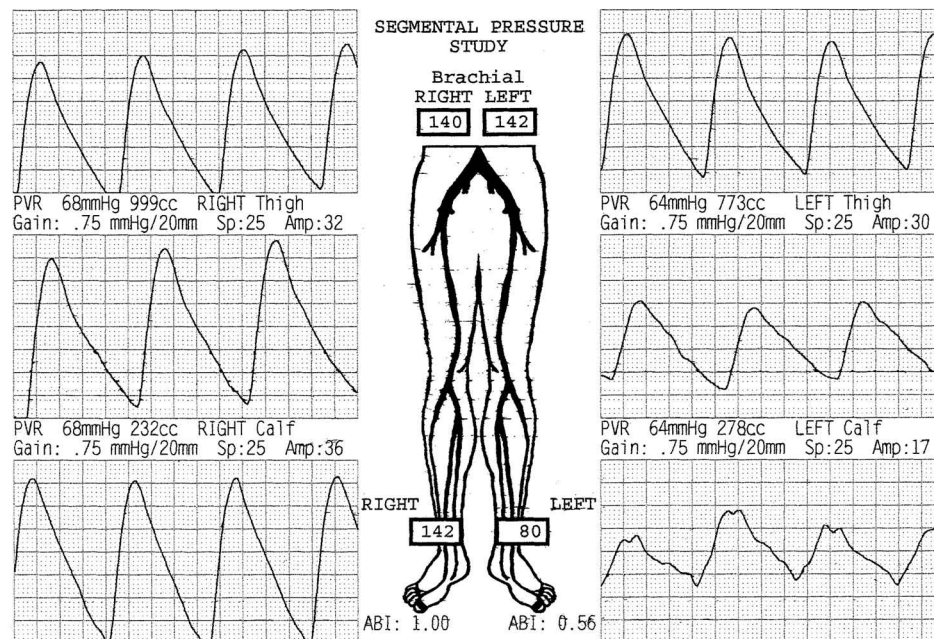


Figure 4

The left leg in this PVR study demonstrates superficial femoral artery disease as indicated by the presence of a normal thigh waveform and abnormal calf and ankle tracings. The right leg is within normal limits.

change is greater within the thigh, the measured pressure change is diluted and reflected as decreased amplitude.

The PVR amplitude is universally affected by exercise. In normal patients, the amplitude increases after a standard exercise protocol as a result in the increased blood flow to the limb. In patients with significant arterial disease, there is diminished amplitude after exercise. There is a definite correlation with the degree of ischemia as measured by the walking distance and the fall in the PVR amplitude.

The contour of the PVR is very important in determining the arterial status of a limb. A normal PVR will demonstrate a sharp systolic upstroke that rises quickly to a peak (Figure 1). The waveform then curves downward toward the baseline and usually displays a prominent dicrotic notch midway between the peak and the baseline. This dicrotic notch or wave represents the reverse flow component of the normal peripheral arterial pulse. If the dicrotic notch is present, this in essence excludes the existence of signifi-

cant proximal disease. If improper pressure is maintained within the cuffs, the pulse contour can be distorted. In the presence of significant arterial occlusive disease, the upstroke is less steep, the peak becomes rounded and delayed, the downslope bows away from the baseline, and the reflected dicrotic wave is absent. As the disease progresses, the rise and fall of the waveform becomes nearly equal and the overall amplitude of the curve decreases.

In the presence of aortoiliac disease, the thigh waveform may lose the dicrotic notch and become slightly rounded with a decrease in amplitude. The waveform contours at all levels will be abnormal, although the amplitude of the calf PVR will remain augmented compared with the thigh. The ankle waveform will be similar to the thigh. If the thigh waveform in one limb is abnormal while the contralateral thigh waveform is normal, this represents iliofemoral disease, because aortoiliac disease would impact both thigh waveforms (Figure 2).

In a patient with combined inflow and outflow dis-

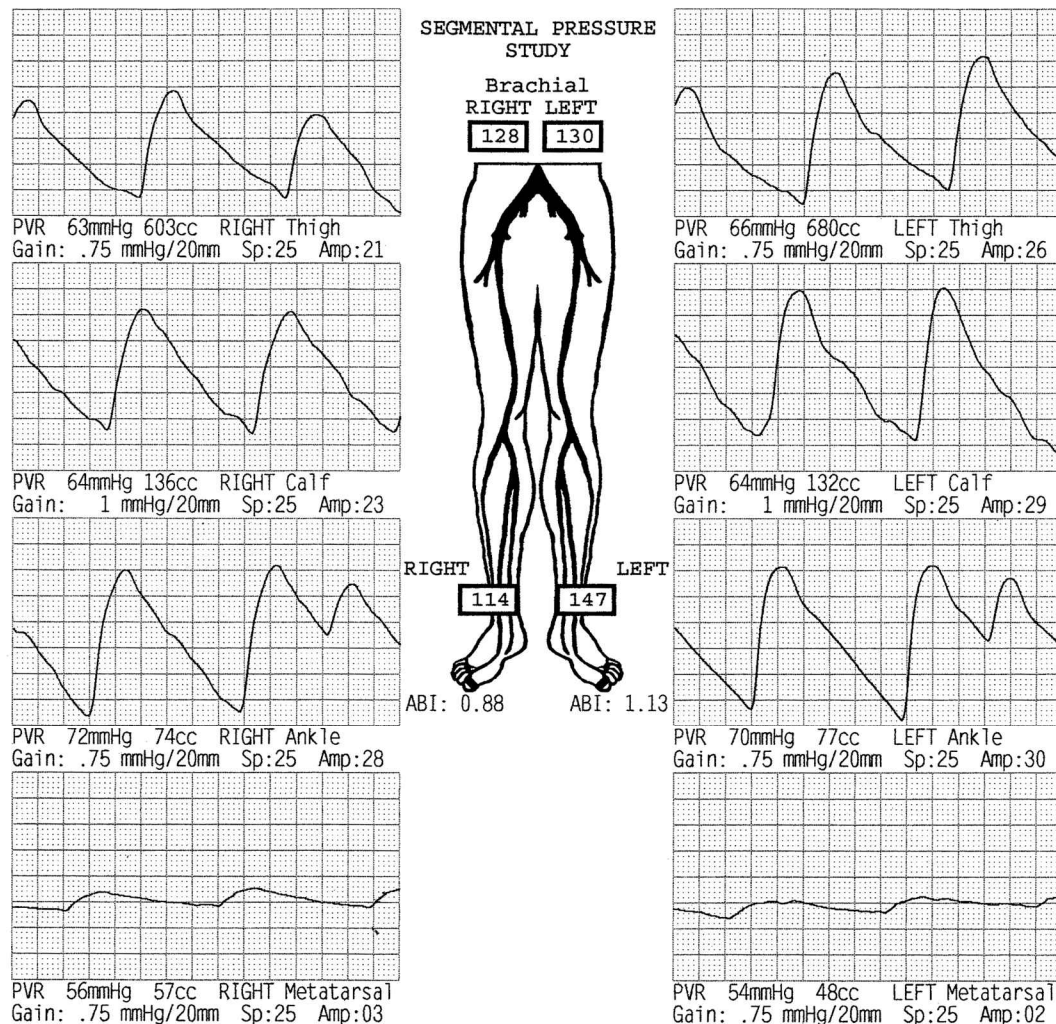


Figure 5

*These PVR waveforms represent distal tibial level disease. The thigh, calf, and ankle tracings demonstrate good pulsatility; however; the waveforms flatten out at the transmetatarsal level.*

ease, the thigh will be abnormal as described in the preceding paragraph (Figure 3). The calf and ankle waveforms will be reduced in amplitude compared with the thigh. The contour will be blunted with a prolonged upstroke at all levels.

A patient with superficial femoral artery disease will display a normal thigh waveform, providing the disease is within the mid to distal portions of this vessel (Figure 4). The calf waveform will be abnormal with a blunted contour and decreased amplitude. The ankle waveforms will look similar in contour to the calf but may have a slightly lower amplitude.

In the presence of more distal disease, the more distal waveforms will be affected. If the popliteal artery is diseased, calf and ankle tracings will be affected. If only tibial level disease exists, the ankle level PVR will be abnormal with the thigh and calf tracings being normal. With very distal tibial level disease, the thigh, calf, and ankle waveforms will be normal, but those at the transmetatarsal level will be abnormal (Figure 5). This level of disease is commonly seen in diabetic patients.

Plethysmographic waveforms provide a reliable indicator of global arterial perfusion. The PVR waveforms and segmental pressures are complimentary tests, and results should be evaluated concomitantly. If a discrepancy exists, possible sources of error should be investigated. If the PVR waveforms indicate disease but ankle pressures are normal or elevated, the possibility of calcified vessels should be considered. Cuff placement should always be checked to rule out any occurrences of cuff artifact.

### Conclusion

More sophisticated equipment may provide greater detail than the simple indirect tests of segmental pressures and PVRs. However, the cost of obtaining this additional information must be taken into consideration. Segmental pressures and plethysmographic waveforms are quick and reliable methods to detect arterial disease. Results from these modalities can help direct the care and management of patients with symptoms of peripheral arterial disease.

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