INTRODUCTION

In 1959 we carried out a retrospective study of our results in the surgical treatment of peripheral arterial disease. This study pointed out clearly that we were greatly hindered in our attempts to evaluate results because of a lack of objective methods to study patients. Thus, patient evaluation was limited strictly to the impressions of multiple observers and arteriography. While these modes of investigation are indispensable, they give relatively little information as to the functional status of the circulation. Arteriograms give precise information as to location of disease but fail to provide an index of disturbed physiology. Also, it is difficult to suggest to the patient and the referring physician that serial arteriograms are required to assess graft patency or to investigate changes in patients' symptomatology.

Fortunately the physiologist has given us the tools with which to study the functional as pects of disease and therapy. Beginning in 1905, Brodie and Russell [1] first demonstrated the value of the plethysmograph in quantitating peripheral blood flow. Since that milestone, intensive efforts by physiologists using the plethysmograph have provided most of the current knowledge relative to skin and muscle flow, sympathetic activity, postural reflexes, exercise studies and the effects of various drugs on the circulation.

It is only natural that the clinician should apply these research technics to the clinical study of patients. This has been hampered greatly by the complexity of the research technics and the difficulty in interpreting the obtained results. The difficulties have not been insurmountable, however, as evidenced by the successful application of these technics by Edwards,[11] Goetz,[14] Smithwick [31] and Winsor.[42]

Because of the need for objective criteria, a simple but sensitive plethysmograph was selected.[13, 32] This report is concerned with the application of this device, the mercury strain gauge plethysmograph and includes illustrative case histories. In utilizing this device, we have leaned heavily upon our predecessors and are grateful to them for their pioneering efforts. It is hoped that this study technic will eventually occupy the same place in peripheral vascular surgery as does the electrocardiograph in internal medicine.

I. THE PROBLEM

The peripheral manifestations of arteriosclerosis obliterans and other arterial diseases present a challenge to the surgeon not only for the salvage of the limb but also for restitution of a pain-free and ambulatory patient. The current procedure is a careful history and physical examination followed by appropriate angiography. This, in turn, leads to either a direct effort on the major blood vessels or interruption of the vasomotor nerves by sympathectomy. There is no question that this approach is an excellent one, which has led to many of the outstanding advances made in vascular surgery. The purpose of this report is to show that with the plethysmograph a great deal more information can be obtained which is helpful in diagnosis, case selection and therapy.

It should be stressed that the information obtained by plethysmography is used to complement, not replace the data obtained by other methods such as angiography. Also, it should be emphasized that this technic is only as good as the care with which the studies are performed. To date a total of 427 patients with a wide variety of vascular problems have been studied with this device (Table 1).

II. INSTRUMENTATION

In 1953 Whitney [37] first described a simple mercury in rubber strain gauge plethysmograph for the study of forearm blood flow. The gauge consisted of a small bore latex rubber tube filled with mercury. When the gauge is placed about the terminal digit, the volume changes that occur with each heart beat produce a corresponding lengthening of the gauge and contained mercury column. These phasic changes in digit volume result in resistance changes in the mercury column which, by using an appropriate matching circuit, can be amplified and recorded. By the methods used currently it is possible to amplify the resistance changes such that a change in the length of the gauge of only one micron will produce a one millimeter deflection of the galvanometer stylus. This marked sensitivity has made it possible to detect and record small changes in digit blood flow.

Early in our experience latex rubber gauges were used exclusively, but they proved unsatisfactory for repeated daily use. The rubber gauges have since been completely replaced by a new synthetic, silastic.* This material is quite elastic and makes excellent gauges without loss of sensitivity. The silastic gauge is much more durable and with proper care will permit many months of continuous use.

The type of electronic equipment required for implementation of plethysmography depends largely upon the intended application. We are currently using two distinctly different types of circuits in our clinical and laboratory studies. The impedance matching circuit (Appendix, B) is the most versatile in that it can be applied to both routine clinical studies and laboratory research. Using this circuit with a strain gauge amplifier such as the Sanborn 150 and 350 series, it is possible to study (1) digit volume pulse changes; (2) sympathetic activity and vasomotor reflexes; (3) to measure segmental leg pressures; (4) to quantitate digit blood flow. Its disadvantages from a practical standpoint are that it requires a strain gauge amplifier and must be balanced several times during each examination.

In order to simplify the technic and make it readily available to physicians who do not have specialized electronic equipment, our electronics consultant † designed a circuit which can be used with commonly available electrocardiograph amplifiers and recorders. This is extremely simple to use since it requires no electronic balancing. Because of the self-centering, stable baseline characteristics of the electrocardiograph, this unit will not permit evaluation of volume changes which are reflected in shifts of the baseline. For this reason this circuit has more limited applications than the originally described matching circuit. For example, in order to adequately evaluate sympathetic activity, it is necessary to observe the phasic changes in digit volume which occur with vasoconstriction and vasodilatation. Similarly, quantitation of digit blood flow is dependent upon observing the changes in the volume of the digit that occur with temporary venous occlusion. While these disadvantages make this new circuit unsuitable for some aspects of a peripheral vascular study, it is sufficiently versatile to recommend its use for routine clinical problems.

Both circuits are used in our clinical studies. For the routine patient studies the self-balancing circuit is adequate. For the study of components of sympathetic activity or the observation of composite changes in digit volume, the impedance matching circuit is used.

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TABLE 1. *Total Patients Studied 427*

Arteriosclerosis obliterans	279
Buerger's disease	8
Vasospastic disease	10
Post traumatic	9
Peripheral emboli	7
Cold injury, chronic	5
Venous disease only	37
No arterial disease found	51
Miscellaneous	18
Arteriovenous fistula	3

III. METHODS OF STUDY

Examinations are performed in a room with a temperature of 74–78° F. Although careful control of temperature and humidity is essential in doing quantitative physiologic studies, it is not essential for clinical purposes. It is desirable to avoid wide swings of temperature, however, and drafts are annoying if the patient being studied is sensitive to cold.

Routinely one arm and both legs are examined. Because of the rarity of upper extremity disease, the pressure and volume pulse measurements in the arm and finger are used

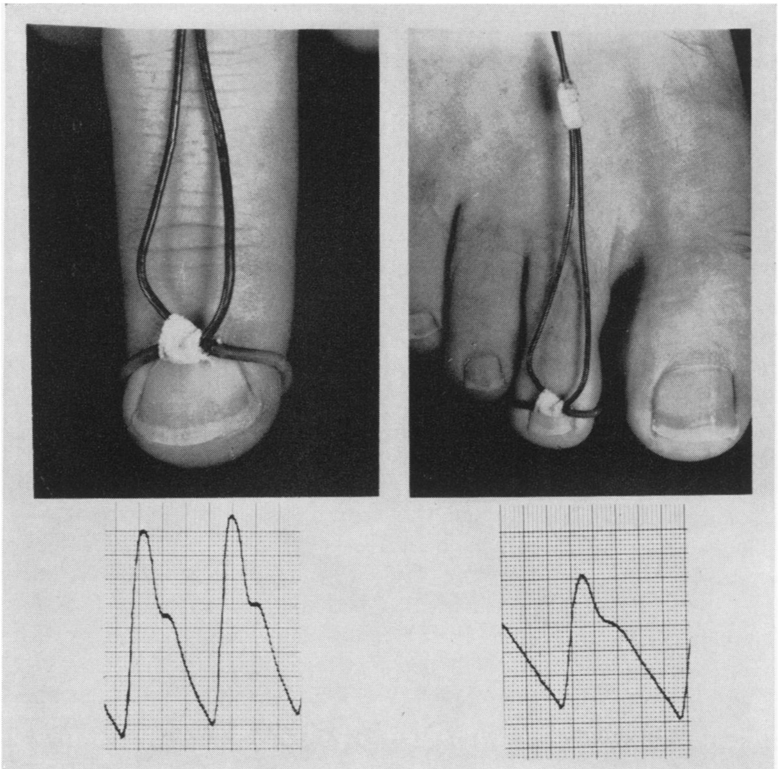


FIG. 1. This illustrates placement of mercury strain gauge on finger and toe with non-expansible portion over base of nail. Digit pulses are normal and are characterized by a sharp systolic peak and a dicrotic wave on the downslope. (Reproduced by permission of *Surgery, Gynecology and Obstetrics.*)

for "normal" standards for comparison. The usual routine of examination is frequently modified, however, depending upon the nature of the disease entity being considered.

The strain gauge loop is placed about the distal phalanx of the finger and toe so that the non-expansile portion of the gauge is over the base of the nail (Fig. 1). Sufficient tension must be placed on the gauge so that the entire digit is in close contact with the gauge. For routine clinical studies this is not critical but such approximation becomes very important if venous congestion tests are to be carried out.

A. *Digit pulse contour and volume.* As the blood enters the digit during systole, the digit volume increases thus stretching the gauge and increasing its electrical resistance. These phasic changes in volume are amplified and recorded as the digit pulse which normally has a characteristic wave form (Fig. 1). In the absence of arterial disease, the contour of the pulse has a very sharp ascending limb, a sharp systolic peak and a dicrotic wave on the downslope. Both the self-balancing circuit and the impedance matching circuit are suitable for studying this aspect.

The phasic changes in digit volume which occur with each heart beat are primarily the reflection of changes in venous volume. Parrish *et al.*[27] in a recent study from our laboratory have presented evidence to support this concept. The marked similarity between the plethysmograph readings and the changes which occur in small vein pressure are in sharp contrast with the pulsatile changes seen in the small artery pressure (Fig. 2). These observations have important implications from a diagnostic standpoint since alterations in either the digit pulse contour and/or volume will occur with obstructive lesions on the arterial side down to and including the arterioles.

B. *Normal variants.* Changes in the volume and contour of the digit pulse accurately reflect the level of vasomotor tone at the time of examination. With arteriolar constriction, the volume of the pulse decreases and the contour is flattened. By virture of its low amplitude, the pulse may appear abnormal but in most instances the dicrotic wave may still be seen on the downslope. To adequately evaluate the contour of the pulse, the vasoconstrictor tone may be temporarily removed by a reactive hyperemia test (Fig. 3). This test is carried out by effecting arterial occlusion at the ankle for a period of five minutes. During this period of occlusion, the products of anaerobic metabolism accumulate; these are potent vasodilators. With release of the cuff, there is a rapid increase in the digit volume accompanied by a marked increase in the amplitude of the digit pulse. When the self-balancing, stable baseline circuit is used, the volume increases in the digit are poorly appreciated, but the digit pulse amplitude increases are readily seen. This procedure (RHT) is not only an effective vasodilating test, but also permits the distinction of arteriolar spasm from other causes of decreased digit blood flow.

The dicrotic wave may be lost without organic arterial obstruction. In patients with extensive medial calcification in the major arteries this is seen frequently. This has no clinical significance as long as the systolic upslope remains rapid and the peak is sharp.

C. *The obstructed pulse.* With obstruction in the arterial tree the higher frequency components of the digit pulse are damped considerably since the blood is forced through smaller high resistance collateral pathways.

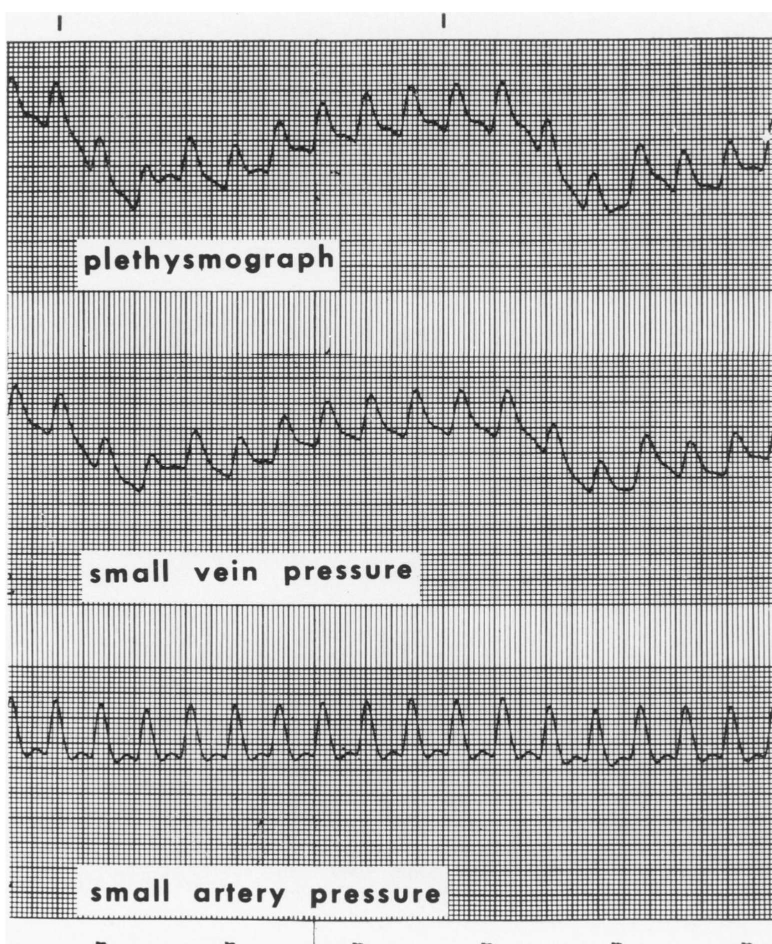


FIG. 2. A record showing marked similarity between plethysmograph readings and small vein pressure and differences between these and small artery pressures. Sensitivities were arbitrarily set on all three channels to produce approximately equal pulse amplitudes. (Reproduced by permission of the *Journal of Laboratory and Clinical Medicine.*)

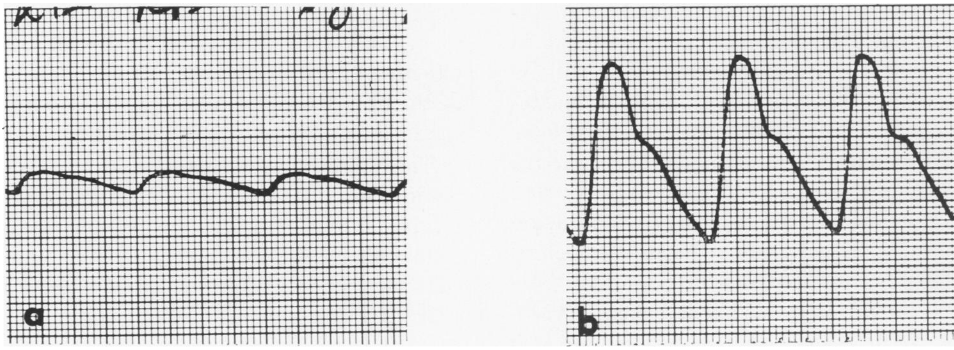


FIG. 3. Tracing A illustrates the typical flattened pulse of vasoconstriction. Normal contour is evident after release of the vasoconstrictor tone by a reactive hyperemia test, tracing B.

It is convenient to classify the types of obstructed pulses into the following groups.

1. *Delay of systolic peak and absence of dicrotic wave* (*Fig. 4*). This type of pulse is seen most frequently with occlusion of the superficial femoral artery in Hunter's canal. The profunda femoris artery and geniculate vessels about the knee are rarely involved with atherosclerosis and are excellent collateral channels. This accounts for the rather sharp ascending limb and good pulse volume. When this type of pulse is seen the distal arterial tree is patent, at least in a functional sense. It is possible for either the anterior or posterior tibial artery to be occluded in addition to the adductor canal occlusion and give the same pulse findings. In our experience patency of just one of these vessels is sufficient to maintain not only a normal distal pressure, but also an asymptomatic extremity. This is because of the excellent collateral potential which exists below the knee. There are multiple segmental branches which intercommunicate and anastomose extensively.[29]

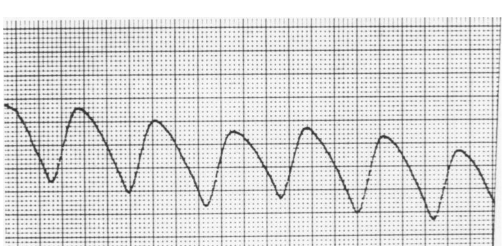


FIG. 4. Pulses shown are of good volume but have some blunting of the systolic peak and an absent dicrotic wave. This is commonly seen with segmental occlusions of the superficial femoral artery.

This same type of pulse may be seen in patients with a patent superficial femoral artery, but in this instance both the anterior tibial and posterior tibial arteries must be involved. Occlusions of only one of these two vesels is not sufficient to alter the volume or contour of the digit pulse since the course of each carries them to the dorsum and plantar surfaces of the foot where anastomotic communication is extensive. Lesions of the peroneal artery cannot be estimated since it is the smallest of the three vessels and does not usually have a major contribution to the blood supply of the foot and digits.

2. *Flat digit pulse* (*Fig. 5*). The usual situation where this is encountered is with occlusions proximal to the inguinal ligament. Although there is good collateral circulation about aortic and iliac occlusions, there appears to be more damping of the higher frequency components through the varied collateral pathways available.

The other common area of involvement which produces this picture is below the knee. More than just short segmental occlusions of both the anterior and posterial tibial arteries are required to result in this pulse abnormality. In our experience extensive involvement is necessary and represents a marked reduction in the collateral capacity in this area.

3. *Absent digit pulses* (*Fig. 6*). If the digit blood flow is completely non-pulsatile even after a vasodilating procedure has been carried out, critical areas of the circulation are involved. Some of these areas are: (1) popliteal artery and its trifurcation; (2) extensive occlusion of all three vessels below the knee; (3) occlusion of the plantar and digital arteries; (4) multiple levels of occlusion. Reduction of collateral circulation to this extent carries an ominous prognosis. Unless the critical areas of involvement are amenable to bypass or endarterectomy, these patients frequently come to an early amputation. These are the patients who enter the hospital with rest pain, ulceration and gangrene.

It must be emphasized that categorization of digit pulses into such groups is useful in a general sense only and the findings from patient to patient may vary somewhat. It is practical to consider pulse categories in these terms when this information is combined with other plethysmographic and clinical data.

D. *Segmental Pressure Measurements.*[41] Specifically constructed pneumatic cuffs * are placed successively on the upper arm, upper thigh, above the knee, below the knee and about the ankle. The inflatable portion of the cuff occupies its entire length so that uniform circumferential pressure may be applied. At each level the cuff is raised to above systolic blood pressure and gradually lowered until there is a sudden increase in digit volume and/or pulsations reappear (Fig. 7). The pressure noted at this point is recorded as the systolic pressure at that level. Unless the end point is definite and reproducible, the pressures recorded are of no value and may be misleading. The systolic pressure at any level in the leg is normally higher than at any corresponding level in the arm. In general, the pressure gradient between any two successive points of

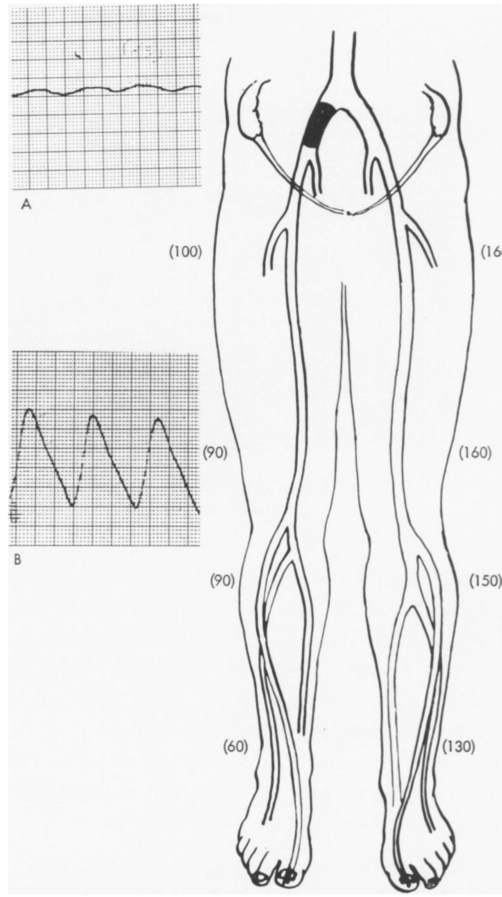
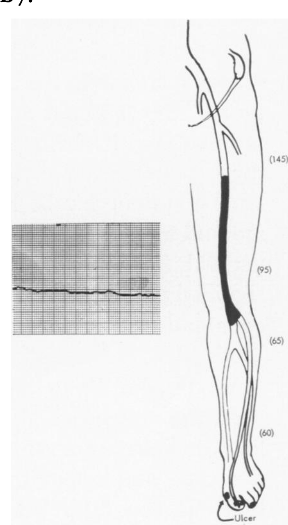


FIG. 5. Low right groin pressure establishes occlusion to be above inguinal ligament and involving iliac artery. Preoperative pulses (A) are typically low in amplitude and flattened. After a successful endarterectomy, digit pulses have a normal volume and contour (B).

FIG. 6. Large pressure drop from upper thigh to below knee suggests extensive occlusive involvement including popliteal artery. Absence of a digit pulse following a reactive hyperemia test suggests that critical areas of collateral circulation are involved.



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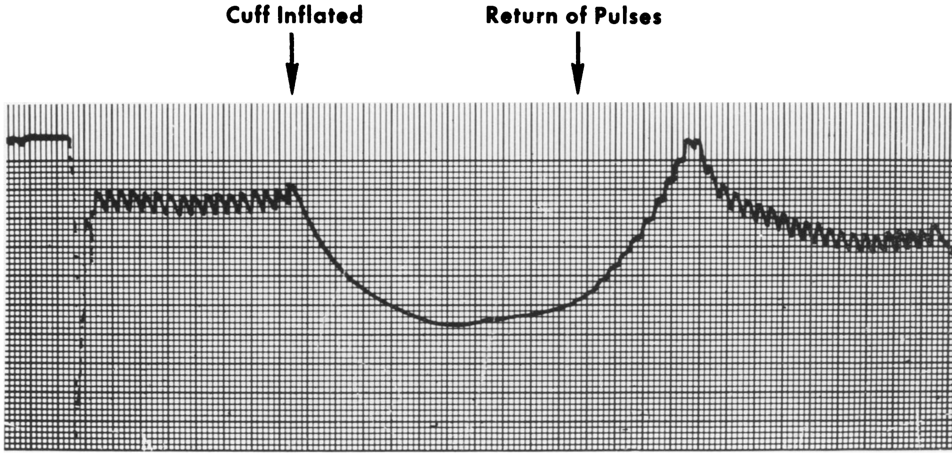

FIG. 7. Segmental systolic pressures can be measured at any level by noting point at which pulses return after complete obliteration of digit blood flow.

the leg should not exceed 20 mm. Hg. If it is greater than 20 mm. Hg, this generally signifies arterial stenosis or obstruction between the two levels. These observations were accurate in 80 per cent of 35 cases studied by subsequent arteriography or dissection of the amputated extremity.[32] There are situations in which caution must be exercised in interpreting the recorded segmental pressures.

1. *Incompressability of arterial inflow.* If there is medial calcification, or if the patient's legs (particularly upper thighs) are very large, it may be impossible to completely occlude arterial inflow and measure satisfactory pressures. This occurs in 5–10 per cent of all cases.

In the case of medial calcification which is very common in the diabetic, the incompressability is noted at all levels of measurement and is obvious by the presence of digit pulses even with pressures above known systolic levels. In this situation the measurements are meaningless but, in general, incompressability at any level has signified patency of the main arteries since collateral vessels are usually easily obliterated with the cuff.

When the limbs are very large the pressures measured at the ankle and below the knee are accurate but those above the knee and upper thigh can be falsely high. If the ratio between the pressure above the elbow and above the knee is less than 1.2, the values measured above the knee are probably falsely high.[42]

2. *Borderline pressure gradients.* Occasionally a gradient as high as 30 mm. Hg will be found in the absence of obstruction. This is probably the result of stenosis or marked intimal thickening, with a resultant increased resistance to flow. With complete segmental occlusion of main artery flow, gradients in the range of 40–80 mm. Hg are generally found.

3. *Normal pressure gradient with arterial obstruction.* If the collateral vessels bypassing an arterial obstruction are large enough, it is possible to have a normal gradient across the occluded segment (Fig. 8). Collateral vessels of this size offer very little additional resistance to flow, hence the gradient remains in the normal range. This finding has been very uncommon in our experience but must be kept in mind.

If either the anterior tibial or posterior tibial artery alone is open, the pressure gradient from below the knee to the ankle is usually normal and the patient asymptomatic. If the gradient from below the knee to the ankle exceeds 30 mm. Hg, it indicates occlusive involvement of both the anterior and posterior tibial arteries.

E. *Digit Blood Flow* (*see Appendix*). Although quantitation of digit blood flow is not used in our clinical studies, we do employ it in the research laboratory. The rate of arterial inflow into the digits is studied by noting the change in digit volume per unit time after temporary venous occlusion.[10] An occlusive cuff is placed immediately proximal to the gauge and suddenly inflated to a pressure of 50 mm. Hg to provide complete venous occlusion. With sudden venous occlusion there is an upward shift of the baseline on the tracing, the slope of which is determined by the volume flow. If a careful calibrating procedure has been followed, it is possible to calculate digit blood flow and express it as cc./100 cc. of tissue/min (Appendix C).

The quantitation of digit blood flow in the clinical evaluation of patients requires a good deal of additional effort and the results are not as meaningful as they might seem. Baseline blood flow in patients with and without occlusive disease is so variable that the results are often meaningless. It has been shown that the digit blood flow in patients with occlusive disease can be and often is within normal ranges.[12] The reason for this great variation is related to the function of the acral circulation which is under sympathetic control. Such factors as a deep inspiration, unpleasant stimuli, cold, etc. will profoundly affect sympathetic tone and digit blood flow.

For qualitative evaluation of flow the amplitude changes of the digit pulse are adequate for routine clinical studies. Burton [4] has clearly shown that the correlation between the changes in the digit volume pulse and flow as measured by venous congestion tests is excellent. We have verified this in our laboratory and have preferred to use the volume pulse amplitude as an indicator of not only the directional changes in flow but also the approximate magnitude. It should be emphasized that these relationships hold true only if the position of the extremity remains unchanged. Changes in the venous volume affect the amplitude of the pulse, making these correlations impossible if the extremity position is changed. This has not been a problem in our clinical studies since only the supine position is utilized for the observations.

FIG. 8. Pressure gradient from above to below knee was normal. This normal gradient is present because of very large collateral vessel bypassing popliteal occlusion.

F. *Vasomotor Activity and Reflexes*

1. *Sympathetic slow waves* (*Fig. 9*). In normal individuals there are regular, rhythmic changes in sympathetic vasomotor activity which appear as cyclic shifts in the baseline of the plethysmographic tracings. These slow wave changes can be further subdivided into α, β and γ waves,[42] but this is of little value in clinical evaluation. In normal individuals there is great variation in the magnitude of these changes which are largely reflected by the emotional set of the person and the ambient temperature. As will be described these changes are primarily of value in the diagnosis of vasospastic diseases and evaluating the completeness of surgical sympathectomy. The impedance matching circuit must be used to demonstrate these shifts.

2. *Inspiration reflex* (*Fig. 10*). Following a deep inspiration, a transient reflex vasocon-

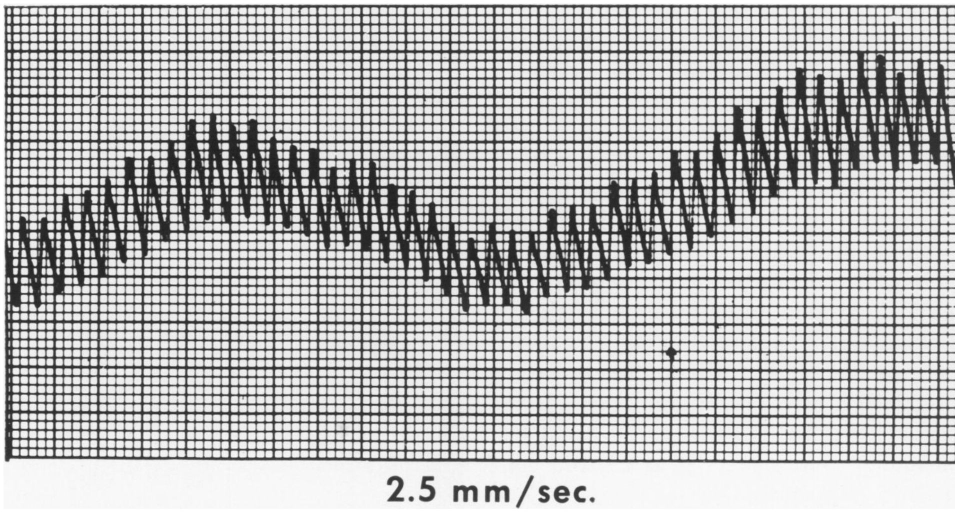

FIG. 9. The normal fluctuations in vasomotor activity are reflected in the change in the amplitude of the volume pulse. With vasodilatation the volume pulse amplitude increases while it decreases with vasoconstriction.

striction occurs. The magnitude of this response depends on the amount of digit blood flow and level of vasomotor tone. The patient with a very active sympathetic nervous system often demonstrates marked changes in digit volume and amplitude of the volume pulse. This reflex is dependent upon intact sympathetic innervation and disappears after complete surgical sympathectomy. Since the reflex vasoconstriction results in a decrease in the amplitude of the digit pulse as well as a decrease in digit volume, the self-balancing circuit can be used in this observation. If the amplitude of the pulse decreases, vasoconstriction has occurred.

3. *Release of vasomotor tone.* As mentioned previously, the reactive hyperemia test may be used to produce vasodilatation and estimate the increase in flow that might be expected with release of vasoconstrictor tone. This test in our opinion represents the safest, quickest and most uniform method of producing vasodilatation. Early in these studies nerve blocks were employed, but were more time consuming and, in general, were not as reliable. If five minutes of occlusion produces no changes in flow, the test should be repeated with 10 to 15 minutes of occlusion. Rather than carry out venous congestion tests, we simply note the changes in the digit pulse amplitude which occur.

G. *Exercise Studies.*[40] A very important part of our studies has been the evaluation of the extremity response to treadmill exercise. The patients are exercised walking on a 12 per cent grade at two mph. The patient has baseline determinations made of the digit volume pulse amplitude and the ankle pressure in the supine position. The patient then exercises to the point of claudication at which time the supine position is quickly resumed and the same parameters evaluated. In the normal response to five minutes of exercise there is a transient decrease in digit blood flow followed by a rapid return to baseline levels often overshooting the initial level (Fig. 11). The ankle pressure remains unchanged or slightly increases. The response of the extremity with arterial occlusion and claudication is remarkably different (Fig. 12). The digit blood flow decreases to very low levels and remains so for several minutes. In addition the ankle pressure may become unrecordable and occasionally require up to 20 minutes to return to the baseline level. This phenomenon probably represents a marked decrease in vascular resistance in the exercised muscle which causes the drop in pressure since the collateral vessels are

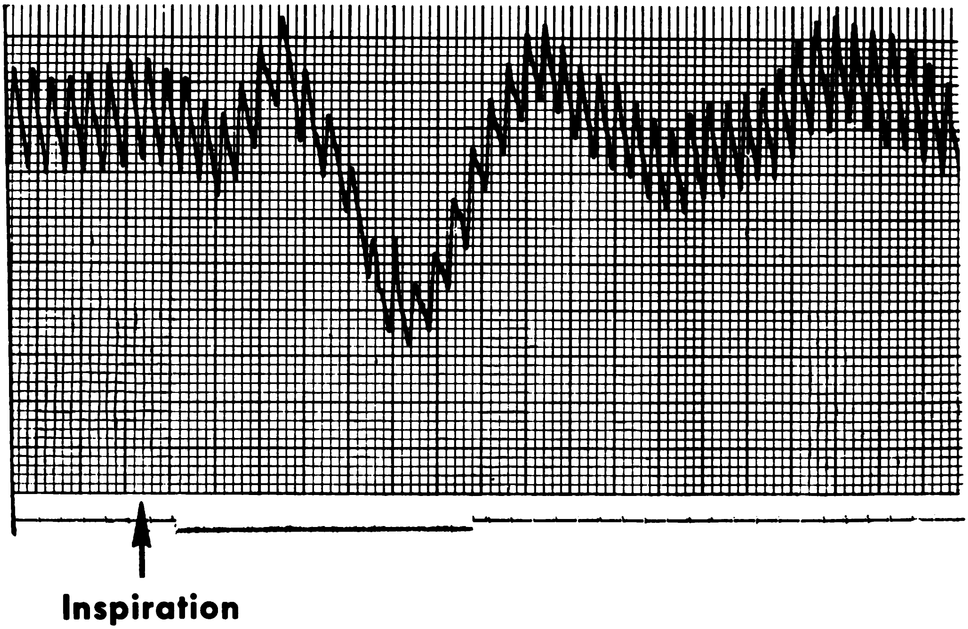

FIG. 10. The transient vasoconstriction which follows deep inspiration is illustrated.

unable to provide the volume of blood required to maintain normal pressure and flow. This phenomenon is seen only in the patient with arterial occlusion and serves as an excellent diagnostic test which can be used in evaluating the patient with atypical calf pain.

The level of occlusive involvement must be proximal to the major muscle masses in the lower leg for this phenomenon to occur. For example, if the occlusive involvement is below the knee and below the supply to the gastrocnemius and soleus muscles, this response will

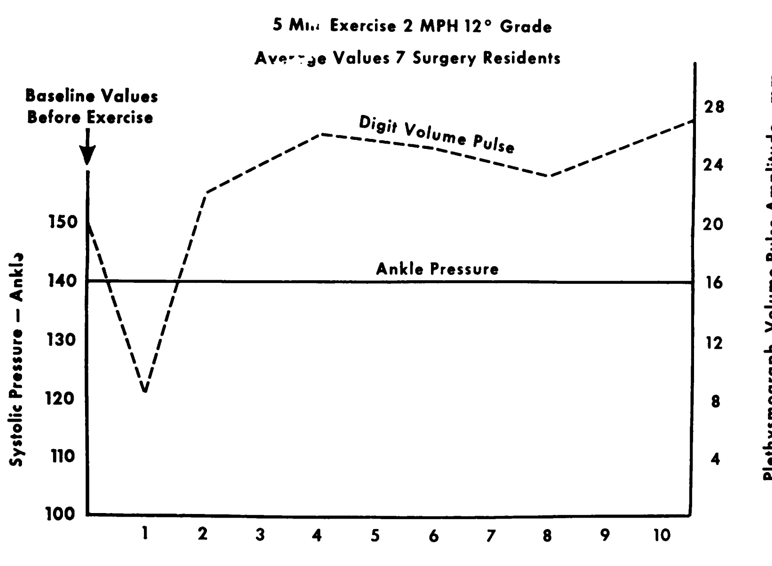

FIG. 11. Immediately after exercise, there is a very transient decrease in digit volume pulse (skin blood flow) which then rapidly returns to normal. Ankle pressure remains unchanged with this amount of exercise. (Reproduced by permission of *Surgery Gynecology and Obstetrics.*)

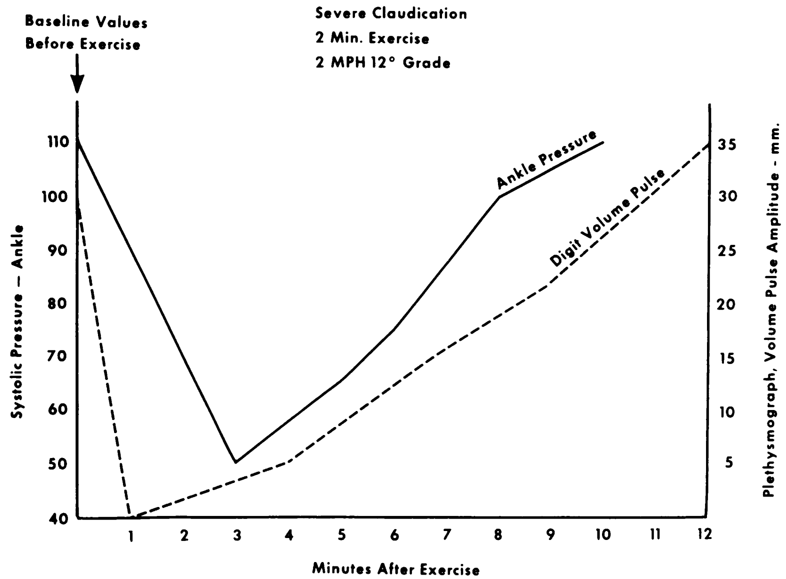

FIG. 12. In patient with occlusive arterial disease, skin blood flow as well as ankle pressure drop to very low levels requiring several minutes to return to baseline levels.

not occur. If the occlusion is proximal to these muscle groups, this phenomenon is always seen.

IV. ARTERIOSCLEROSIS OBLITERANS

The diagnosis of occlusive arterial disease secondary to atherosclerosis is usually relatively simple. The patient gives a history of claudication, coldness, night pain, etc. and physical examination often reveals a decrease in hair growth, trophic nail changes and absence of palpable pulses, the level of which are determined by the occlusive process. Occasionally, however, atypical calf pain in a patient with either diminished or normal pedal pulses may pose a problem in diagnosis. De Weese [8] emphasized that the diagnosis in these cases may be established by noting change in the pedal pulses with exercise. The pedal pulses in patients with stenosis or occlusive arterial disease disappear with exercise, thus establishing the diagnosis with certainty. This is true but interpretation of foot pulses even by experienced observers is often uncertain. In this regard the treadmill response to exercise is very valuable in ruling in or out the presence of arterial obstruction as the etiology of the pain.

Arteriosclerosis obliterans and diabetes mellitus. There are some very important differences in the diabetic and nondiabetic with arterial disease which are easily evaluated by plethysmography. The location of the occlusive disease in these two groups is different in that the diabetic has the same incidence in the femoral-popliteal area but a statistically significant higher incidence of involvement of the three vessels below the knee while having a lower incidence in the aorto-iliac region.[34] This can be detected by noting the abnormal pressure gradient from below the knee to the ankle. If the pressure drop here exceeds 20–30 mm. Hg, occlusive disease is a certainty. Reconstructive surgery for a patient with distal occlusive disease is more hazardous since compromise of the arterial runoff has been associated with a higher incidence of failure.

Another very important difference between the two groups is in the occurrence of a peripheral neuropathy. Twenty-seven per cent of the diabetic patients in our study have this complication. This neuropathy which usually manifests itself as a sensory deficit predisposes the patient to a higher incidence of ulceration which rarely heals even under good care. From a plethysmographic standpoint, these cases are easily recognized by the complete absence of slow wave activity and inspiratory reflex (Fig. 13). These patients are autosympathectomized and have essentially a complete vasomotor paralysis of the lower extremity. Of course lumbar sympathectomy would be completely ineffective in this group of patients.

In recent years a great deal of attention has been directed toward the small arteries, arterioles and capillaries in patients with diabetes mellitus. It has been stated that there is a specific non-atheromatous lesion involving small arteries and arterioles which distinguishes the diabetic from the non-diabetic. We have been looking since 1959 for diabetic patients with this lesion and to date have been unable to find any. In a recently completed study of amputation specimens in our laboratory, we were unable to separate the diabetic patients from the non-diabetic patients or to accurately categorize them using the diagnostic criteria of Goldenberg.[15] Our data to date have not supported this concept of a specific lesion, nor do we believe arteriolar changes are important in the genesis of the local ischemia and tissue necrosis. Since our studies did not include an electron microscopic examination of capillary basement membranes, we have no information concerning this new area.

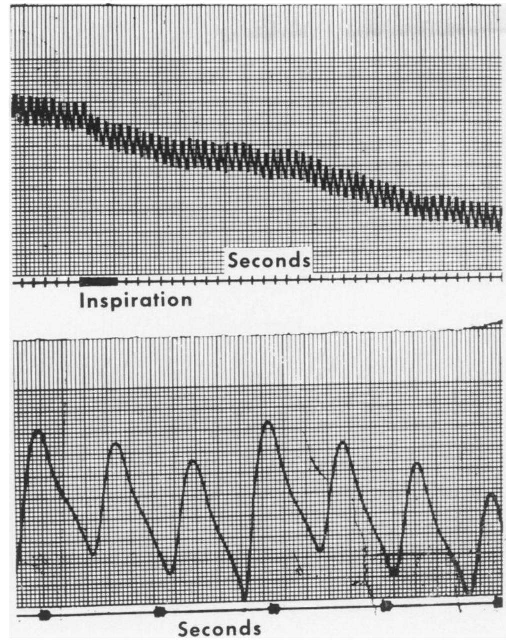

FIG. 13. With diabetes mellitus and a peripheral neuropathy, slow wave autonomic activity is absent as is inspiratory reflex. Digit pulses illustrated are normal. (Reproduced by permission of *Diabetes.*)

V. SELECTION OF CANDIDATES FOR RECONSTRUCTIVE SURGERY

"Ideal" patients for these procedures are those who can be shown to have segmental occlusive involvement with patent vessels distal to the obstruction. An obstruction, whether embolic or thrombotic, increases the local pressure gradient, the magnitude of which is determined by the amount of resistance to flow through the collateral channels. Winblad *et al.*[38] in studying the arterial pressure below an obstruction found that a small gradient of pressure from below the obstruction to the foot indicates that the distal vessels are open and functional.

By studying the pressure gradients and the digit pulses, it is possible to accurately predict the site of occlusion and the functional state of the distal vessels. We do not believe routine aortography is necessary in each patient with occlusive arterial disease. We are aware that this is strongly recommended by some surgeons particularly in those cases where reconstructive surgery is contemplated for occlusive disease below the inguinal ligament. Blaisdell[2] has emphasized that without such information stenotic lesions in the iliac system may be missed which will lead to graft or endarterectomy failure. We fully agree that grafting in the region of superficial femoral artery may well fail if a lesion exists in the aorto-iliac system which is significant enough to reduce pressure and flow. Aortography is not needed to obtain this information and it can be misleading. For example, if a stenotic lesion is seen by x-ray, this tells the surgeon nothing about its hemodynamic significance. Recent experimental and clinical studies have clearly shown that when a stenosis becomes significant, both pressure and flow fall off stimultaneously.[24] For this reason the groin pressure determination is very useful. If the groin pressure is higher than the arm pressure, a hemodynamically significant iliac stenosis cannot exist. To date we have not hesitated to consider a femoral-popliteal bypass graft in a patient with an iliac stenosis but normal groin pressures, nor have we had a failure of the procedure attributable to such a lesion. The following report illustrates such a case.

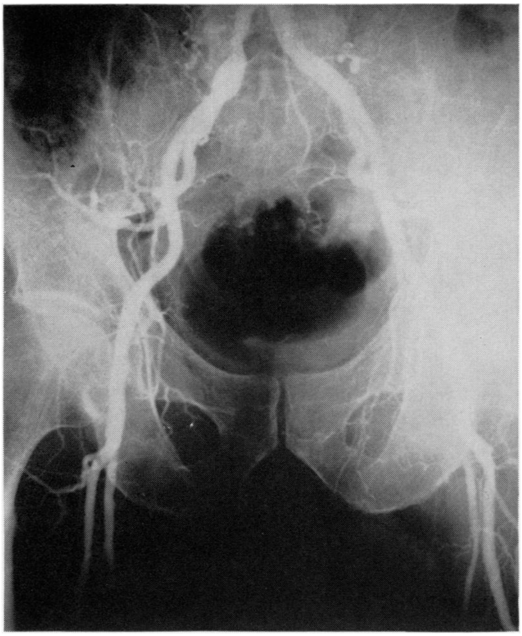

FIG. 14. There is a minimal stenosis in right common iliac artery without a pressure drop across this area as evidenced by normal and equal groin pressures.

Case Report: This 64-year-old white man was first seen on 8-29-63 for evaluation of bilateral calf claudication. He was noted to have normal femoral pulses but bilateral bruits were heard over the iliac arteries. Plethysmographic studies revealed normal groin pressures bilaterally (180 mm. Hg as compared to an arm pressure of 165 mm. Hg) and a large drop in pressure to above the knee with normal gradients below. He recently had been seen in another hospital where aortography and femoral angiography had been carried out. The aortogram had revealed a stenosis of the right iliac artery (Fig. 14). He was refused a femoral-popliteal procedure because of the iliac stenosis. With the knowledge that his stenosis was not hemodynamically significant, a femoral-popliteal vein graft was performed with an excellent (early) result.

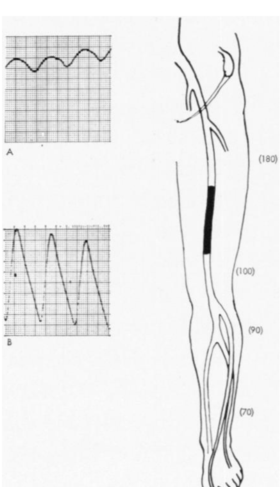

FIG. 15. Large pressure drop from groin to above knee establishes occlusion in superficial femoral artery. Normal gradients below this point indicate patency at least in a functional sense. Changes in volume pulse (A) with a successful bypass graft (B) are shown.

Comment: It seemed illogical to us to either refuse a bypass below the groin or do a combined procedure correcting the iliac stenosis as well. We have no good information as to the natural history of such lesions and it appears ill advised to remove or bypass hemodynamically insignificant lesions.

The following cases illustrate some of the typical situations encountered and the value of the mercury strain gauge plethysmograph in selecting patients for reconstructive surgery.

1. *Superficial femoral artery obstruction.* Plethysmographic findings of an excellent candidate for a bypass graft are shown in Figure 15. The important features of this case are:

a. A normal femoral pulse and absent distal pulses.

b. A normal upper thigh pressure which rules out hemodynamically significant stenosis or obstruction above the inguinal ligament.

c. The large pressure drop from the groin to above the knee localizes the obstruction to the superficial femoral artery.

d. The normal pressure gradients below the obstruction indicate a functionally patent distal arterial tree.

e. A good baseline volume pulse indicates good collateral circulation and patent vessels to and including the digital arteries.

On the basis of this information, an open operative femoral arteriogram was performed which verified the above findings. A femoral to popliteal bypass graft was successfully placed. The good response was immediately verified in the operating room by an increase in the digit volume pulse and ankle pressure.

Comment: It has been emphasized repeatedly in the literature that the ultimate success of grafting or endarterectomy may depend upon the state of the arterial tree distal to an occlusion. The two methods of studying the distal bed give complementary yet different types of information. Arteriography gives anatomic information as to the location and extent of intimal disease. This information is absolutely necessary for performance of vascular surgery yet does not always give the more important data as to the functional capacity of the distal bed. Measurements of the pressure gradients in the extremity provide this additional information. If an extremity can maintain the normal systolic gradients below an obstruction, it should be able to perform functionally with a bypass graft or endarterectomy. If these two diagnostic technics are used in a mutually dependent fashion, very few errors should be made in proper case selection.

2. *Superficial femoral artery obstruction.* A patient with the plethysmographic pattern shown in Figure 6 is not a candidate for arterial grafting. In this patient a toe ulcer and moderate rest pain were present. The important features of this case are:

a. All pulses were absent distal to the femoral.

b. The abnormal pressure gradients to below the knee suggested that the occlusive process extended below the popliteal artery.

c. The absent digital pulse with no change after a reactive hyperemia test suggested involvement of the critical areas of the collateral circulation about the knee and/or far-advanced distal occlusive involvement.

An open femoral arteriogram revealed a superficial femoral artery occlusion without visualization of the popliteal or its major branches. An above-the-knee amputation was performed. Dissection of the extremity revealed complete occlusion of the femoral-popliteal and the origins of the three major vessels below the knee.

3. *Common iliac obstruction.* A patient with the plethysmographic findings shown in Figure 5 is a good candidate for endarterectomy or grafting. The salient features of this case are:

a. Absent pulses in the entire right leg, normal pulses in the opposite asymptomatic extremity.

b. The low groin pressure on the right establishes the obstruction about this level. The normal groin pressure on the left rules out occlusive involvement of the aorta and localizes the obstruction to the right common or external iliac artery.

c. The flattened obstructive pulse on the right side is commonly seen with complete iliac or aortic occlusion. In general, the more proximal the occlusive involvement, the flatter the pulse contour.

An open femoral arteriogram verified the patent distal bed. A laparotomy was then carried out and the occlusion found to involve the common iliac artery. A thrombo-endarterectomy was performed and a prompt increase in the ankle pressure verified the success of the procedure. The patient's endarterectomy remained open until death occurred from a myocardial infarction nine months after surgery.

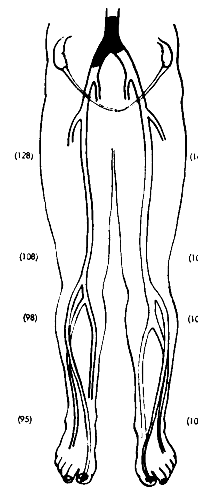

FIG. 16. Groin pressures are unequal and below arm pressure with aorto-iliac occlusion. Pressure drop from left groin to above knee suggested a femoral occlusion which was not present.

4. *Abdominal aortic occlusion.* Plethysmographic findings in a patient who is an excellent candidate for aorto-iliac reconstructive surgery are shown in Figures 16 and 17. The important features of this type case are:

a. Absent palpable pulses throughout both legs.

b. Both groin pressures are lower than the upper arm systolic pressure, establishing the occlusion either in the aorta or bilaterally between the bifurcation and the inguinal ligament (Fig. 16).

c. The distal gradients are normal. Occasionally the systolic gradient from the groin to above the knee in patients with chronic aortic occlusion may exceed 30 mm. Hg in the absence of occlusion in the superficial femoral artery. This was true in this patient.

d. The typical flattened pulses of aorto-iliac occlusive disease are seen (Fig. 17). The dramatic improvement with surgery is illustrated.

In recent years more consideration has been given to the salvaging of limbs with far-advanced occlusive disease with ischemic rest pain and/or impending gangrene.[23, 26] Although the results are not as good as in patients with more limited disease, the early returns with this type of patient have been very rewarding. A great improvement in the treatment of these patients has been the use of autogenous vein grafts either as patches on endarterectomized segments or as bypasses. As Linton has emphasized,[21] an autogeneous vein graft can and will remain patent even with poor distal runoff. We wholeheartedly agree with this concept and have had striking success in a few patients who prior to this time

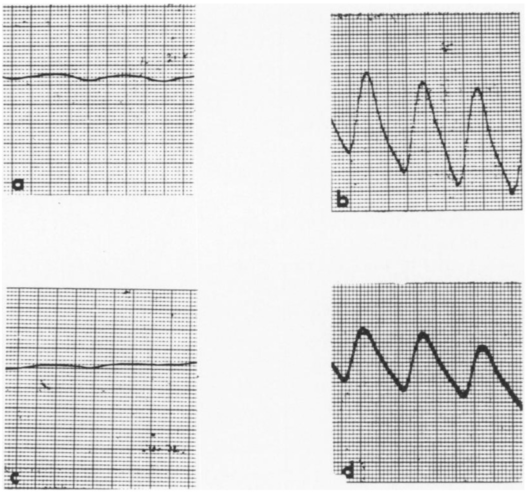

FIG. 17. These are pulses from patient illustrated in Figure 16. Preoperative pulses (A,C) dramatically increased in volume and approached a normal contour after aorto-iliac endarterectomy.

would have been considered inoperable. The following report illustrates the salient features of such a case.

Case Report: In 1961 this 65-year-old white man had a successful aorta-common femoral bypass graft. Arteriography at that time revealed open posterior tibial and peroneal arteries but the anterior tibial was not visualized. Postoperatively the patient's right ankle pressure was 140 mm. Hg and pedal pulses were palpable, although weak. Over the ensuing two years, the pedal pulses disappeared and the ankle pressure dropped to a low of 80 mm. Hg. The popliteal pulse remained strong and the patient was free of claudication. He was gradually occluding the main arteries distal to the sural artery.

On 4-24-63 the patient noted sudden onset of right foot pain and coldness. The previously palpable popliteal pulse was now absent but the graft continued to pulsate vigorously. A percutaneous arteriogram revealed a segmental occlusion of superficial femoral and an old occlusion of the popliteal below the origin of the sural artery (Fig. 18). A femoral endarterectomy with saphenous vein patch was carried out without correction of the popliteal occlusion. The response was dramatic; the previously unrecordable ankle pressure rose to 80 mm. Hg and the patient was able to ambulate easily without claudication.

Comment: The patient was able to ambulate without claudication because the location of the occlusion was below the origin of the sural artery. The patient remained pain free for eight months when he entered the hospital with an acute thrombosis of the aorta. Attempts at correction were unsuccessful and the patient expired 24 hours after surgery. This patient had significant palliation for a condition which otherwies would have resulted in an above-the-knee amputation.

VI. OPERATIVE MONITORING

Utilizing our early observations that a successful graft or endarterectomy resulted in a dramatic increase in the amplitude of the digit pulse and ankle pressure, we have applied our plethysmographic studies during the actual performance of surgery.[28] This was carried out to determine the immediate response of the extremity to a graft or endarterectomy and to detect, if possible, operative accidents such as peripheral emboli or thrombi. The immediate appearance of pedal pulses signifies an initial good result but many times pulses are difficult to assess in the operating room, making this an uncertain determination. On the other hand, a pulsating graft, although reassuring, is not

FIG. 18. Right femoral arteriogram was taken in 1961 prior to an aorto-femoral bypass graft. His peripheral atherosclerosis progressed to a popliteal occlusion but aorto-femoral graft remained patent. On 4-24-63 right superficial artery acutely occluded with resulting severe rest pain. Short occlusion in Hunter's canal illustrated on right was successfully treated by an endarterectomy and vein patch.

TABLE 2. *Results of Operative Monitoring in 55 Cases of Reconstructive Arterial Surgery*

		Operative Accidents	
Region	Immediate Good Results	Corrected	Failures
Aorto-iliac	16	5	5
Aorto-femoral	6	1	
Iliac-femoral	4	1	
Femoral-popliteal	10	4	3
Total	36	11	8
% over-all excellent results		85.5%	

absolute proof that the graft is functioning properly and on occasion has been very misleading.

To date we have monitored 55 arterial reconstructive procedures and detected operative complications in 19 instances. The sites of the operative procedure by region and eventual outcome are illustrated in Table 2. The detection of these accidents plus immediate attempts at correction have prevented many immediate failures. Eighty-five per cent of our patients have left the hospital with complete patency. We believe this represents excellent immediate results since most of our cases are carried out by residents with limited experience with this type of procedure.

The procedure used in the operating room is as follows:

1. Baseline ankle pressure and digit pulses are obtained after induction of anesthesia. There is usually an initial vasodilatation, depending upon the type of anesthesia used. As the procedure is carried out, vasoconstriction often occurs but the ankle pressure remains stable.

2. There is *always* an increase in the ankle pressure if the graft or endarterectomy is open and there is no distal obstruction. When an aneurysm is resected and the preoperative ankle pressures are equal, they must be equal after opening the graft. If they are not equal an obstruction must be present on the side of the low pressure.

If the toe pulses show a marked increase in volume, this is additional supporting evidence of immediate success. The absence of digit pulse increase cannot be used to suggest a failure, since vasoconstriction may be present making this an unreliable index.

The following case report illustrates the technic and interpretation:

Case Report: A 70-year-old white man entered the hospital with a very large, symptomatic abdominal aortic aneurysm. In addition to the aneurysm he had occlusive arterial disease bilaterally. On the right side he had only a femoral artery pulse and an ankle pressure of 100 mm. Hg. On the left he had femoral and popliteal pulses only and an ankle pressure of 125 mm. Hg. In the left popliteal fossa there was a definite fusiform swelling consistent with a popliteal aneurysm.

On 9-17-63 a very difficult aneurysmectomy, requiring five hours to complete, was carried out. After completion of the anastomoses it was noted that the left ankle pressure at 60 mm. Hg was lower than the right. A femoral arteriogram was performed which revealed that the popliteal artery was incompletely occluded by a clot (Fig. 19). Because the ankle pressure was 60 mm. Hg and compatible with limb survival, nothing more was done because of the patient's general condition. The following day the left foot was cool but the patient was not having foot pain. Over the next five days the ankle pressure rose to 80 mm. Hg. A repeat femoral arteriogram eight days after surgery showed complete obstruction with good collateral circulation (Fig. 20).

Comment: Ideally, of course, this popliteal occlusion should have been remedied immediately. Failure to do so resulted in the development of mild intermittent claudication.

The results of these studies are in close agreement with the observations of De Weese,[9] that most failures probably occur in the operating theater or in the recovery room.

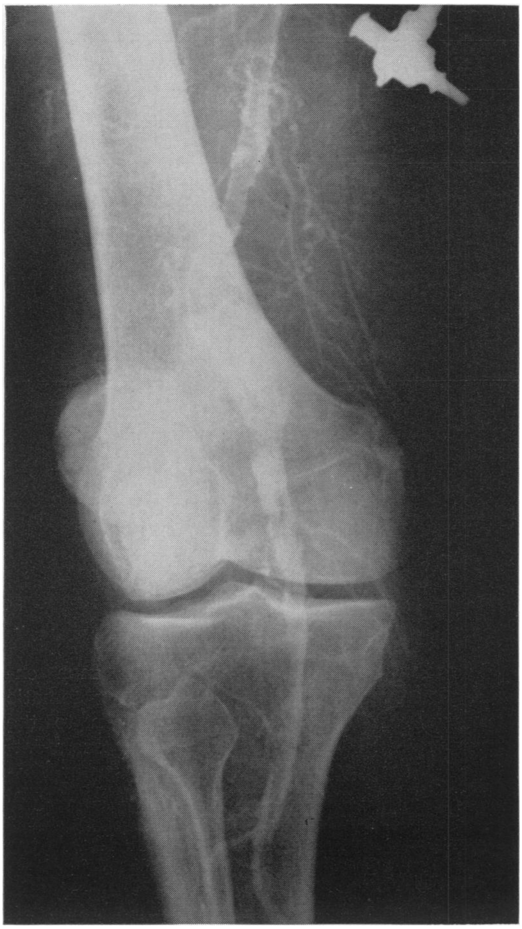

FIG. 19. After removal of aortic clamps, a long thrombus partially occluding distal superficial femoral and popliteal artery was demonstrated.

Although our series is not large, we have yet to lose a graft, which was patent in the recovery room, in the immediate postoperative period.

VII. POSTOPERATIVE EVALUATION

A paramount advantage of the use of the mercury strain gauge plethysmograph is that the same objective tests can be utilized in the immediately postoperative and later follow-up periods in determining the response to surgery. Arteriography is no longer utilized postoperatively to determine the success of reconstructive surgery because this is accomplished more simply by plethysmographic techincs. This can best be described in three phases.

1. *Immediate (in recovery room)*. Several hours after the patient is returned to the recovery room, ankle pressures and toe pulses are measured. If the previously obtained ankle pressure in surgery is not maintained graft failure is a certainty. One patient with an endarterectomy of the common femoral artery developed an occlusion in the recovery room. This was immediately recognized and the patient was returned to the operating room; an end-to-end teflon graft was placed with a good early result.

2. *Early (24 hours to six weeks)*. During this phase the ankle pressure always remains normal. The digit pulse often exceeds normal amplitude during this period, gradually returning to normal within six weeks. This interesting phenomenon has been carefully studied by Simeone and Husni [30] and is described as the hyperemia of reconstructive arterial surgery. During this time the foot and lower leg are extremely warm, dry and often accompanied by edema. This phenomenon is usually seen in a mild form, but certainly raises some doubt as to the need for a concomitant sympathectomy as has been suggested by some. During this period marked vasodilatation is occurring without sympathetic denervation, so it seems illogical to further complicate the picture by an unnecessary operative procedure.

3. *Late (six weeks to years)*. The digit volume pulse returns to normal; however, the contour is variable and we have seen two patients whose pedal pulses have disappeared but the ankle pressures have remained normal, indicating a patent graft.

Follow-up studies of our graft failures to date have failed to reveal acceleration of distal disease as a cause of the occlusion. The plethysmographic studies of these patients have been, with one exception, identical to those noted preoperatively. It is our impression that the probable causes of failure have been related to the failure of prosthetic grafts or technical factors related to placement.

An interesting facet of our study program during the late follow-up period has been the state of the limb and collateral vessels after the occlusion occurred. Statements have appeared in the literature suggesting that after successful graft placement or endarterectomy the collaterals regress.[5, 19] This would mean that occlusion of the graft or endarterectomy would at least temporarily place the extremity in a dangerous situation such that limb survival might be in question. We have studied seven patients with acute graft occlusion and in only two of these cases was the extremity in difficulty due to ischemia. One of these patients had his graft actually removed for a bleeding false aneurysm which required a very difficult dissection resulting in ligation of large collateral vessels. The other patient had an acute occlusion of a femoral-popliteal teflon graft six weeks after placement. The difficulty here arose from the propagation of the thrombus into the popliteal from the distal anastomosis or vice versa. In any event, there was significant obstruction of major collateral vessels which bypass the superficial femoral artery. In the remaining five cases we noted only transient coldness, numbness and return of the claudication. Either the collaterals again rapidly develop with gradual graft occlusion or the fail to regress even with a patent graft.

FIG. 20. A repeat femoral arteriogram performed on case illustrated in Figure 19. Eight days after surgery showed complete occlusion of proximal popliteal artery with good collaterals.

VIII. LUMBAR SYMPATHECTOMY IN THE TREATMENT OF ARTERIOSCLEROSIS OBLITERANS

While most surgeons would agree that this operative procedure may be of value in the treatment of mild rest pain, night cramps and superficial ulcers, there is no unanimity of opinion with regard to the results when used for claudication.

The reasons for this wide discrepancy in results are probably related to one or more of the following factors: 1. Lack of satisfactory and uniform method of selection; 2. Lack of objective method of evaluating results; 3. Frequent improvement without any therapy.

Our efforts in this are began in 1959 when we surveyed our past experience with this procedure. This was entirely a retrospective study using the patients' evaluation alone as to whether the operation was a success or failure. Fifty-eight per cent of the patients stated their claudication was improved. Utilizing this type of survey was clearly inadequate since it was entirely subjective and depended completely on the patients' evaluation.

Coinciding with the institution of plethysmographic evaluation, we began a prospective study of patients undergoing lumbar sympathectomy for claudication, skin problems and rest pain. Lumbar sympathectomy (L2-L4) was fairly liberally recommended for those patients not undergoing reconstructive surgery. This study was instituted for two reasons: To ascertain the value of the plethysmograph in patient selection, and to evaluate the over-all results of the procedure. The indications for sympathectomy were: Claudication, regardless of the level of occlusive involvement; Mild rest pain, not requiring narcotics or prolonged dependency for relief, and superficial ulceration of distal extremity and digits.

All patients having frank gangrene, deep ulcers involving tendon or bone and severe rest pain requiring prolonged dependency on narcotics were not offered this procedure.

The study program at the initial workup was identical with that mentioned earlier with one

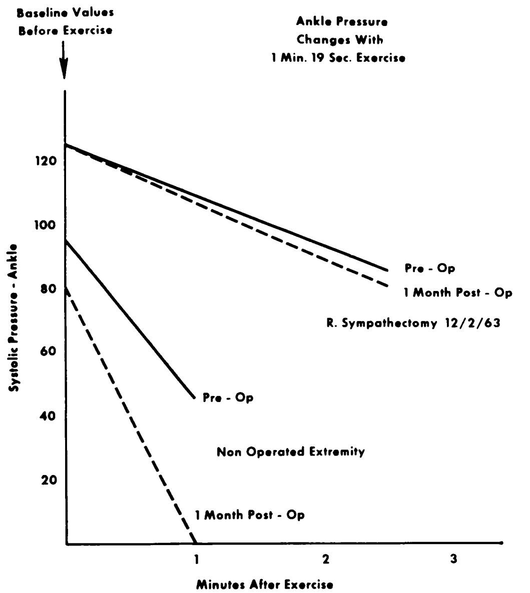

FIG. 21. No change in hemodynamic response of sympathectomized extremity was noted. Nonoperated extremity showed an exaggerated response. (See text for possible explanation.)

exception. In the spring of 1962 we began carrying out treadmill exercise tests (see Methods) on those patients having had the procedure and preoperatively on the new cases.

In reviewing our results of 39 sympathectomies in 29 patients, 14 of the extremities were improved if patient evaluation alone was used. Twenty-three were unimproved and it was too early for evaluation of two patients. When the patients were carefully questioned and the plethysmographic response to exercise evaluated, four patients appeared to derive real benefit from the procedure (five sympathectomies). Two of these patients had not only a dramatic increase in walking distance but also had a normal or nearly normal response to exercise. A careful study of these four patients, however, further eliminated two of them. In one patient there was improvement in the presence of incomplete sympathetic denervation. The other patient claiming improvement could walk for only one to two minutes on the treadmill, which represents a severe limitation in walking distance. Another patient in this series had a marked increase in walking distance and initially appeared to show dramatic improvement. Upon careful questioning it was found that he had gone on a diet and lost a total of 30 pounds. The effect of added weight on claudication has been studied by Hillestad.[17] It hardly seems logical to recommend sympathectomy with this sort of results.[35] It should be emphasized that the patients in whom this procedure was done were not those with the most advanced disease.

Although unusual, unilateral lumbar sympathectomy may have a deleterious effect upon the opposite extremity during exercise. We have had an opportunity to study this objectively in a patient whose case report follows:

Case Report: This 49-year-old white man entered the hospital with bilateral calf claudication. On the right side all pulses were palpable and normal except for an absent dorsalis pedis. On the left all pulses were absent except for a normal femoral pulse. The pressure gradients on the right were normal except for a 30 mm. Hg drop in pressure from the upper thigh to above the knee. The digit pulse was only slightly abnormal, but had an absent dicrotic wave. On the left the groin pressure was normal but there was a 50 mm. Hg drop to above the knee. The digit pulses were grossly abnormal and compatible with a superficial femoral occlusion. Bilateral femoral arteriograms revealed only some posterior plaquing in the right superficial femoral artery and nearly complete occlusion of the left superficial femoral artery. A translumbar aortogram revealed normal distal aorta and iliac arteries. With one minute, 19 seconds of exercise the right ankle pressure dropped from 120 mm. Hg to 80 mm. Hg. The left ankle pressure decreased from 90 mm. Hg to 45 mm. Hg. A right lumbar sympathectomy was performed and the patient re-evaluated during the first week and at one month. His response to the same duration of treadmill exercise remained the same on the sympathectomized side but he noted more severe calf pain in the unoperated leg. In particular, he noted that a longer period of time was required for the left calf pain to disappear after cessation of exercise. The pressure drop with exercise was entirely different in the unoperated leg in that now the ankle pressure dropped to unrecordable levels, requiring up to five minutes to reach a recordable level of 45 mm. Hg (Fig. 21).

Comment: This phenomenon undoubtedly represents a shunting of blood to the sympathectomized leg away from the more diseased areas as has been described and probably occurred here since the sympathectomized leg had much less occlusive disease. This is a reasonable possibility and is compatible with the concept of hemometakinesia as originally described by De Bakey *et al.*[6] Another possible explanation is the development of additional disease in the nonoperated leg, but this is very unlikely since his resting pressures in this leg remained unchanged.

Eleven patients underwent 13 sympathectomies for rest pain or ulceration (Table 3). The plethysmograph is useful in selecting patients for this procedure. When the rest pain is mild or moderate, there is usually pulsatile digit blood flow. These patients are often helped by lumbar sympathectomy. This is especially true if there is an increaes in the pulse amplitude following a reactive hyperemia test. When the pain is relieved, it is usually complete. None of the five patients who were improved had recurrence of this difficulty. Although the outlook is not as good when ulcers are present, a sympathectomy should be carried out when the digit pulse amplitude increases with reactive hyperemia. Although impossible to quantitate exactly the increase in blood flow required to relieve rest pain or aid in the healing of ulcers, it must be quite small. In general, the better the response to reactive hyperemia, the better the outlook.

The basis for selection is illustrated in the following case reports.

Case 1. Skin ulceration and mild rest pain (Fig. 22). This 72-year-old white man complained of a non-healing shallow ulcer involving the medial aspect of the right great toe. In addition, mild rest pain was present which was relieved by analgesics with dependency. The plethysmographic data revealed: a. Pressure gradients consistent with a superficial femoral artery occlusion and a patent distal arterial tree; b. Good baseline volume pulse which indicated excellent collateral circulation and further verified the patency of the distal arterial tree; c. The reactive hyperemia test was performed and the volume pulse amplitude increased over 50

TABLE 3. *Results of 52 Lumbar Sympathectomies in 42 Patients*

	Intermittent* Claudication	Rest Pain	Toe Ulcers
Improved	5	5	2
No Change	32	2	4
	—	–	–
Total	37	7	6

* Too early postoperatively to adequately evaluate two patients.

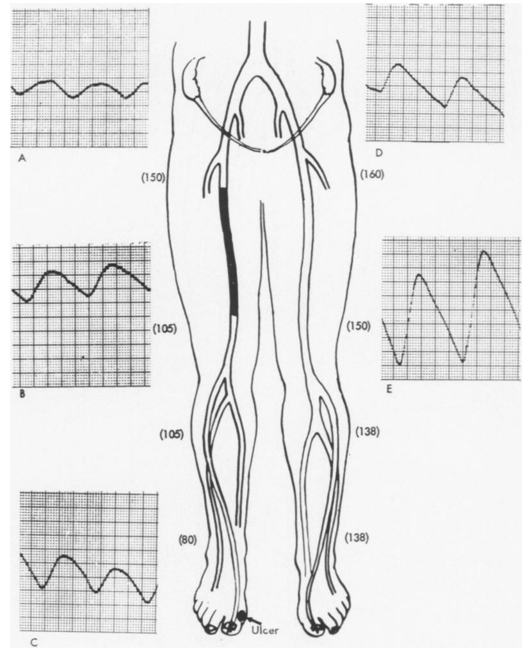

FIG. 22. Baseline toe pulses on right (A) increased by 50% with reactive hyperemia (B). Three days post-sympathectomy volume pulse showed predicted increase (C). Response of opposite normal extremity to a reactive hyperemia test is illustrated in tracings (D) and (E).

per cent. Since the position of the extremity remained unchanged, this volume pulse increase represented at least a doubling of the digital blood flow. d. The patient demonstrated an active inspiratory reflex.

A right lumbar sympathectomy was performed and within 48 hours postoperatively the rest pain completely disappeared and the ulcer began to heal. The increase in the recorded volume pulse coincided well with the predicted increase noted by the reactive hyperemia test. Complete denervation was verified by disappearance of the previously active inspiratory reflex. The ulcer has remained healed and the patient continues to be pain free. The last follow-up was at one year.

Case 2. Skin ulceration and calf claudication (Fig. 23). This 70-year-old white man had a small, shallow ulcer between the fourth and fifth digits of the right leg. Moderate calf claudication was also present, but not particularly bothersome to the patient. The plethysmographic data revealed: a. The pressure gradients suggested a superficial femoral artery occlusion which probably involved the popliteal artery as well. Arteriography was performed and showed an obstruction which extended into the upper popliteal artery. b. The digital pulses were absent at rest and did not increase following a reactive hyperemia test. This has two possible meanings: (1) The collateral cir-

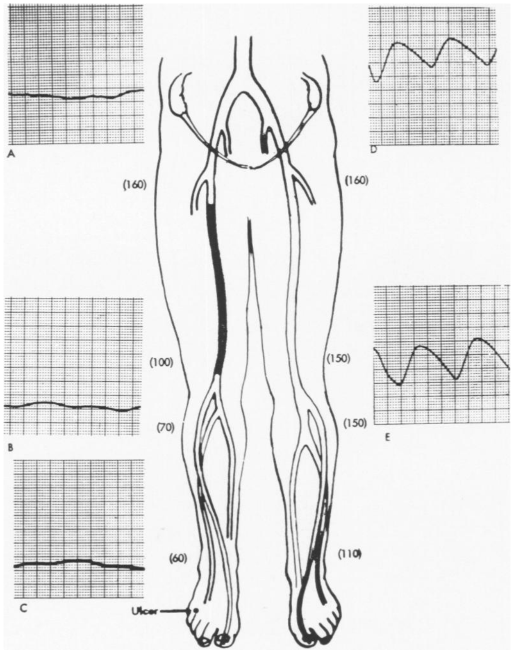

FIG. 23. Absence of digit pulses on right (A) and virtually no change with vasodilatation (B) suggested a poor response to lumbar sympathectomy. As illustrated, no change occurred with lumbar sympathectomy (C). Occlusive involvement below knee on left is early and patient was asymptomatic.

culation is so poor that no increase in flow can be expected; and/or (2) There is additional occlusive disease in the plantar or digital vessels. c. Because of the absence of pulsatile digital blood flow it was not possible to determine the level of vasomotor activity. The slow wave activity and inspiratory reflex cannot be studied with such striking reductions in digit flow.

A right lumbar sympathectomy was performed. Six days following denervation there was no change in the volume pulse amplitude, the inference being that no increase in digit flow occurred. This patient has now been followed for 18 months, with the same findings. The ulcer healed after this 18-month interval probably due to meticulous foot care by the patient.

Comment: Cases 1 and 2, from a clinical standpoint, were almost identical, yet the results of sympathectomy were remarkably different. The differences not evident clinically were easily detected utilizing the plethysmograph and illustrate the value of the technic when distal ischemia is the problem.

The time sequence in the development of collateral circulation is easily evaluated by making serial measurements of the digit pulses and angle pressure. From these measurements it is possible to accurately predict the subsequent course of events in these patients. The development of collaterals in some instances may be rapid, in terms of days or may require several months. The following case illustrates this type of problem.

Case Report: This 74-year-old white man had a successful femoral-popliteal teflon graft on 5-13-60. He did very well until 6-20-61 when he suddenly ruptured a false aneurysm at the proximal anastomosis. The graft was removed under very difficult circumstances. Immediately after surgery he had ischemic rest pain and a cold lower leg. Ankle pressures were unrecordable. By the ninth postoperative day the ankle pressure was 40 mm. Hg and his rest pain had greatly decreased. The patient has been followed continuously and his ankle pressure gradually increased reaching a maximal level of 105 mm. Hg in August, 1962.

Comment: Coinciding with the increase in ankle pressure, there was corresponding improvement in the patient's symptoms. It took several months to reach his preoperative ankle pressure level.

IX. THROMBO-ANGIITIS OBLITERANS

In 1960 Wessler and associates [36] published a provocative article on this disease pointing out that the disease originally described by Buerger is indistinguishable from atherosclerosis, embolization or thrombosis. They stated that thrombo-angiitis cannot be considered an entity in either the clinical or pathological sense and recommended that the term be discarded. Since this article appeared, there have been other reports [20, 25] which strongly disagree with these conclusions.

We have had the opportunity to completely evaluate eight patients who have certain features which are not commonly seen in patients with arteriosclerosis obliterans. The characteristics exhibited by these patients which separates them from those with arteriosclerosis obliterans are as follows:

1. Age at onset of disease—average 24 years, range 15–41 years.

2. History of migratory superficial phlebitis (four patients). This has not been seen in the arteriosclerotic patients. A biopsy taken of one of these early lesions showed the microabscess and giant cells described by Buerger (Fig. 24).

3. History of cold sensitivity. Although the arteriosclerotic patient may complain of coldness, difficulty in warming feet, etc., this is distinctly different from that seen in our cases.

4. Distribution of occlusive involvement. The patient with Buerger's Disease has more distal, extensive involvement of the vessels below the knee and of the foot. This gives rise to the frequent complaint of foot claudication which is rarely seen in arteriosclerotic patients.

5. Hand and upper extremity involvement. This is an extremely important distinction. We have never seen arteriosclerosis of the vessels of the hand or digits. This occurred in five of our cases and may be extremely patchy as demonstrated by our plethysmographic studies (Fig. 25). Two of this group have required finger amputations which we have not seen in the patients with arteriosclerosis obliterans.

6. Arteriography. Some claims have been made as to the specificity of the arteriographic pattern, but this had not been characteristic or pathognomonic in our patients. The most important evidence in our experience is the picture of completely normal vessels immediately above the area of involvement.

7. Pathologic findings. When the disease progresses to the point where amputation is necessary, the findings of thrombosis with recanalization are seen. The internal elastic membrane is intact and there is no evidence of atherosclerosis.

We are uncertain as to the etiology of this syndrome, but it does represent an entity which is clinically, plethysmographically and pathologically distinct and separate from arteriosclerosis obliterans.

The following case report illustrates the clinical features of this disease which in our experience have never been seen in arteriosclerosis obliterans.

Case Report: This 30-year-old white man first began to smoke heavily at age 12. At age 13 he developed his first episode of a transient, nodular superficial phlebitis. He was asymptomatic until he entered the Navy where the phlebitis recurred and he developed his first symptoms of arterial involvement in the left leg. The nodular phlebitis was

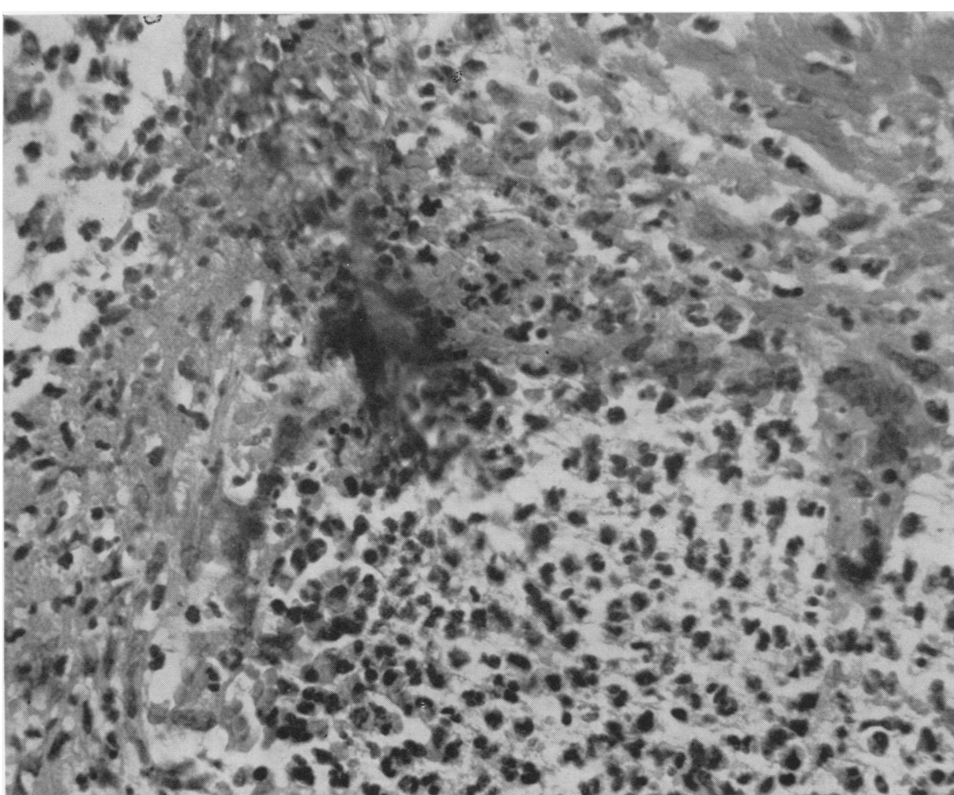

FIG. 24. A biopsy of an area of nodular phlebitis showed a micro-abscess with a giant cell.

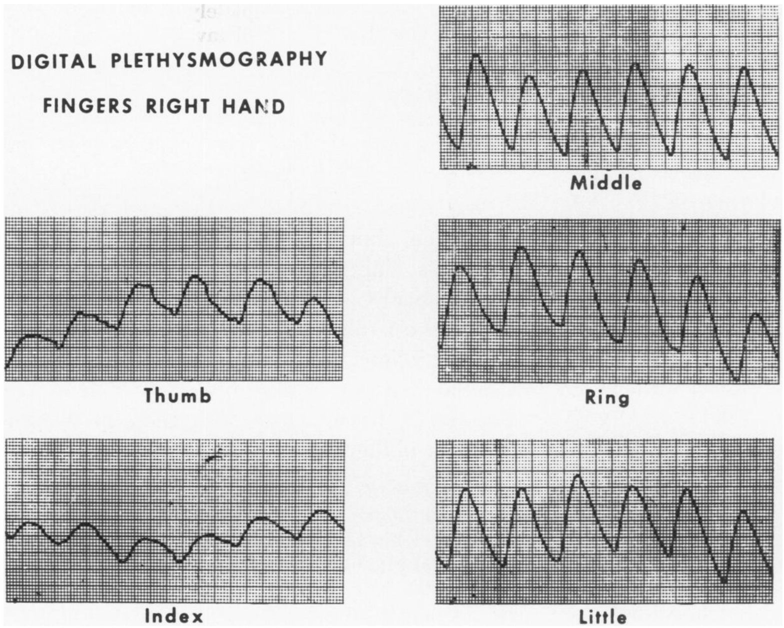

FIG. 25. Patchy involvement of smaller arteries of hand is illustrated. Involvement of thumb and index is greater than other digits but contour of pulse in middle, ring and little finger is distinctly abnormal in a young man.

biopsied and a micro-abscess was seen with giant cell formation.

The arterial component progressed with the development of bilateral foot claudication and ischemic rest pain on the left. At age 28 he had a left below-the-knee amputation. The specimen revealed thrombotic occlusion of the arteries, with preservation of vessel architecture. No evidence of atherosclerosis was seen.

Comment: This patient has continued to smoke with steady progression of his disease. When last seen (December, 1963) he again had developed nodular, superficial phlebitis in the right leg.

X. VASOSPASTIC DISEASES

The Veterans Administration Hospital, Seattle, Washington, is predominantly a hospital for male patients; thus, we see relatively few cases of the vasospastic diseases. To date we have studied only ten.

The plethysmograph can be useful in evalu-

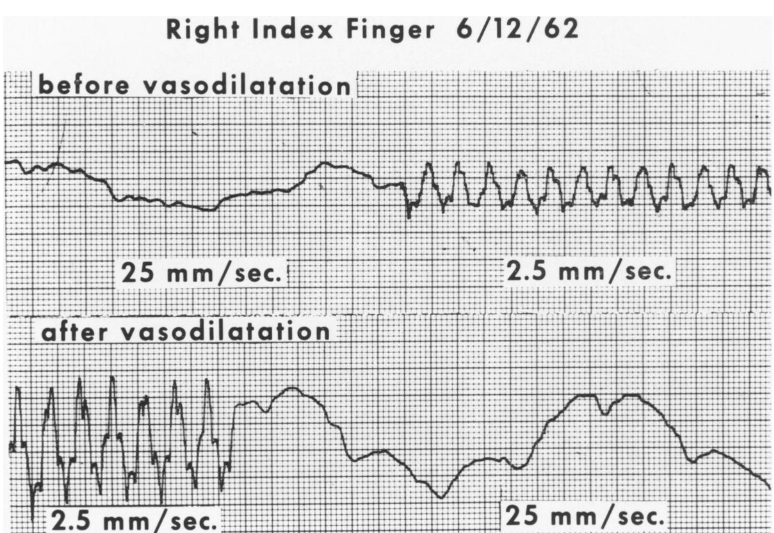

FIG. 26. Virtually no pulses were noted before vasodilatation with only slight improvement after vasodilatation.

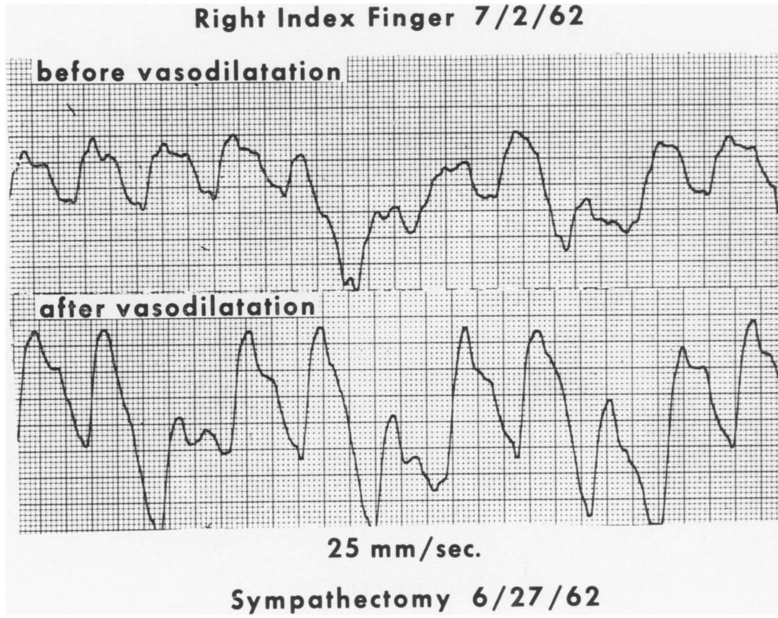

FIG. 27. Baseline digit pulses are increased in volume but still exhibit some residual tone as evidenced by dramatic change with vasodilitation.

ating these patients and the possible respones to therapy. With Raynaud's Disease the lack of actual organic involvement of the vessels can easily be verified by studying the pulse contour after a reactive hyperemia test. If there is a completely normal pulse contour, then structural alterations can be ruled out. We have had the opportunity of studying three patients with scleroderma and Raynaud's phenomenon and a distinctly different plethysmographic pattern has been seen in these cases. The following case report is an example of this type of case:

Case Report: A forty-nine-year-old white man gave a one-year history of marked cold sensitivity of his hands and feet. The typical color changes could be precipitated by washing his hands in cool water and would persist for several minutes. The digit pulses were flat with a very abnormal slow wave pattern (Fig. 26). After the reactive hyperemia test, the pulses increased slightly in amplitude but were distinctly abnormal. A cervico-dorsal sympathectomy was performed, resecting the lower one-half of the stellate ganglion and upper four thoracic ganglia. Five days after the denervation there was an increase in the volume pulse amplitude but there was considerable residual tone as illustrated by the increase in pulse height after reactive hyperemia (Fig. 27). Four months later the tracings were nearly indistinguishable from the preoperative tracings indicating complete return of extreme vasomotor tone (Fig. 28).

Comment: Further evaluation of this patient suggested that underlying disease was probably scleroderma. As De Takats [7] has pointed out, patients with a collagen disease and Raynaud's phenomenon do poorly after sympathectomy. We have one other case with a similar response and it may be that the increase in tone is in the vessel wall itself and not under the control of the sympathectic nervous system. Our two cases experienced very transient improvement and rapid return in vasomotor tone in the affected digits.

XI. SPECIAL APPLICATIONS

A. *Arterial Injury:* Introduction of needles or catheters into the arterial system for either cardiac catheterization or angiocardiography may result in an arterial injury with subsequent difficulties.[1, 22] Prompt recognition of the complications which can occur is mandatory if successful corrective therapy is to be carried out. Although the incidence of such complications is quite low, we have studied four patients with femoro-iliac injuries and five patients with thrombosis of various segments of the brachial, radial-ulnar arterial system of the arm.[1]

Complications from retrograde femoral catheterization would appear to be related to

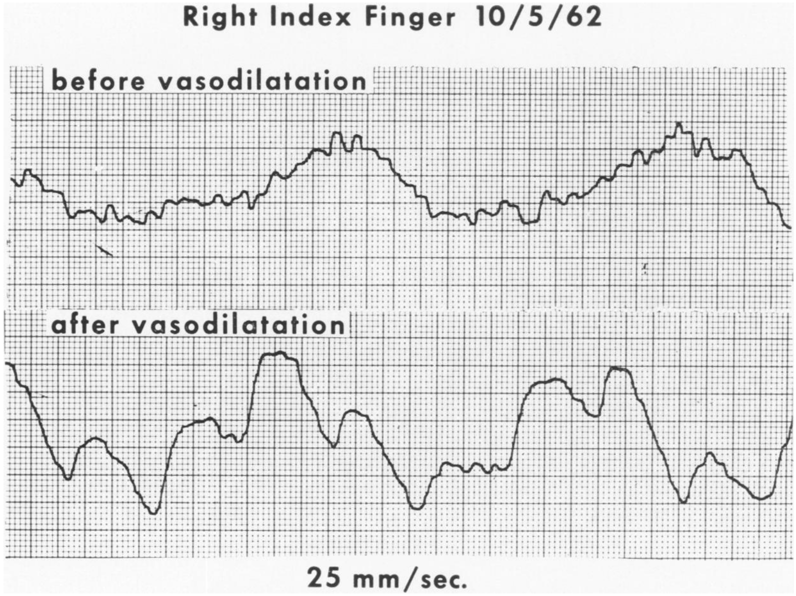

FIG. 28. Four months later almost complete return in vasomotor tone has occurred as evidenced by baseline pulses and change which occurred with vasodilatation.

the extent of the atheromatous disease in the femoral artery and those vessels proximal to it. A careful plethysmographic examination before carrying out such studies is very helpful since an accurate estimate of the location and extent of existing occlusive disease may be obtained. The following case report illustrates such an example.

Case Report: This 63-year-old white man noted the recent onset of left calf and hip claudication with walking. On physical examination the right femoral pulse was normal with no pulses distal to this point. On the left side no pulses were palpable in the entire leg. Segmental leg pressures revealed that the right upper thigh pressure was below the arm pressure indicating some stenosis either in the external or common iliac arteries on that side. The pressure in the left upper thigh was low, indicating a complete iliac occlusion. The patient returned to the referring hospital where a right retrograde femoral catheterization was attempted in order to visualize the distal aorta and iliac vessels. The catheter placement was achieved but when the contrast media was injected, the patient suddenly complained of severe pelvic discomfort. An x-ray revealed extravasation of the contrast material into the pelvis. Fortunately, the rent created by the catheter immediately sealed over and the patient did not require surgical exploration.

Comment: Apparently the individuals carrying out the radiologic procedure did not appreciate the significance of this stenotic lesion. The catheter penetrated the wall of the vessel at the site of the stenosis resulting in an extraluminal injection of the dye. The low groin pressure on the right should not have been ignored since a stenosis which is capable of producing a pressure drop is usually of the magnitude of 80 per cent. Attempts to pass guide wires or catheters through a vessel compromised to this extent is fraught with danger. The plethysmographic information not only accurately categorizes the extent of the disease but also gives baseline information in case a complication does occur.

Although the arm has abundant collateral circulation at nearly all levels, the opportunity for the development of serious sequelae from diagnostic procedures still exists. In our experience the most important single factor in the genesis of such complications is prolonged exposure of the arterial intima to a foreign body such as an angiographic catheter. Of the five cases with complications one thrombosed the entire brachial artery and a portion of the ulnar artery, finally culminating in an above-the-elbow amputation.

Pre-catheterization plethysmography is useful if the arm is to be used for retrograde catheterization but occlusive disease is extremely rare in our experience. We have not yet encountered a patient with occlusive disease distal to the subclavian artery secondary to atherosclerosis. The most frequent complication is thrombosis at the site of catheter insertion. Shortly after completion of the procedure the patient may complain of a cold hand, numbness, tingling and pain. Often the initial interpretation of these complaints is that arterial spasm has occurred and stellate ganglion blocks are performed. The plethysmographic studies are useful because the differentiation between spasm and actual arterial occlusion is easily made. The volume and, in particular, the contour of the pulse are studied and if the contour shows a flattened peak and absent dicrotic wave, arterial thrombosis is very likely. If the pulses are extremely small, vasodilatation is carried out either by a reactive hyperemia test or stellate block. The contour in the vasodilated state is often more useful and diagnostic as to the underlying problem.

The following case illustrates the course which is frequently observed in these cases.

Case Report: This 67-year-old white man entered the hospital for treatment of a herniated nucleus pulposus. Because of a history of cerebral difficulties on 6-7-63 an open retrograde brachial artery catheterization was performed to visualize the carotid and vertebral arteries. Following the procedure the patient noted numbness, tingling and weakness of the right hand. Stellate blocks were immediately performed with a tentative diagnosis of arterial spasm. The plethysmographic tracings (Fig. 29) indicated that arterial thrombosis had occurred. By the third day, 6-10-63, there was dramatic improvement in distal blood flow as the collateral circulation improved. Six months after the complication the digit pulses were still grossly abnormal but the patient was asymptomatic.

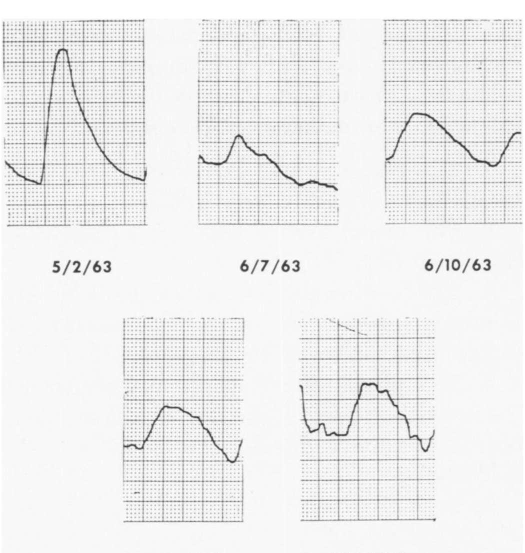

FIG. 29. Sequence of events following a catheter injury to brachial artery is illustrated. Baseline pulses on 5-2-63 are normal. On 6-7-63 after a stellate ganglion block, digit pulses remained low in amplitude and had an abnormal contour.

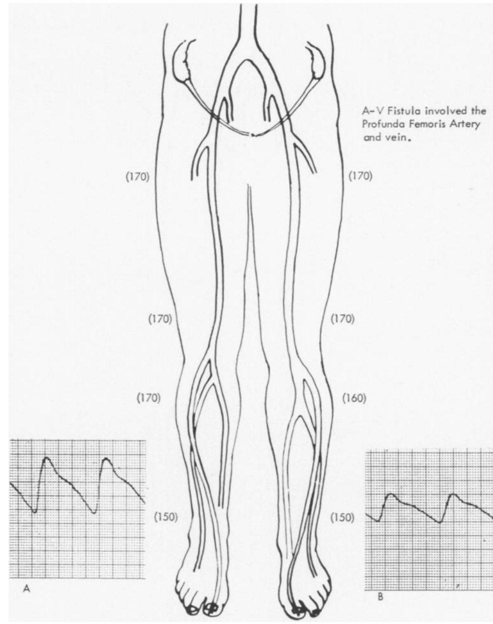

FIG. 30. Systolic pressures in both legs are essentially the same and normal. Digit pulses are normal.

Comment: This complication had a very favorable outcome and represents local occlusion at the site of catheter insertion. One of the other patients in this group developed severe arm claudication which would occur with minimal effort.

B. *Arteriovenous Fistula*—We have had the opportunity of studying three patients with acquired arteriovenous fistulas.[33] Information as to the size, location and peripheral effects of an arteriovenous fistula can be obtained by plethysmography.

1. *Size of the fistula.* The complications of arteriovenous fistulas are usually related to the size and volume of blood shunted. The larger

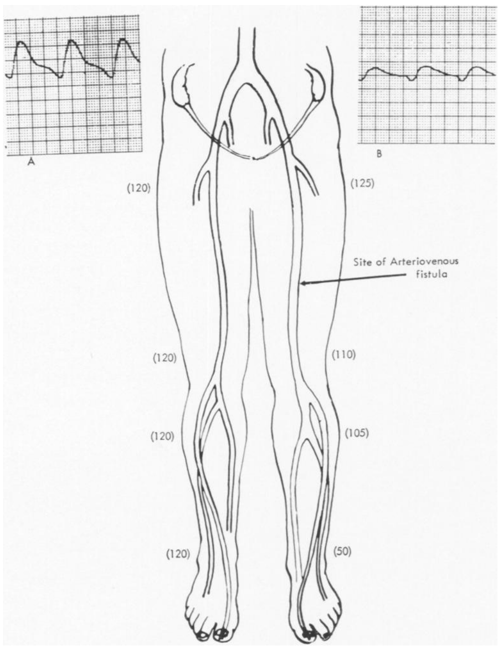

FIG. 31. On uninvolved side digit pulses (A) and pressures are normal. Ankle pressure on involved side was 50 mm. Hg and digit pulses had a smaller amplitude and an abnormal contour.

the fistula, the greater the volume of blood shunted away from the distal tissues and the greater the collateral circulation. A small fistula between the profunda femoris artery and vein was not large enough to affect the digit volume pulse or ankle pressure (Fig. 30). In a fistula involving the superficial femoral artery and vein the volume shunted was much greater, resulting in an abnormal digit pulse and a low ankle pressure on the affected side (Fig. 31).

2. *Magnitude of the collateral circulation.* If quadruple ligation of a fistula is necessary, demonstration of the extent of the collateral circulation becomes important. This is particularly true in a very early fistula. A simple clinical method of noting the amount of pulsation in the distal artery with proximal artery occlusion has been used in the past (Henle-Coenen phenomenon). In the case of the superficial femoral artery-vein fistula (Fig. 31), proximal artery occlusion resulted in a 55 mm. Hg rise in the ankle pressure, demonstrating the excellent collateral circulation which existed. This appears to be a very simple, reliable method of verifying the presence of good collaterals.

3. *Postoperative evaluation of results.* As Hughes and Jahnke [18] have indicated, it is often difficult to evaluate residual complaints after surgery for fistula repair without objective methods of study. In the patient (Fig. 31) with the superficial femoral artery-vein fistula the vein was ligated and the fistula repaired by lateral arteriorrhaphy. Postoperatively, the ankle pressure remained 40 mm. Hg below the normal limb and the digit pulses had the contour typically seen with superficial femoral artery obstruction. The pedal pulses were palpable but the patient complained of calf claudication on the involved side. A femoral arteriogram revealed marked narrowing at the site of the arterial repair. This stenotic area was subsequently repaired with a patch graft of saphenous vein. Immediately postoperatively pulses of normal contour and increased volume were noted. The calf claudication disappeared.

SUMMARY AND CONCLUSIONS

The application of the mercury strain gauge plethysmograph to the study of peripheral arterial disease has been presented. The simplicity, great sensitivity and utility permits its routine use in the clinical evaluation of these problems. With proper implementation the following information may be obtained:

1. The diagnosis of arterial disease at all levels may be clearly established.
2. The extent and location of occlusive lesions may be ascertained.
3. The functional adequacy of the distal arterial tree may be determined when reconstructive arterial surgery is contempleted.
4. The physiologic response to exercise of the normal extremity and the extremity with occlusive arterial disease can be objectively evaluated.
5. Operative accidents during performance of arterial surgery can be promptly detected and corrected.
6. Long-term results are simply evaluated without resorting to angiography.
7. The immediate and long-term resultse of sympathetic denervation are easily studied.

8. Thrombo-angiitis obliterans can be strongly suspected by distribution of disease and plethysmographic evidence of hand involvement.

9. Organic arterial changes in patients with vasospastic phenomenon are readily identified. The probable effect of sympathetic denervation in these cases can be determined.

10. In arteriovenous fistula information as to the size of the fistula and the magnitude of the developed collateral circulation may be obtained.

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APPENDIX

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A. Construction of the Gauge

The use and construction of a mercury-filled, highly distensible rubber tubing to measure changes in human limbs was first described by Whitney in 1953.[8] Since that first report major modifications and improvements have been made so that, at the present time, a wide choice of materials and methods of construction are in use. In addition there are at least two commercial manufacturers of inexpensive, high quality gauges in a variety of sizes.*

The gauges consist of either a latex rubber or silicone plastic tube filled with mercury with suitable length lead wires inserted into each end. Both the latex rubber and silicone plastic are available in a large choice of internal and external diameters and the selection of both material and size will be dictated, to a large extent, by the particular application of the gauge. For example, rather thick-walled silicone plastic gauges would be selected for chronic implantation studies because of their durability and relative freedom from tissue reaction. On the other hand, very small delicate but highly sensitive gauges can be made of either silicone plastic or latex rubber for studies of individual blood vessels as small as the femoral artery of the dog (10 to 20 mm. in circumference). Gauges for digital plethysmography in humans are currently being manufactured of silicone plastic fixed in a permanent loop configuration which can quickly and easily be slipped onto a finger or toe with the lead wires taped to the digit by a short strip of adhesive.† These gauges have a great advantage in clinical studies where, for example, one might wish to measure the immediate peripheral response to graded exercise. A recent publication [2] has added to the usefulness of this type of gauge by describing a method of calibration which, until now, has been impossible.

B. The Matching Circuit

The resistance of an average strain gauge is on the order of 0.5 to 1.0 ohms. Direct coupling of such a low resistance device to the input of an amplifier would result in a marked limitation of sensitivity. To overcome this limitation an impedance matching circuit was designed by Elsner [4] which is basically an A-C Wheatstone bridge. It was designed to operate in conjunction with any carrier preamplifier with A-C excitation, such as the type commonly used with capacitance manometers. The actual circuit can take several configurations, one of which is shown in Figure 1A. The upper arms of this bridge are matched carbon resistors on the order of 1,000 ohms and the

* Parks Electronic Laboratories, Route 2, Box 35, Beaverton, Oregon. Brudy Instrument Company, 129 Ellsworth, Toronto, Canada.

† Parks Electronic Laboratories.

transformers are inexpensive speaker-matching units. The strain gauge is attached directly to the secondary of one transformer and a low resistance potentiometer is chosen such that the minimum and maximum values bracket the resistance of the strain gauge. These circuits are commercially available †† and when coupled to an A-C carrier preamplifier, both pulsatile and baseline information can be recorded. The frequency response of an entire system, i.e., strain gauge, matching circuit and recorder, has been measured and found to be essentially linear from DC to 100 cps.[7] It was also demonstrated that the system is completely free from resonance effects from DC and to about 30 cps., no significant phase shift between gauge output and gauge stretch is present. Thus, this arrangement can be used both for venous occlusion flow studies as well as detailed investigation of pulsatile phenomena including Fourier analysis of pulse form.

Another type of circuit suitable for coupling a strain gauge to appropriate recording equipment is also commercially available.††† The units are made in two versions. One is designed for the research laboratory and gives both baseline (venous occlusion studies) and pulsatile information. The other is less complicated in design and use and is especially suitable for clinical evaluation of patients with peripheral vascular disease. Both units can be recorded on ordinary ECG machines but it must be remembered that for venous occlusion studies some of the smaller office-type ECG recorders are not suitable because the recorder itself does not give baesline information.

C. Calibration Procedure

Several methods have been described for calibration of a mercury strain gauge [1, 3] one of which will be given here. The technic uses a calibrated stretching device (Fig. 2A) in which the gauge can be mounted under a known static tension and then subjected to repeated stretches of precisely known amounts. This is done while the output of the impedance matching circuit is being recorded. In this manner, the deflection of the recorder (at any suitable sensitivity setting) can be related to a per cent change of resistance of the gauge,

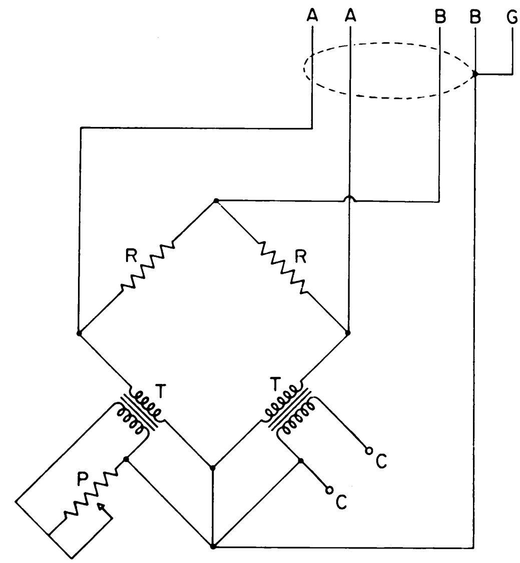

FIG. 1A. A—A excitation voltage—4.5 v AC, 2,400 cps. (when used with Sanborn 150–1,600 carrier preamplifier)
B—B Signal
C—C Connections for mercury strain gauge
G—Preamplifier ground
P—Variable resistance 1.5–3.0 ohms
R—Matched resistors, approximately 500 ohms
T—Speaker matching transformers, Stancor model or equal

which in turn can be related to a per cent change of volume of the digit. An example will serve to illustrate the method.*

Suppose volume changes of a finger of 50 mm. circumference are to be recorded. A gauge is selected of a length as close as possible to the circumference of the finger. For this example, assume the gauge length to be 50 mm. under the standard tension applied (usually about 10 grams). The error which results when gauge length does not equal finger circumference will be discussed later. The gauge is first mounted in the calibration device under 10 grams tension and the impedance matching circuit is balanced by adjusting its potentiometer (R in Fig. 1A). This is done at a low sensitivity setting of the carrier pre-amplifier. Fine balance at high sensitivity is achieved by adjusting the resistance and capacitance controls of the pre-amplifier. When fine balance has been effected, the amplifier is switched to its "operate" mode and a suitable baseline se-

†† Mr. Rudy Helmer, 7951-16th Avenue, S.W., Seattle 6, Washington.

††† Parks Electronics Laboratories.

* The following discussion assumes a familiarity with the operation of a Sanborn Carrier preamplifier Model 150-1100.

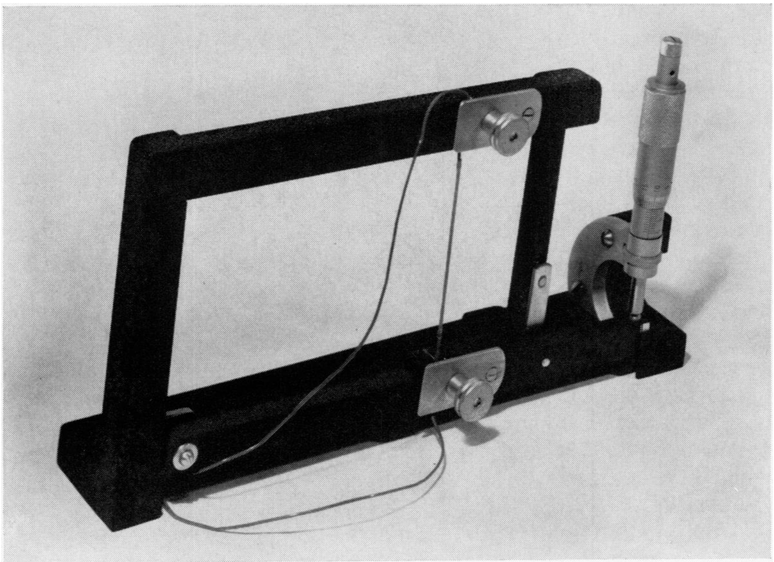

FIG. 2A. This bar is utilized in calibrating the mercury strain gauge.

lected. With the amplifier on low sensitivity, the gauge is subjected to repeated stretches of exactly one millimeter. The attenuator setting of the amplifier is noted as well as the number of millimeters deflection which result from a one millimeter stretch of the gauge. Let this be equal to 10 mm. on an attenuator setting of $\times$ 100. Now, with this gauge applied to a finger of 50 mm. circumference in such a manner that gauge length is approximately equal to finger circumference, a one millimeter elongation of the gauge would represent a per cent change of finger circumference (% ΔC) of $1/50 \times 100$ or 2% ΔC. Thus a 2% ΔC of the finger would cause a 10 mm. deflection of the recorder with the amplifier at a sensitivity of $\times$ 100. It will be shown in a later section that the per cent change in volume (% ΔV) of a digit is, to a very close approximation, twice the per cent change in circumference and so, in this example, a recorder deflection of 10 mm. (with the attenuator set on $\times$ 100) would represent a 4% ΔV of the digit. From this the % ΔV per mm. deflection at any attenuator setting can be calculated.

Concerning the relationship between gauge length and digit circumference, it has been shown [2] that with this method of calibration the error which results when gauge length does not equal digit circumference is insignificant. For example, in the extreme case where gauge length is only one-half digit circumference, the error in a volume measurement would be only about 1.3 per cent.

D. Physical Properties of the Mercury Strain Gauge

The physical and mathematical relationships relevant to the mercury strain gauge and its application to digital plethysmography have recently been presented in detail.[2] In this section some of the more important results will be considered.

The digit dimension directly measured by the mercury plethysmograph is per cent change in circumference (% ΔC). This produces a per cent change in length (% ΔL) of the gauge which, in turn, produces a per cent change in resistance (% ΔR) which can be quantified and recorded. From this the per cent change in volume (% ΔV) of the digit can be inferred if the relationship between % ΔV and % ΔC is known. This relationship is of the form, $\% \ \Delta V = 2\% \ \Delta C + 1/100 \ (\% \ \Delta C)$. The equation is based on purely geometrical considerations with no simplifying assumptions. However, the validity of its application to a digit depends on two assumptions: (1) The digit can be represented by a cylinder of constant length whose volume change is the result of a change in circumference only; and (2) The digit approximates a circle in cross section. These assumptions have been evaluated [5] and it was found that they present no practical limitations to the technic. The equation as stated is the exact relationship between the per cent change in circumference and the per cent change in volume of a digit. It is apparent that for the average changes seen in plethysmography (about 3–4% ΔV) the second term on the right hand side can be ignored and the simpler expression, $\% \Delta V = 2\% \Delta C$, is valid. It is this relationship which is generally used in calibration of a gauge.

The other important consideration in digital plethysmography is the equation relating $\% \Delta L$ and ΔR of the gauge. The exact relationship is $\% \Delta R = 2\% \Delta L + 1/100 (\% \Delta L)$. Comparing this equation with the one describing $\% \Delta V$ versus $\% \Delta C$, it is apparent that if $L = C$ (i.e., gauge length equals finger circumference), $\% \Delta L = \% \Delta C$ and the right hand sides of the two equations are identical. This leads to the very important result that when $L = C$, $\% \Delta V = \% \Delta R$. That is, the per cent change in volume of the digit is exactly equal to the per cent change in resistance of the gauge which, in turn, can be linearly related to the deflection of the recording device. As stated previously, the error which results when L does not exactly equal C is insignificant if the gauge is calibrated by the method given above.

Since the gauge is usually calibrated at room temperature of about 20° C. and applied to a digit of close to body temperature, the effect of a change in temperature on volume measurements was studied. The results indicate that, for a 10° C. change in gauge temperature, there is a change in apparent volume of slightly less than 1 per cent. In cases where vascular responses to changes in ambient temperature are being studied, temperature effects of the gauge can be more significant. For example, if a digit at 37° C. were immersed in water at 0° C. there would be an apparent volume change of 3 per cent. For studies of this sort, a method has been devised to compensate for the resulting error.[6]

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