Indirect Systolic Pressures and Pulse Waves in Arterial Occlusive Disease of the Lower Extremities

By Stefan A. Carter, M.D.

SUMMARY

Measurements were carried out in 146 limbs with angiographically documented arterial occlusive disease (AOD) and in 85 limbs without AOD. Ankle systolic pressure (AP) was equal to or higher than brachial systolic pressure in limbs without AOD. It was below 82% of the brachial in all limbs with complete occlusion, usually below 50% in those with multiple occlusions, and above 50% in limbs with single block. AP was below normal in 19 of 25 limbs with severe and in five of nine with mild stenosis. All limbs with complete occlusion and 14 of 16 with stenosis had abnormal pressures in the thigh. The foot-to-peak time (CT) and the width of pulse waves at half amplitude (WD) were related to heart rate in normal limbs. Considering the heart rate, the majority of limbs with AOD had abnormally prolonged CT and WD. Normal pressures and pulse waves were found together in only two limbs with stenosis and symptoms. The findings indicate that pressures and pulse waves provide a sensitive method for diagnosis and follow-up of patients with AOD.

Additional Indexing Words:
Ankle systolic blood pressure  Pedal pulse waves  Thigh systolic blood pressure
Popliteal pulse waves  Crest time  Peripheral vascular disease
Width of pulse waves  Arterial stenosis  Intermittent claudication

Severe arterial narrowing and arterial occlusion both result in diminished mean pressure and in decreased amplitude of the pressure wave distal to the lesion. Although diastolic pressure distal to arterial stenosis does not fall until the narrowing is severe, systolic pressure decreases with lesser degrees of narrowing.1 Systolic pressure has been known to be diminished in the limbs of patients with arterial occlusive disease (AOD).2,8 In 1956 Gaskell4 found that it was as sensitive an index of the occlusive process as the measurement of blood flow during reactive hyperemia. More recently, Strandness and co-workers5-10 successfully applied measurements of systolic pressures to the study of various aspects of the occlusive process. Alterations in the shape and time components of the pulse waves recorded from the limbs with AOD have also been reported.7, 11, 12

Although externally recorded pressures and pulse waves may be of help in the diagnosis of patients with AOD,3-5, 7, 12 the clinical value of such studies is uncertain because detailed results in large series of angiographically documented cases are not available. For this reason, the present study was undertaken.

Methods

Groups Studied

Control Groups

A "normal" group consisted of 44 limbs of healthy volunteers or patients without clinical evidence of cardiovascular disease. Their average age was 40 ± 18 years (SD). A second control group which resembled more closely the group with AOD consisted of 41 limbs of pa-
patients with conditions which are generally associated with a greater degree of atherosclerosis but in which there was no evidence of the occlusive process. Patients with ischemic heart disease, cerebrovascular disease, hypertension, or diabetes mellitus, singly or in combination, as well as normal limbs of patients with unilateral occlusive or stenotic process were included in this group. In all the limbs there were strong, easily palpable femoral, popliteal, and pedal pulses, and no ischemic symptoms. The average age of this group was 56 ± 14 years (SD). Because aortic stenosis alters peripheral pressure pulses in the upper limbs, two patients with systolic pressure gradients of 100 and 127 mm Hg across the aortic valve, but without regurgitation, were included in the study.

Arterial Occlusive Disease (AOD)

This group consisted of 146 limbs of patients with angiographic evidence of an occlusive process in the arteries supplying the lower limbs including the abdominal aorta. The average age of the patients was 62 ± 13 years (SD). There were 112 limbs with complete occlusion and 34 with stenosis. In 41 limbs with occlusion, the vessels were well visualized down to the ankles and these limbs were divided into 22 with a single block and 19 with two or more occlusions in series. There were 25 limbs with severe and nine with mild stenosis. Stenosis was considered to be mild when the encroachment on the diameter was between 25 and 40% in the vessels distal to the bifurcation of the common femoral artery and between 33 and 50% for the vessels proximal to this point. The stenosis was graded as severe when the encroachment on the diameter exceeded 40% and 50%, respectively. The different criteria for larger and smaller vessels were used because a relatively greater encroachment on the diameter is required in larger vessels before a hemodynamic effect is manifested. For the purpose of classification of the limbs into categories according to angiographic findings, isolated occlusions or narrowings in branch arteries such as the internal iliac, the deep femoral, or a tibial vessel were not considered.

Follow-up Studies

Measurements were carried out before and after reconstructive arterial surgery in 25 limbs. In 19 other limbs with clinical and hemodynamic evidence of occlusive arterial disease in which surgery was not performed, measurements were repeated after an interval of one or more years. Angiographic confirmation of the occlusive process was available in six of the 19 limbs.

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Figure 1

(A) Experimental setup for the measurement of systolic pressure at the ankles. (B) Record obtained during measurement. The arrows point to where the pickups signal systolic pressures by the change in base line and, if recordable pulse is present, by the onset of pulsation.

Techniques

Angiography

Angiography was carried out by injecting contrast material through a translumbar needle or through a catheter introduced retrogradely from the femoral artery at the groin. Four to six serial films, 14 by 17 inches, were taken in the frontal projection and the run was repeated when necessary.

Determination of Systolic Pressures

Measurements were carried out with the subjects supine and covered by a blanket. Systolic pressures were determined at the ankles and at the level of the lower part of the thighs. The blood pressure cuffs were applied with the lower edge above the malleoli and above the patella. The inflatable portions measured 30 by 12.5 cm for the ankle cuff and 45 by 15 cm for the thigh cuffs. This length of cuff encircled at least 90% of the circumference of the limbs. Figure 1 shows schematically the setup for measurement of pressure at the ankles and the type of record obtained. The cuffs were connected to a pressure source, a mercury manometer, and a Statham pressure transducer. Capacitance pulse pickups were applied over the site of the dorsalis pedis or posterior tibial arteries and were held in place.

*Model PM6TC± 5-350, Statham Instruments, Inc., Los Angeles, California.
†“Infraton,” Model D-3, Beckman Instruments, Inc., Palo Alto, California.
under tension by means of an encircling tape. The outputs of the pickups and of the pressure transducer were recorded on an optical oscillograph. The pickups signaled the systolic pressure during deflation of the cuffs by the onset of pulsations and by a shift in base line. The shift in base line was due to the resumption of arterial inflow into the foot which led to increased limb volume and thus to increased pressure on the pickups. This shift in base line occurred even in the absence of a recordable pulse. Brachial blood pressure was measured in both arms prior to the recording of the pressure in the lower limbs and was determined again during the recording. Three or more determinations of pressure were carried out and the values were averaged. Reproducibility of measurements within the experiment was assessed in consecutive studies on 160 ankles and 60 thighs. The maximal deviations of an individual determination from the average were within 14 mm Hg of the average in 95% of cases, at both sites. The 95% limit for the maximal deviations of the simultaneously measured brachial systolic pressures was 11 mm Hg. When individual measurements in the lower limbs were calculated as percentage of the brachial pressure, 95% of values of the maximal deviations were within 9% of the average for the systolic pressure at the ankle (AP), and within 13% for the systolic pressure at the lower thigh (TP). There was no significant difference between the reproducibility of low and high pressures. In 43 lower limbs determinations of systolic pressure were repeated within 1 month. The mean absolute difference between the measurements of pressure in the lower limbs was 6 ± 5% (sd) of the brachial pressure.

In the limbs with severe impairment of blood flow manifested by skin lesions or pain at rest, or both, the pickups were not applied. Instead, the systolic pressures were determined by the flush or spectroscopic\textsuperscript{15} techniques. The feet were elevated to decrease the amount of blood in the superficial vessels. The cuffs were then inflated and the limbs returned to horizontal position. The pressure in the cuff was lowered by decrements of 5 mm Hg at intervals of about 10 sec. The appearance of a pink flush on the sole of the foot signaled the systolic pressure, or, when a hand spectroscope was used, the end-point was signaled by the appearance of a black band of oxyhemoglobin at 578 m\textmu in the light reflected from the sole of the foot.\textsuperscript{15} Figure 2 shows the agreement between systolic pressures obtained by the flush technique and by the use of pulse pickups in 160 lower limbs. Similar results were

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Comparison of systolic pressures at the ankles obtained by means of pickups and by visual flush technique in mm Hg (A) and expressed as percent of simultaneously determined brachial systolic pressure (B). The solid line represents the line of identity; the broken lines encompass differences of 10 mm Hg (A) and 10% of brachial systolic pressure (B).}
\end{figure}
obtained by use of the spectrocope and the pickups.

Recording of Pulse Waves

Pulse waves were recorded by the same pulse pickups which were used in the measurements of systolic pressure. With a little practice the pickups could be applied with appropriate degree of tension and recordings free from obvious artifacts were obtained. Pulse waves were frequently recorded in the absence of a palpable pulse. Waves were recorded from over the dorsalis pedis or posterior tibial arteries and from the popliteal fossa. For the application of the pickups in the popliteal region the feet were elevated on a pillow. The waves were recorded on paper moving with a speed of 100 mm/sec. Although the amplitude of the arterial pressure pulses cannot be quantitated reliably from the records obtained using external pulse pickups, the shape and the time components of the externally recorded brachial pulse waves correspond closely to the intra-arterially recorded waves.* Two time components were measured as shown in figure 3. Crest time (CT) was measured from the beginning of the systolic rise to the peak of the wave and the width of the wave at half amplitude (WD) was measured from the point on the upstroke when half of the amplitude was reached to the time when half of the amplitude was reached on the downstroke. The records were measured using a magnifying glass with divisions of 0.1 mm which corresponded to 0.001 sec. The measurements of three or more pulse waves were averaged. Both time components were expressed as per cent of the cardiac cycle. In 23 limbs recordings were repeated within 1 month. The mean absolute difference between the repeated measurements was $2 \pm 2\%$ (SD) for CT and $6 \pm 5\%$ (SD) for WD. The mean difference between the heart rate was $7 \pm 6$ beats/min (SD).

In seven subjects, six without evidence of AOD and one with a proximal stenosis, pulse waves recorded from over the dorsalis pedis artery using pulse pickups were compared with pressure pulses recorded within 45 min from the same site using intra-arterial needles and a recording system with adequate dynamic characteristics. The CT and WD of the pedal waves were expressed in per cent of the cardiac cycle. The mean difference between the CT of the pressure pulses recorded by the pickups and through the intra-arterial needles was $0.4 \pm 0.4\%$ se ($P > 0.2$). The WD, however, was significantly longer when the pickups were used with the mean difference of $2.7 \pm 0.9\%$ se ($P < 0.05$).

Pressure and pulse wave measurements were not carried out in all the extremities at the proximal and distal sites. The number of measurements at different sites is given in the results.

Results

Systolic Pressures

Figure 4 shows AP expressed as per cent of brachial systolic pressure. The higher of

![Figure 3](image)

**Figure 3**

Measurement of crest time (CT) and of the width of the wave at half amplitude (WD). Normal dorsalis pedis pulse wave and a wave recorded distal to an occlusive lesion. Note abnormal prolongation of CT and of WD in the wave recorded distal to the lesion.

![Figure 4](image)

**Figure 4**

Systolic pressure at the ankle (AP) as per cent of the brachial systolic pressure. S = limbs of patients with severe aortic stenosis. The broken lines represent the 95% confidence limits for the limbs without evidence of the occlusive process. Mult. = multiple. C.V. = cardiovascular.
the two arm pressures was used for calculation of the percentage. In the limbs without evidence of occlusive process AP was equal to or higher than the brachial in all but one limb, in which it was 99% of the brachial. The mean in the normal group was 115% of the brachial and in the group with cardiovascular disease it was 110% ($P < 0.05$). The 95% confidence limits were 97 to 124% for the group with cardiovascular disease and 98 to 131% for the normal group. AP was normal in the limbs of the two patients with aortic stenosis. In all 112 limbs with complete occlusion, AP was below normal. The highest value in this group was 81% of the brachial. In 19 of 22 limbs with a single block the AP was greater than 50%, whereas in 16 of 19 limbs with multiple blocks it was less than 50%. In nearly half of the limbs with severe or mild stenosis, the pressure was less than 80% of the brachial. In five of 25 with severe and in four of nine with mild stenosis, the pressures were within normal limits. There was no significant difference between the mean ankle pressure of the limbs with severe and mild stenosis. Figure 5 shows systolic pressures measured at the lower thigh. In all the limbs without occlusive process the TP exceeded the brachial pressure by 8% or more. There was no significant difference between the means of the two control groups without occlusive process. The TP for the combined control groups was 116% of the brachial with the 95% confidence limits of 107 to 127%. The pressures in the limbs of patients with aortic stenosis were normal. The TP was below normal in all 20 limbs with complete occlusion, in nine of 11 with severe, and in all five with mild, stenosis. There was no significant difference between the mean pressure of the limbs with severe and mild stenosis proximal to the knee.

**Pulse Waves**

Figures 6 and 7 show the CT of the pedal and popliteal pulse waves, respectively, plotted against heart rate. The graphs of the WD of the pedal and popliteal waves are shown in figures 8 and 9. The CT of the pedal and popliteal waves increased with increase in heart rate in the limbs of both control groups without AOD ($P < 0.01$), and the WD of the pedal ($P < 0.01$) and popliteal ($P < 0.05$) waves of the normal control group increased. The WD of pedal and popliteal waves recorded from the limbs of the control group with cardiovascular disease did not change with heart rate. Analysis of covariance* was carried out on the relationship of CT and WD to heart rate in the control groups. There was a significant difference between the two control groups in the relationship of WD of the pedal and popliteal waves and in the relationship of CT of the popliteal waves to heart rate ($P < 0.01$), but no significant difference in the case of the CT of the pedal waves. The 95% confidence limits were computed separately when there was a significant difference between the two control groups, whereas in the case of CT of the pedal waves the two groups were combined. Where confidence limits were computed separately, the higher value at a given heart rate was considered to be the upper limit of normal.

*Computations were done by the University of Manitoba computer center's IBM 360, using techniques described by Snedecor.¹⁰

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The relationship of crest time (CT) of the pedal pulse waves to heart rate. Symbols as in figure 4. The solid lines represent the regression of CT on heart rate for the two combined control groups without AOD and the 95% confidence limits.

The limbs of patients with aortic stenosis, the CT of the pedal and popliteal waves was abnormally prolonged, but the WD of both waves was within normal limits.

The values of CT and WD were usually abnormally prolonged in the limbs with AOD. The CT of the pedal waves (fig. 6) was abnormal in 41 of 45 limbs with occlusion, in 22 of 24 with severe and in four of nine with mild stenosis. The CT of the popliteal waves (fig. 7) was within normal limits in a larger proportion of limbs with AOD. On the other hand, the WD of the pedal waves (fig. 8) was abnormal in all limbs with complete occlusion and the WD of the popliteal waves (fig. 9) in all but two. The WD of the pedal waves was also abnormal in 19 of 24 limbs with severe and in four of nine with mild stenosis. Abnormalities of the WD of the popliteal waves were found in 14 of 18 limbs with severe and in three of seven with mild stenosis.

Table 1 shows further analysis of the results in the limbs with arterial narrowing. The limbs with mild and severe stenosis were combined for this purpose. Among 20 limbs in which there was history of intermittent claudication, the AP and the WD of the pedal pulse waves were abnormal in 16 and the CT was abnormal in 18. In 14 of the 20 limbs all three parameters were abnormal, in four limbs two parameters were abnormal, and in two, both with mild stenosis, all three parameters were normal. In the latter two cases, there was complete arterial occlusion and more severe symptoms in the contralateral limb.
Each parameter showed abnormality in eight or nine of the 13 limbs without intermittent claudication. The absence of symptoms in many of these limbs was probably due to the existence of a more severe occlusive process in the contralateral limb or to a cardiac condition which may have limited the amount of walking by the patient. All three parameters were within normal limits in only three of the 13 limbs in this group.

**Figure 7**
The relationship of CT of the popliteal pulse waves to heart rate. Symbols as in figure 4. The solid lines represent the regression of CT on heart rate and the lower 95% confidence limit for the normal control group; the broken lines represent the regression and the upper 95% confidence limit for the control group with cardiovascular disease. There was a significant difference between the regressions of the two control groups.

**Table 1**

<table>
<thead>
<tr>
<th>Intermittent claudication</th>
<th>Total no. limbs</th>
<th>No. of limbs with abnormal measurements</th>
<th>Individual parameters</th>
<th>No. of abnormal parameters per limb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>AP  CT  WD</td>
<td>3  2  1  0</td>
</tr>
<tr>
<td>Present</td>
<td>20</td>
<td></td>
<td>16  18  16</td>
<td>14  4 — 2</td>
</tr>
<tr>
<td>Absent</td>
<td>13</td>
<td></td>
<td>8  9  9</td>
<td>7  2  1  3</td>
</tr>
</tbody>
</table>

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Follow-up Studies

Figure 10 shows ankle systolic pressures measured during the initial and follow-up studies. Among 15 limbs with essentially normal vessels distal to the occlusive or stenotic lesion, there was a substantial increase in the pressure after arterial reconstruction in 14 (fig. 10A). In 11, the postoperative pressure was within normal limits, and in one it was just below normal. There was no change in pressure in a case of an early graft failure. There was a marked improvement in the case in which the pressure rose from 42 to 70%, but 6 months later the graft occluded. Figure 10B shows the results before and after arterial reconstruction in 10 limbs in which a residual distal occlusive or stenotic lesion was present in addition to the lesion which was corrected by surgery. In four limbs the change in AP was less than 10% of the brachial, whereas in six the AP increased by 10 to 35% of the brachial pressure. However, all the postoperative pressures were below normal. Figure 10C shows AP measured at intervals of 1 to 2% years in 19 limbs in which arterial reconstruction was not undertaken. In five limbs, the pressure changed by less than 5%. In 10, the pressure decreased by 10% or more of the brachial. In many of these, larger decreases in pressure were associated with development or increase in symptoms. In four limbs increases of 18 to 27% of the brachial pressure were found. In two of the four the pressure increased but to a level still well below normal. In one of them, the initial measurement was carried out shortly after an acute occlusive episode. In the other two limbs, an initially abnormal pressure of 80 and 85% of the brachial pressure increased to values within normal limits. In one of the two, this was associated with disappearance of symptoms. Angiograms were not carried out in these two cases.
CARTER

Discussion

Systolic Pressures

Clinical Applications

The techniques presented in this report lend themselves well to the study of patients with peripheral vascular disease. About 600 studies were performed in this laboratory over 4 years without the patients having any ill effects. Estimation of the local systolic pressure is easy to perform and its reproducibility is comparable to that of the auscultatory estimation of the brachial systolic pressure. Although electronic equipment was used in the majority of the reported measurements, it was found that the flush technique, which does not require any special equipment, gives results which are equally reliable for clinical application. Therefore, measurement of systolic pressure in the lower limbs may be performed at bedside by any interested physician. Results of the study indicate that measurement of systolic pressure provides a valuable and sensitive objective method for the evaluation of patients with occlusive arterial disease of the extremities, a conclusion which is in agreement with previous reports based on smaller series of cases.3-5,7 The use of this technique may eliminate the need for angiography in a number of cases, whereas in others it may enhance the diagnostic precision by complementing the angiographic findings.

In subjects without occlusive arterial disease, AP exceeded the brachial systolic pressure, which is in keeping with the peripheral amplification of the arterial pressure pulse found using intra-arterial recording.20 AP was

Figure 9

The relationship of the width of the popliteal pulse waves at half amplitude (WD) to heart rate. Symbols as in figure 4. The solid lines represent the regression of WD on heart rate and the 95% confidence limits for the normal control group; the broken lines represent the 95% confidence limits of the control group with cardiovascular disease in which the relationship of WD to heart rate was not significant.
Systolic pressures at the ankle. (A) Before and after arterial surgery in limbs with a single occlusion or stenosis. (B) Before and after arterial surgery in limbs with a residual lesion in addition to the lesion corrected by surgery. (C) Repeated studies at intervals of 1 to 2½ years in limbs in which arterial surgery was not undertaken.

slightly but significantly higher in the normal control group than in the controls with cardiovascular disease who did not have occlusive disease in the arteries of the extremities. Since the mean age was 16 years higher in the latter group \( (P < 0.01) \), the lower systolic pressure may be due to a greater degree of damping of the pulse wave associated with gradual decrease in the diameter of the vessels to the lower limbs with increasing age.²¹ There was complete separation of the values of the AP between the control limbs and the limbs with complete arterial occlusion, and there were only four limbs with stenosis and symptoms in which the pressures were within normal limits. Therefore, in patients with questionable or borderline physical signs and poor or atypical history, a normal AP might help to rule out the presence of a hemodynamically significant occlusive arterial process and thus to eliminate the need for angiography, a procedure which is associated with a small but definite incidence of serious complications.²² Measurements of systolic pressure often complement angiography. They are of value in assessing the hemodynamic significance of the arterial narrowing and may be helpful in determining the adequacy of the
"runoff" distal to an occlusive lesion. Abnormal AP was recorded in five of nine limbs with mild arterial narrowing, as judged by the degree of encroachment of the lesion on the diameter of the lumen in the frontal projection. In four of these five limbs intermittent claudication was present. Also, there was no significant difference in the mean AP between the limbs with mild and severe stenosis. This finding, which is in agreement with similar results on the pressures across the stenoses of the renal arteries, confirms the observation that estimation of the severity of the stenotic lesion by the encroachment on the diameter in a single projection is not reliable. Demonstration of an abnormal AP in a limb with stenosis establishes the physiological significance of the lesion. On the other hand, it is hazardous to assume the clinical importance of a mild or moderate narrowing if a physiological abnormality cannot be demonstrated. Measurement of AP is valuable, not only in the demonstration of the presence or absence of the occlusive process, but also in the evaluation of its severity. This was shown by the good, although not complete, separation of the limbs with a single block from those with multiple occlusions on the basis of the AP. AP should be useful as an index of the runoff distal to the lesion with the pressure of over 50% of the brachial indicating at least a reasonably good runoff. This information may be helpful in deciding whether or not surgery for intermittent claudication should be done on an individual patient, particularly since angiography is frequently unreliable in the demonstration of the vessels distal to an occlusive lesion. Since estimation of systolic pressure is easy, reliable, and without ill effects, it can be carried out repeatedly to follow the patient's condition and to evaluate the result of arterial surgery, thereby eliminating the need for repeated angiography.

Systolic pressures measured at the level of the lower thigh appear to be clinically as reliable as those measured at the ankle. It is important to use a cuff with a long inflatable bag which encircles all or most of the circumference of the limb. Otherwise the pressure in the cuff may not be transmitted fully into the tissues and too high values will be obtained. As was the case with AP, abnormal TP was recorded in the large majority of limbs with proximal stenosis (14 of 16) and in all the limbs with complete proximal occlusion.

Limitations

No appreciable discomfort is associated with the inflation of the ankle cuffs; however, the sensation of pressure is much more intense when the thigh cuffs are inflated, and many patients complain of considerable discomfort. In an occasional limb with heavy calcification of the arterial media, measurement of the systolic pressure may be impossible because of the incompressibility of the wall of the vessel. This occurred in one of 146 limbs with angiographic documentation of the occlusive vascular disease in the present series and in a total of six limbs among over 600 studied during the past 4 years, an incidence of about 1%. Although measurement of local systolic pressure is a sensitive method for the evaluation of an occlusive or stenotic lesion located proximally in the main arterial pathway to the limb, it provides no information about the presence or absence of lesions in the branch vessels such as the internal iliac, the deep femoral, or the individual branches of the popliteal artery. Normal AP will be recorded in the presence of only one patent artery in the leg. Normal pressure was obtained in a limb with the occlusion of both anterior and posterior tibial vessels, but with a patent peroneal artery. This limitation of the method is probably of minor importance, because isolated lesions of the internal iliac and deep femoral arteries are relatively rare and reconstructive surgery on the vessels below the popliteal artery is not as yet in general use.

In some cases in which the occlusion is at the same site as the blood pressure cuff, the systolic pressures show an abnormality, but they may underestimate the hemodynamic significance of the lesion. In two cases of
complete occlusion of the superficial femoral artery in the adductor canal, the TP was only slightly below normal limits. This was probably due to the large collateral branches from the deep femoral artery which transmitted near normal pressure to a level distal to the site of the block before connecting with smaller collateral vessels in the region of the knee. Normal AP was recorded in four of 20 and normal TP in one of 14 limbs with proximal stenosis and symptoms consistent with intermittent claudication. Abnormal pulse waves were found in two of the four limbs with normal AP and in the one with normal TP, thus decreasing to two the total number of limbs in this study in which “false negative” results were obtained. It appears, therefore, that pulse waves and systolic pressures recorded at rest will be abnormal in a large majority of patients with symptoms due to occlusive arterial disease. However, in a small percentage of cases with arterial narrowing, exercise studies may be necessary to demonstrate the hemodynamic abnormality by showing an abnormal fall in the AP or an abnormal change in pulse wave or blood flow.

Pulse Waves

Clinical Applications

Indirect recording of pulse waves from over the arterial sites in the human extremities provides a useful adjunct to the measurement of systolic pressures. Good agreement of the CT and WD was found between the pedal waves recorded by the pickups and by the intra-arterial route, although the pickups overestimated the WD by about 10%. These findings are similar to the comparison of the brachial pressure waves recorded through intra-arterial needles and from externally applied cuffs. Pulse waves can often be recorded in the absence of a palpable pulse. The same externally applied pulse pickups can be used both to record the waves and to signal the systolic pressure during deflation of the pneumatic cuffs. Therefore, recording of the pulse waves can be obtained rapidly and without ill effects, together with the measurement of systolic pressure. However, since the pickups have to be applied with a certain degree of tension, application to severely ischemic parts of the limbs should be avoided.

There was complete separation of the WD of the pedal pulse waves between the control limbs and those with complete proximal occlusion and, with the exception of two limbs with occlusion, complete separation of the WD of the popliteal waves. Therefore, the WD was essentially as good as the systolic pressure in separating the limbs with complete occlusion from the normal. The incidence of normal WD of the pedal pulse waves among the limbs with proximal stenosis was the same as the incidence of normal systolic pressures, but it was greater in the case of the popliteal waves. Information derived from pulse waves complements the study of systolic pressures and it may increase the diagnostic sensitivity of the procedure. As indicated above, abnormal pulse waves recorded in three of five symptomatic limbs with stenosis and normal systolic pressures reduced the number of symptomatic limbs with “false negative” results to two in the present series. Recording of pulse waves provides other advantages. There is no discomfort to the patient, so that the information derived from the popliteal waves may eliminate the need for measurement of systolic pressure in the thigh which is frequently associated with considerable discomfort. When systolic pressure cannot be determined because of incompressibility of the calcified arterial walls, the pulse waves may provide valuable information about the presence or absence of a proximal occlusive lesion. Since the pickups are applied distal to the pneumatic cuffs, they may provide additional information about the arterial segment between the cuff and the pickup. For example, in the two cases of complete occlusion of the femoral artery in the adductor canal, in which TP was only slightly below normal limits, the popliteal waves were grossly abnormal in keeping with proximal occlusion. Similarly, in the case of occlusion of the anterior and
posterior tibial vessels, in which normal pressure was recorded at the ankle because of the patent peroneal artery, the pedal wave was grossly abnormal because of damping in the small collaterals which connected the peroneal artery to the vessels in the foot.

Limitations

A certain amount of distortion may be associated with external recording of the arterial pressure pulses. Although there was a good agreement of the time components of the externally and directly recorded pulse waves from the dorsalis pedis artery, more distortion may be present in the records from the popliteal fossa, because of the greater volume of soft tissues between the popliteal artery and the skin. It is likely that the peak of the wave may be particularly sensitive to such distortion. This might explain the relatively large overlap between the CT of the popliteal waves recorded from the limbs with and without arterial occlusive disease. The reproducibility of the time components of the pulse waves was not as good as that of the systolic pressures. This may be due to the different amount of distortion associated with the application of pickups on different days and to the differences in heart rate and in the vasomotor state of the subjects. The lesser degree of overlap of the values of WD between the control limbs and those with AOD suggests that this part of the wave is less affected by distortions than CT. Also, WD (as well as systolic pressure) was normal in the limbs of patients with aortic stenosis, while the CT was abnormal. None of the patients in this series was in overt heart failure. It is possible, however, that abnormal peripheral pulse waves may be recorded in patients with gross abnormalities of the cardiac function which are associated with marked alterations of the central pressure wave.

Since the results of this study indicate that abnormal systolic pressures, or pulse waves, or both, are found at rest in the large majority of limbs with AOD, it appears that, for clinical purpose, the more cumbersome exercise stud-


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