PREOPERATIVE ARTERIAL EVALUATION OF THE DIABETIC FOOT

David D. Mullens, D.P.M., M.S.

INTRODUCTION

The chapter deals with the problem of preoperative arterial evaluation of the diabetic patient undergoing elective foot surgery. The second and much shorter section focuses on the topic of *increased* arterial inflow associated with Charcot arthropathy.

Preoperative Arterial Evaluation of the Diabetic Foot.

The need for preoperative arterial evaluation of the diabetic patient undergoing elective foot surgery—an overview.

Diabetic patients are in an increased risk category for complications in elective foot surgery. The number of amputations following surgery on diabetic feet is disproportionately high and obviously tragic for all concerned.

There are too many diabetic foot deformities which predictably result in disability, infection, and amputation if treatment is limited to conservative care only. Many of these deformities can and should be surgically corrected.

The diabetic patient can undergo surgery and still avoid postoperative vascular disasters resulting in amputation. The physician's responsibility is: *better patient selection.*

The following is a review of the mechanics of diabetic angiopathy. A simplified approach to preoperative arterial evaluation of the diabetic patient is presented. This format may be followed in any private practice—with a minimum of time and expense.

Functional arterial anatomy of the lower extremity:

A. Abdomen, thigh, and leg
B. Foot

The arterial anatomy of the lower extremity is presented in a simple but accurate fashion. The necessary information must be included and the extraneous details deleted.

With information provided later in this chapter, the reader should be able to diagnose:

1. The presence or absence of significant arterial disease of the lower extremity in question and,
2. The severity of the arterial disease process.

Functional Arterial Anatomy of the Lower Extremity:

abdomen, thigh, and leg.

The accompanying diagram represents the main stem arteries from the abdominal aorta to the tibioperoneal arteries at the level of the ankle (Diagram 1).

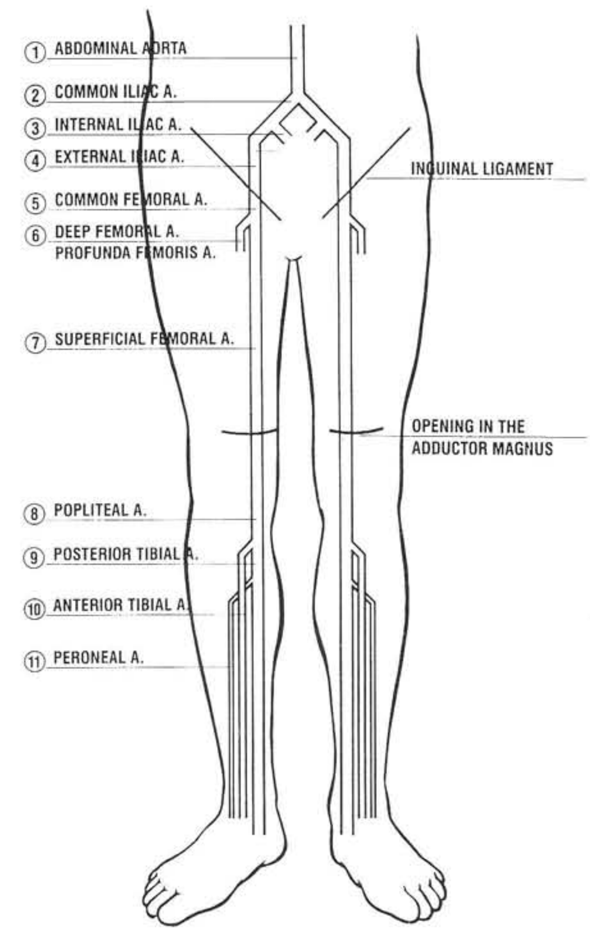


Diagram 1. Functional arterial anatomy of lower extremity: abdomen, thigh, and leg.

Functional Arterial Anatomy of the Foot.

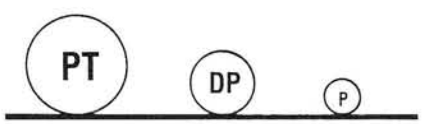
A. The three source arteries of the foot are the:

1. posterior tibial,
2. dorsalis pedis and
3. peroneal

B. Generally, these three source arteries are unequal in size or significance.

1. The posterior tibial is the largest of the three and bears the major responsibility for perfusing all of the plantar intrinsic muscles as well as the distal forefoot.
2. The dorsalis pedis is second in importance to the posterior tibial and is responsible for perfusing the dorsum of the foot and the proximal dorsal aspect of the toes.
   When the posterior tibial is absent, the dorsalis pedis may function as the primary source artery of the foot.
3. The peroneal artery helps perfuse the lateral aspect of the foot and is usually of minor importance. However, on rare occasion, the peroneal artery may function as a primary source artery of the foot.

C. The differences in size and functional significance of the three source arteries can be summarized by the following diagram:



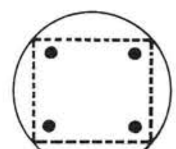
The posterior tibial artery is given a relative value of 3, the dorsalis pedis a relative value of 2, and the peroneal artery a relative value of 1. The importance of this grading scale will become obvious as we discuss measurements of the ankle/arm ratio.

D. Clinically:

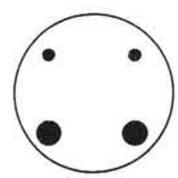
1. The posterior tibial and dorsalis pedis arteries are easily palpated at and just distal to the ankle.
2. The anterior perforating branch of the peroneal artery is accessible at and distal to the ankle.
   a. Note: the peroneal artery is almost always too small to be palpable.
   b. The peroneal artery is almost always audible on Doppler examination.
3. The entire foot can be perfused by only one or two of the three source arteries because: The three source arteries of the foot connect with each other at multiple sites in the foot. As a result, there is a constant admixture of arterial blood through the connecting tributaries of the three source arteries.

E. The digital arteries.

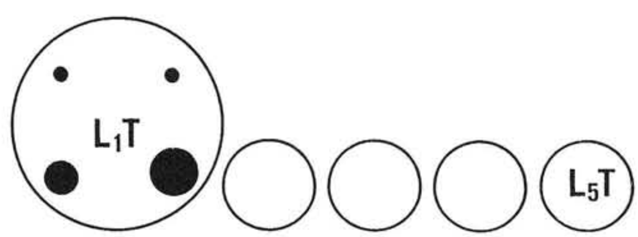
1. The following statements represent the *idealized* arterial plan for the toes. These statements:
   a. are based on several anatomical studies and reflect the actual findings of these studies, and
   b. are consistent with a general body plan principle: e.g., the larger and more important nerves and arteries are found on the inside protected surfaces of the extremities.
2. Each toe has four digital arteries. On cross section, these digital arteries can be found at the *four corners* of the toe.



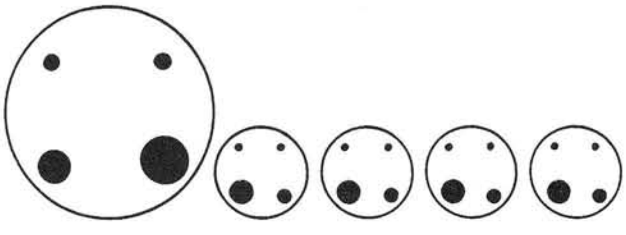
3. Usually, the plantar digital arteries are larger than the dorsal digital arteries.



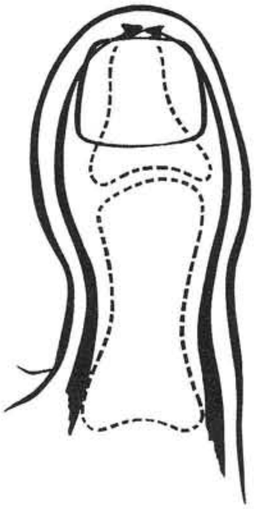
4. Also, the lateral plantar digital artery of the hallux is larger than the medial plantar digital artery of the hallux.



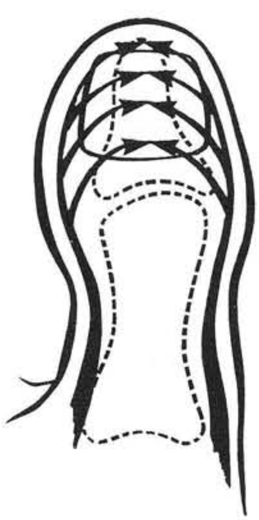
5. The medial plantar digital artery of lesser toes 2, 3, 4, and 5 is larger than the lateral plantar digital artery of lesser toes 2, 3, 4, and 5.



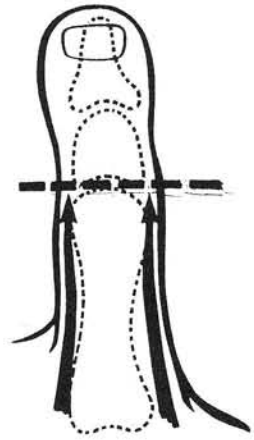
6. The dorsal digital arteries of the *hallux*, continue all the way out to the tip of the hallux.



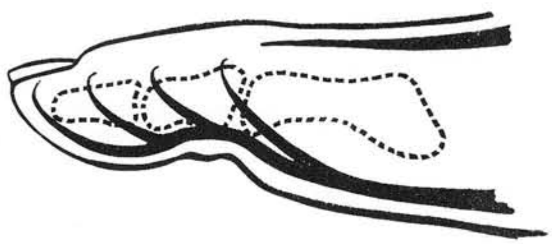
7. The dorsal digital arteries of the hallux give off many smaller branches over the distal phalanx. These smaller branches anastomose freely. As a result, a dorsal distal arterial tuft is formed.



8. The dorsal digital arteries of the lesser toes 2, 3 4, 5 *stop* at the level of the proximal interphalangeal (pip) joint.

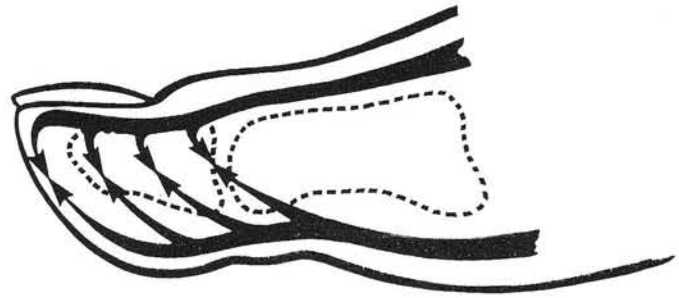


9. Arterial inflow distal to the pip joint (of lesser toes 2, 3, 4, and 5) arrives by way of the plantar digital arteries. This is demonstrated on lateral view.



The plantar medial and plantar lateral digital arteries (of lesser toes 2, 3, 4, and 5) give off a rete network of arterial branches which wrap up and around the sides of the toes. These rete branches anastomose over the dorsal aspect of the toes.

10. By contrast, the responsibility for arterial inflow distal to the IP joint of the hallux is carried equally by the dorsal and plantar digital arteries of the hallux. On lateral view, one can see how the dorsal and plantar distal arterial tufts of the hallux give off branches which freely anastomose along the sides and end of the hallux.



11. Anatomically, the distal tip of a toe receives the last portion of arterial inflow. In the event of ischemia, the tip of the toe is frequently the first area to suffer and the hardest hit.

The single test for arterial inflow on the diabetic foot where the most information may be obtained concerning the overall arterial inflow to the foot is a test that *measures* arterial inflow tips of the toes.

There is such a test.

DIABETIC ANGIOPATHY

The term diabetic angiopathy refers to a group of disease processes that affect the systemic arteries of diabetic patients. For the purpose of this paper, the major diabetic process examined is that which is responsible for diabetic gangrene: diabetic arteriosclerosis obliterans (ASO). Monkeberg's medial calcific sclerosis will also be studied. This is a disease which is not seen exclusively in diabetics, but which makes diabetic preoperative arterial evaluation very difficult.

In ASO, the *basic lesion* is the same whether we are discussing diabetic ASO or non diabetic ASO. This basic lesion is the atheromatous plaque.

The clinical differences between diabetic ASO and non diabetic ASO will be discussed later. For now, it is enough to know that the atheromatous plaque is *the* lesion responsible for obstructing the systemic arteries in both diabetic and non diabetic ASO.

Arteriosclerosis obliterans (ASO) literally means *hardening of the arteries with narrowing of the arterial lumen*. This marginally descriptive and only partially accurate phrase is so firmly entrenched in the literature that it is used without argument.

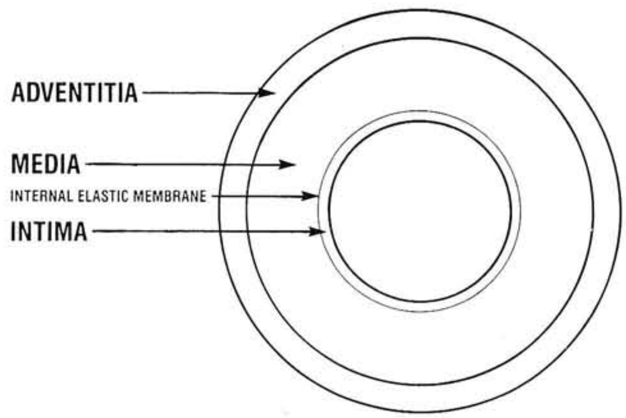
ASO refers to the deposition of lipid material under the endothelial intimal layer of the systemic arteries. As the amount of fat incorporated within the artery wall increases, the shape of the arterial wall changes and the arterial lumen is reduced.

In order to better understand the sequence of events associated with ASO (diabetic or non diabetic), a series of diagrams will be used. The diagrams will illustrate normal arterial anatomy and the chronological changes occurring with ASO.

Finally, the possible clinical scenarios will be discussed that can occur once the atheromatous plaque has formed.

Typical lower extremity artery consists of three layers:

1. intima,
2. media,
3. adventitia.



Most histology textbooks discuss cross-sectional arterial anatomy from outside in. That is, the textbooks start with a description of the adventitia, move on to describe the contents of the media, and conclude with a description of the intima. Our discussion is going in the reverse of that order.

Because formation of the atheromatous plaque starts at the intima and then extends through the internal elastic membrane into the media, the cross-sectional arterial anatomy will be described from deep to superficial. That is, the same direction will be followed as the atheromatous disease process itself.

The intima is the innermost layer of the artery and is composed of a thin sheet of endothelial cells along with an underlying internal elastic membrane. The internal elastic membrane separates the intima from the media.

By the process of diffusion, nutrients and other substances from the passing blood stream penetrate the intima through the gaps between the endothelial cells. In this fashion, the intimal endothelial cells and the deepest cells of the media get to *eat* and to give off their cellular waste products.

This diffusion process is important for the well being of the intima and the deepest portion of the media. The small arteries responsible for bringing nutrient arterial blood flow to the cells of the arterial wall are called the vasa vasorum. Vasa vasorum means *blood vessels of the blood vessels*. The vasa vasorum do not penetrate to the deepest layers of the artery wall. The deepest media cells and the intimal endothelial cells must receive their nutrients and must get rid of their metabolic waste products by the process of diffusion, as described above.

In the initial stages of atheromatous plaque formation, cholesterol, in the from of lipoprotein, diffuses across the endothelial layer and accumulates locally—between the endothelial cells and the internal elastic membrane. At this stage, the patient develops the earliest grossly visible atheromatous lesion—the fatty streak (Diagram 2).

Looking directly at the endothelial surface, the fatty streak appears as a linear elevation of endothelial cells. From a mechanical standpoint, the endothelial cells are bulging into the artery lumen due to the local underlying accumulation of cholesterol.

This fatty streak is considered to be a precursor lesion to the atheromatous plaque. As the process continues, the cholesterol deposit enlarges and spreads across the internal elastic membrane to involve the muscular media (Diagram 3).

The media is the middle layer and is composed of smooth muscle cells. As the atheromatous plaque develops, these smooth muscle cells are either replaced by or become lipid containing macrophages. The macrophages, also called foam cells,continue to eat more and more of the cholesterol which has diffused from the blood stream across the intima and is *deposited* in the media.

As the process continues, the atheromatous plaque enlarges and the covering sheet of intima is pushed further and further into the lumen of the artery. As a result, the lumen size gets smaller and smaller (Diagram 4).

Unfortunately, the cholesterol becomes toxic as it accumulates in the foam cells and eventually, the lipid filled foam cells burst. The extruded cholesterol *pieces* are locally scattered throughout the extracellular space of the media. In addition, the previously functioning smooth muscle cell is lost forever and is replaced by scar tissue and cellular debris. At this stage, the atheromatous plaque may, and frequently will, calcify.

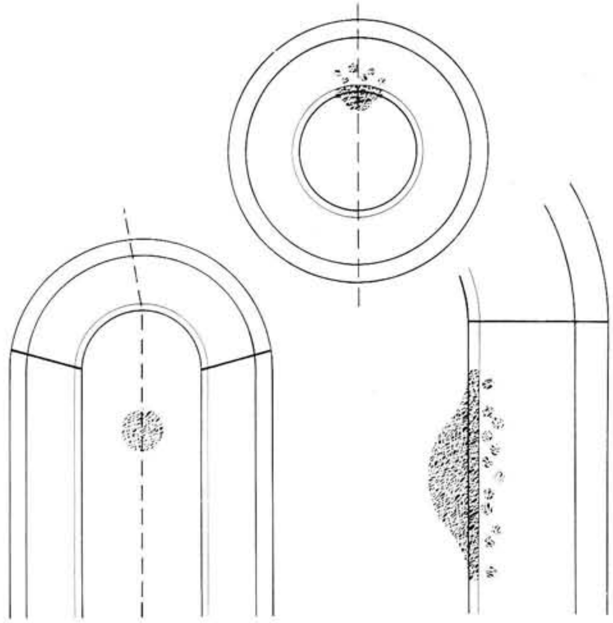


Diagram 3. Atheromatous plaque with involvement of intima and early involvement of media.

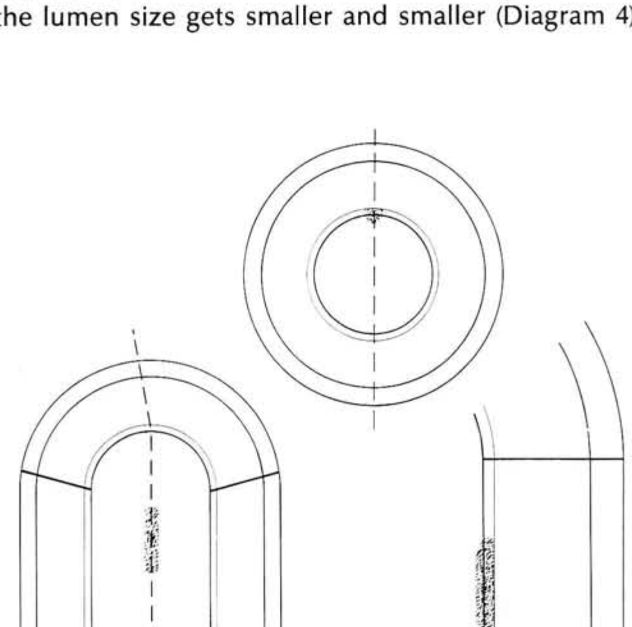


Diagram 2. The fatty streak.

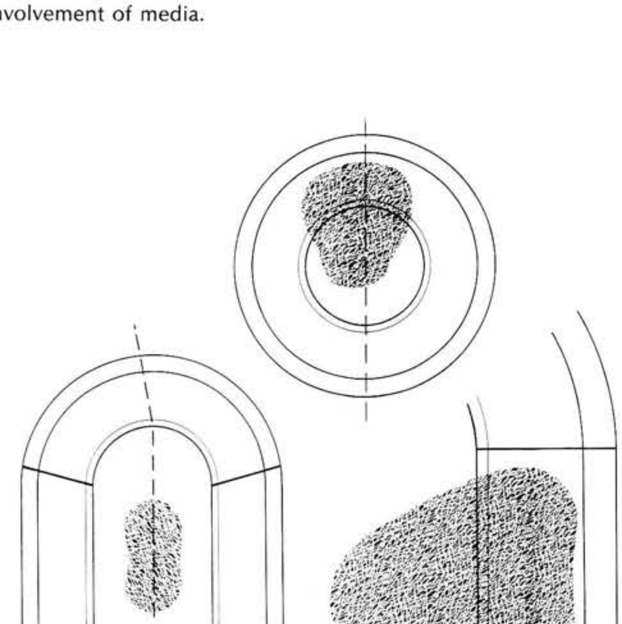


Diagram 4. Well developed atheromatous plaque with significant bulging of plaque and covering intima into arterial lumen.

The adventitia is the outermost layer and consists of connective tissue. The adventitia does not play an important role in ASO.

The atheromatous plaque results in diabetic gangrene as follows.

1. The atheromatous plaque becomes so large that the plaque completely fills and obliterates the artery lumen (Diagram 5). Or,
2. The endothelial surface overlying the atheromatous plaque ulcerates and the plaque extrudes shards of cholesterol into the bloodstream. These pieces of cholesterol travel distally in the arterial stream to produce arterial emboli (Diagram 6). Or,
3. The endothelial surface overlying the atheromatous plaque ulcerates and a thrombus forms at the site of ulceration. The thrombus grows and grows in size and eventually, part or all of the thrombus breaks off and travels distally in the arterial blood stream to produce an arterial embolism (Diagram 7). Or,
4. The endothelial surface overlying the atheromatous plaque ulcerates and a thrombus forms at the site of ulceration. The thrombus grows and grows in size and eventually completely occludes the arterial lumen (Diagram 8).

   Note, this only occurs when there is such extensive upstream (proximal) arterial obstruction that local arterial pressure is extremely reduced. Otherwise the thrombus would be torn away from the ulcerated endothelial surface long before it could grow large enough to completely occlude the lumen.

NON-INVASIVE MEASUREMENTS OF ARTERIAL INFLOW TO THE FOOT

The most important measurements of arterial inflow to the foot are the easiest to perform. These indirect measurements of arterial inflow consist of the following:

1. ankle systolic pressure
2. ankle/arm ratio
3. transmetatarsal (forefoot) systolic pressure
4. digital systolic pressure
5. toe/arm ratio
6. digital artery Doppler examination
7. distal plantar pulp Doppler examination

Please note: These tests are listed in the order in which they should be used clinically.

1. Ankle systolic pressure

   a. The technique for determining the segmental systolic pressure at each of the three pedal source arteries:

      1. posterior tibial
      2. dorsalis pedis
      3. peroneal

   b. The definition of ankle systolic pressure.

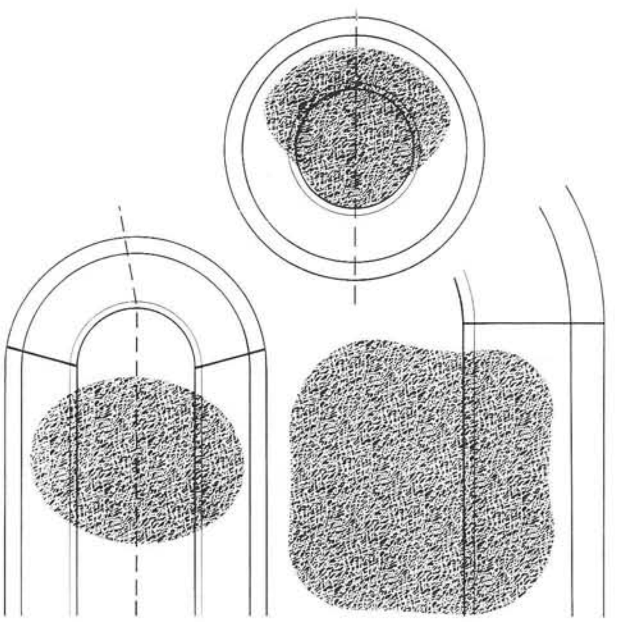


Diagram 5. How atheromatous plaque results in diabetic gangrene. Plaque becomes so large that it completely fills and obliterates lumen.

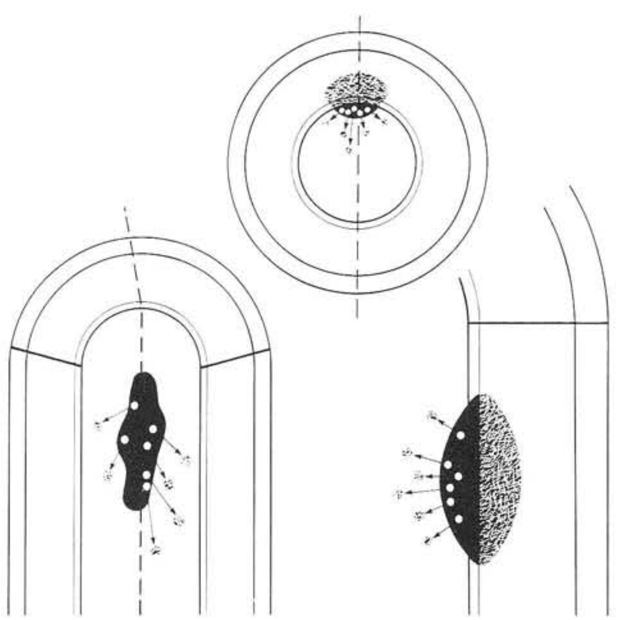


Diagram 6. Endothelial surface ulcerates and plaque extrudes shards of cholesterol and debris which travel distally to produce arterial emboli.

Technique

The ankle systolic pressure is determined by measuring the segmental systolic pressure at each of the three source pedal arteries (posterior tibial, dorsalis pedis, and peroneal). The technique for this measurement is as follows:

1. A blood pressure cuff is applied just above the ankle.
2. Using a Doppler probe, the posterior tibial arterial pulsation is located at the ankle—just distal to the cuff.
3. Keeping the Doppler probe in position over the posterior tibial artery, the pressure at the ankle cuff is elevated until no arterial sounds can be heard through the Doppler probe (over the posterior tibial artery).
4. The pressure at the ankle cuff is slowly lowered while the Doppler probe continues to be held over the posterior tibial artery.
5. The point at which the arterial sounds return is taken as the segmental systolic pressure of the posterior tibial artery.

This technique is repeated with the Doppler probe held over the dorsalis pedis artery and is then repeated again with the Doppler probe held over the peroneal artery. In this fashion, the dorsalis pedis and peroneal artery segmental systolic pressures are determined.

If there is still any question as to how to determine the segmental systolic pressures at the dorsalis pedis and peroneal arteries, the reader can substitute the words *dorsalis pedis* and then *peroneal* for the words *posterior tibial* in the above steps 1-5.

Definition

The highest of the three source artery segmental systolic pressures is taken as the ankle systolic pressure. Two examples are here to make this clear.

1. If the dorsalis pedis segmental systolic pressure is 110 mm Hg, the posterior tibial segmental systolic pressure is 122 mm Hg, and the peroneal segmental systolic pressure is 108 mm Hg ... then the ankle systolic pressure is 122 mm Hg.
2. If the dorsalis pedis segmental systolic pressure is 120 mm Hg, the posterior tibial segmental systolic pressure is 116 mm Hg, and the peroneal segmental systolic pressure is 118 mm Hg ... then the ankle systolic pressure is 120 mm Hg.

The highest of the three source arteries segmental systolic pressures is used as the ankle systolic pressure. The reason is simple, the explanation is long.

A sensing device is needed that will allow the clinician to continually monitor blood flow in the area of the sensor. A photoplethysmographic (PPG) probe will do this well. Place the PPG probe distally on the forefoot, and the blood flow can continually be monitored through the piece of skin under the PPG probe. If the blood pressure

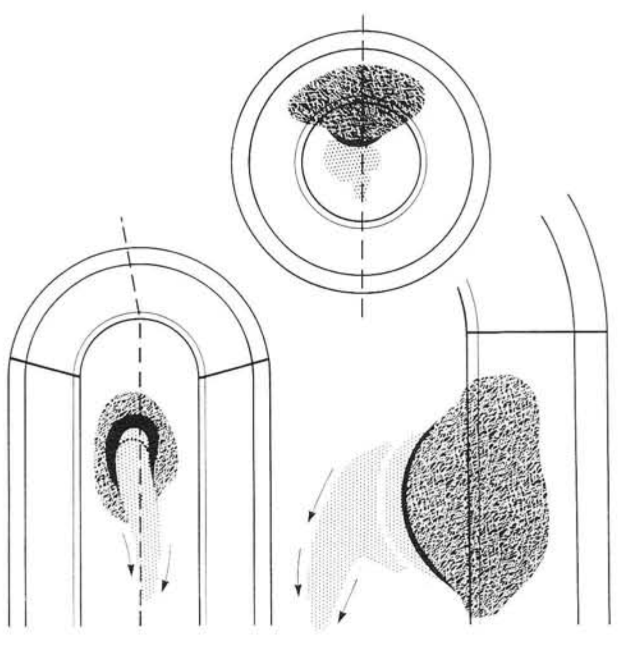


Diagram 7. Endothelial surface ulcerates and thrombus forms at site of ulceration. As thrombus grows, piece of thrombus breaks off and travels distally to produce arterial embolism.

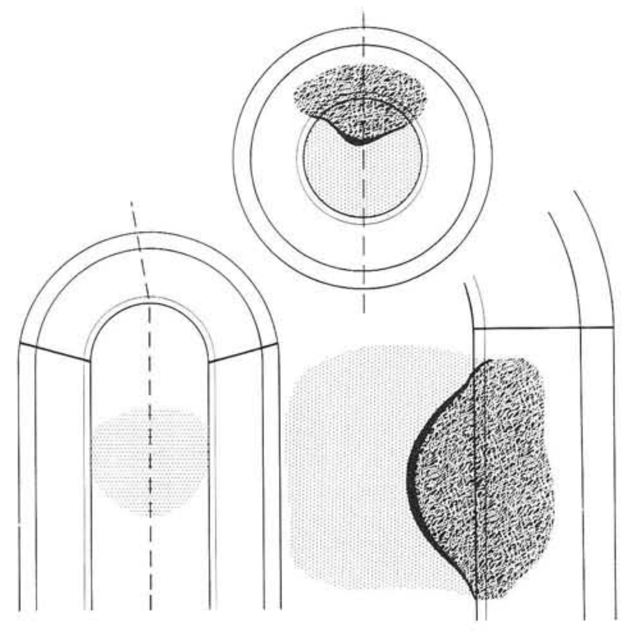


Diagram 8. Endothelial surface ulcerates and thrombus forms at site of ulceration. Local arterial flow is slow enough (additional upstream obstruction) so that thrombus grows and grows, and eventually occludes the lumen.

cuff is wrapped around the ankle, the clinician has the ability to stop arterial inflow into the foot by raising the pressure of the cuff to a value greater than the segmental systolic pressure at each of the three source arteries.

If the three source arteries have different segmental systolic pressures, and the pressure is raised at the ankle cuff to a value higher than the segmental systolic pressures at two of the source arteries but lower than the segmental systolic pressure at the third source artery, then the distally placed PPG probe will correctly continue to monitor arterial inflow coming into the forefoot. The arterial inflow to the forefoot can not be stopped until the pressure at the ankle cuff exceeds the systolic pressure at all three of the source arteries. For this reason, the highest of the three source artery systolic pressures is taken as the ankle systolic pressure.

A previous example can be used to illustrate this point:

Example 1:

Dorsalis pedis systolic pressure	110 mm Hg
Posterior tibial systolic pressure	122 mm Hg
Peroneal systolic pressure	108 mm Hg

If the ankle cuff pressure is raised to a value of 112 mm Hg, the blood flow will be successfully stopped through the dorsalis pedis and peroneal arteries. However, arterial inflow to the forefoot will continue through the still open posterior tibial artery. When the ankle cuff pressure is raised to a value of 123 mm Hg, the posterior tibial artery will be squeezed shut and all blood flow into the foot will stop.

Remember, the three source arteries have enough interconnections so that any one of the three has the potential to perfuse the entire forefoot.

The Ankle/Arm Ratio

1. The definition of ankle/arm ratio
2. Calculation of the ankle/arm ratio
3. General application of the ankle/arm ratio for non-diabetic patients
4. Surgical application of the ankle/arm ratio for non-diabetic patients.
5. General application of the ankle/arm ratio for diabetic patients.
6. Surgical application of the ankle/arm ratio for diabetic patients.

The ankle/arm ratio is synonymous with *ankle/brachial index* (ABI) and *ischemic index*. The ankle/arm ratio is determined by dividing the ankle systolic pressure by the arm systolic pressure.

The calculation of the ankle/arm ratio follows.

To understand the concept of ankle/arm ratio, please read through and answer the following short exercises. The answers and explanations for these problems may be found on the following pages.

Exercise 1

Blood pressure (arm)	200/80
Dorsalis pedis systolic pressure	96 mm Hg
Posterior tibial systolic pressure	100 mm Hg
Peroneal systolic pressure	98 mm Hg

What is the ankle/arm ratio?

Exercise 2

Blood pressure (arm)	110/70
Dorsalis pedis systolic pressure	220 mm Hg
Posterior tibial systolic pressure	216 mm Hg
Peroneal systolic pressure	180 mm Hg

What is the ankle/arm ratio?

Exercise 3

Blood pressure (arm)	140/90
Dorsalis pedis systolic pressure	180 mm Hg
Posterior tibial systolic pressure	210 mm Hg
Peroneal systolic pressure	200 mm Hg

What is the ankle/arm ratio?

Exercise 4

Blood pressure (arm)	160/86
Dorsalis pedis systolic pressure	158 mm Hg
Posterior tibial systolic pressure	158 mm Hg
Peroneal systolic pressure	160 mm Hg

What is the ankle/arm ratio?

ANSWERS:

Exercise 1

The arm systolic pressure is 200 mm Hg.
The highest of the three pedal source artery systolic pressures is the posterior tibial at 100 mm Hg.
The ankle/arm ratio = 100/200 = 0.5

Exercise 2

The arm systolic pressure is 110 mm Hg.
The highest of the three pedal source artery systolic pressures is the dorsalis pedis at 200 mm Hg.
The ankle/arm ratio = 220/110 = 2.0

Exercise 3

The arm systolic pressure is 110 mm Hg.
The highest of the three pedal source artery systolic

pressures is the posterior tibial at 210 mm Hg.
The ankle/arm ratio = 210/140 = 1.5

Exercise 4
The arm systolic pressure is 160 mm Hg
The highest of the three pedal source artery systolic pressures is the peroneal at 160 mm Hg
The ankle/arm ratio = 160/160 = 1.0

GENERAL APPLICATION OF THE ANKLE/ARM RATIO FOR NON-DIABETIC PATIENTS

The ankle/arm ratio is extremely significant in the evaluation of overall arterial inflow to the foot of a non-diabetic patient. The correlation between ankle/arm ratio and clinical findings can be summarized by Yao's conclusions:

ANKLE/ARM RATIO	CLINICAL FINDING
1. Ankle/arm = 1.0	normal
2. Ankle/arm = 0.5—0.6	intermittent claudication
3. Ankle/arm = 0.25—0.3	rest pain
4. Ankle/arm = 0.1	impending gangrene

Note—these findings apply only to non-diabetic patients. For reasons which will become clear later in this section, these findings cannot be applied to diabetic patients.

SURGICAL APPLICATION OF THE ANKLE/ARM RATIO FOR NON-DIABETIC PATIENTS

Even for the non-diabetic surgical patient, we must remember a practical point regarding preoperative arterial evaluation:

Beware of the ankle/arm ratio!

A simple clinical story will highlight this point. A non-diabetic patient has a left bunion deformity. The left foot is pulseless. Using the blood pressure cuff and Doppler technique, a segmental systolic pressure study is performed at the left ankle. The recorded pressures are: 20 mm Hg at the left posterior tibial artery, 30 mm Hg at the left dorsalis pedis artery and 120 mm Hg at the left peroneal artery. The recorded systolic pressure at the arm is 120 mm Hg. What is the ankle/ arm ratio?

By definition, the highest of the three source artery systolic pressures is taken as the ankle systolic pressure. In this example, the peroneal artery pressure of 120 mm Hg is used. This would give us a ratio of 120/120 which equals 1.0. Does this *normal* ankle arm ratio mean the patient has a normal amount of arterial inflow to the left foot? The implied answer is yes. The real answer is no.

This patient has significant obstruction of the left dorsalis pedis and posterior tibial arteries. Yet the ankle/arm ratio is normal. Would the patient have problems with healing following a bunionectomy procedure? Probably.

What questions should then be asked regarding the use of the ankle/arm ratio in the preoperative arterial evaluation of the non-diabetic patient?

1. What is the ankle/arm ratio?
2. What is the dorsalis pedis pressure?
3. What is the posterior tibial pressure?
4. What is the peroneal pressure?
5. Has the patient had previous surgery at the contemplated surgical site?

If the answers to these questions are less than reassuring, use of the non-invasive flow sheet (at the end of this article) is strongly advised. Specifically: if the ankle/arm ratio is less than .75, if the dorsalis pedis and/or posterior tibial pressure is abnormally low (e.g., less than .75), or if the patient has had previous surgery at the contemplated surgical site—all of the tests on the non-invasive flow sheet should be considered. These tests take less than ten minutes to perform and are highly recommended.

GENERAL APPLICATION OF THE ANKLE/ARM RATIO FOR DIABETIC PATIENTS

The relationship between Monkeberg's medial calcific sclerosis, diabetes, and the ankle/arm ratio is extremely important. Unfortunately, this relationship is frequently confused. As a result, the ankle/arm ratio is erroneously applied to diabetic patients.

You are encouraged to read the following short cardiovascular physiology review carefully. This brief discussion holds the key to understanding the concept of *segmental* systolic pressure.

With each cardiac cycle, the left ventricle contracts and ejects a systolic *bolus* of arterial blood into the aorta. This systolic bolus continues though the peripheral arteries branching off the aorta.

As the systolic bolus continues through the aorta and its branches, a moving wave of arterial expansion is created. In more descriptive terms, a *piece* of arterial blood is pushed through the systemic arteries by the force of left ventricular contraction. However, the piece of arterial blood is too fat to slide through the arteries. As a result, the arteries must expand to accommodate the distally traveling fat piece of blood. Once the fat piece of arterial blood has passed by, the expanded segment of artery contracts back to its *resting* size.

It is this rhythmic systolic ejection of arterial blood from the left ventricle that is responsible for the recurrently palpable arterial pulsation at the dorsalis pedis and posterior tibial arteries. However, these arteries are not always pulsatile on clinical examination.

Pulsation of a peripheral artery may be diminished or absent due to one or both of the following reasons:

1. There is an upstream obstruction which will not allow enough of the systolic bolus to reach the peripheral artery with enough energy to expand the artery wall. Or,
2. The wall of the peripheral artery is rigid and will not expand.

In the first case, there is simply not enough blood flow to mechanically distend the arterial wall. In addition, the forward driving pressure of the arterial column has been reduced. As a result of the upstream obstruction then, both the volume and force of the systolic bolus have been reduced.

Note, the upstream obstruction may be partial or complete. In the case of partial obstruction, arterial blood flow will still be audible on Doppler examination at the distal artery being examined.

In the second case, the wall of the artery is calcified and will not distend as the systolic bolus passes. More importantly, from our standpoint of preoperative evaluation, this calcified artery will not completely collapse with external pressure.

We are now ready to discuss the pitfall associated with ankle/arm ratio in diabetic patients.

Monkeberg's medial calcific sclerosis frequently occurs in the lower extremity arteries of diabetic patients. This disease process is characterized by calcification of the arterial wall. Specifically, the muscular media becomes calcified and this results in a rigid tube that cannot expand and will not compress. The normal, distally transmitted systolic pulse wave will not be palpable through the calcified arterial wall.

Normally, when a blood pressure cuff is applied just above the ankle and the cuff pressure is elevated, blood will continue to flow through the arteries being *squeezed* until the external squeezing pressure exceeds the intraluminal pressure. That is, a normal artery with a normal elastic wall, will stay open as long as the intraluminal arterial pressure keeping the artery open exceeds the external squeezing pressure. Once the external squeezing pressure exceeds the intraluminal pressure, the artery closes.

In the case of Monkeberg's medial calcific sclerosis, however, the artery will not close, regardless of the amount of external squeezing pressure applied.

It is necessary to simultaneously review the co-existing vascular disease process of diabetic ASO and Monkeberg's medial calcific sclerosis in a diabetic patient.

Diabetic ASO	**Monkeberg's**
The patient has proximal obstruction of the thigh and/or leg arteries—due to diabetic ASO	The patient has distal calcification of the ankle arteries due to Monkeberg's medial calcific sclerosis
The intraluminal systolic pressure is greatly reduced at the ankle arteries — due to the upstream obstruction	A blood pressure cuff applied at the level of the ankle is unable to squeeze the ankle arteries closed — due to the calicification

The Doppler probe is held in place over one of the source arteries—distal to the ankle cuff.

The pressure at the ankle cuff is elevated higher and higher and yet, the arterial sound is still audible distal to the cuff.

This is true because the ankle arteries will not collapse.

As a result, the true segmental systolic pressure (of the source artery being examined) cannot be accurately determined.

CONCLUSION: The ankle/arm ratio should not be used as a *single* test of arterial inflow to the feet of diabetic patients.

CLINICAL PEARL: If the ankle systolic pressure is 1.5x (or greater) than the systolic pressure at the arm, be very suspicious of Monkeberg's.

SURGICAL APPLICATION OF THE ANKLE/ARM RATIO FOR THE DIABETIC PATIENT

Simply stated, the ankle/arm ratio should not be relied upon as a stand *alone* test for diabetic patients. There is a small army of surgeons who have been embarrassed postoperatively by seemingly normal preoperative ankle/arm studies on diabetic patients.

The Transmetatarsal (Forefoot) Systolic Pressure

Definition

The transmetatarsal systolic pressure is an indirect measurement of arterial inflow through the entire cross section of the forefoot. The transmetatarsal systolic pressure does not measure the pressure at a single artery. Instead, this test is a reflection of the composite pressures of all the midfoot arteries—without distinguishing the pressure contribution of one artery from another.

Technique

1. Wrap a transmetatarsal pressure cuff around the patient's midfoot.
2. Using a piece of adhesive tape that is sticky on both sides, apply a PPG probe to any area of skin distal to the pressure cuff.
3. Turn the PPG on and let the recording paper run at slow speed.
4. Turn up the electrical gain (size control knob) in order to increase the size of the PPG wave forms being recorded.
5. With the recording paper running at slow speed and the enlarged PPG wave forms being recorded, raise the pressure at the transmetatarsal cuff.
6. Continue to raise the pressure at the transmetatarsal cuff until no PPG wave forms are being recorded and the stylus *falls* on the recording paper and inscribes a straight line.
7. Lower the pressure at the transmetatarsal cuff slowly.
8. The pressure at which the PPG wave forms begin to reappear is taken as the transmetatarsal (forefoot) systolic pressure.

When and Why This Test Should be Used

Even in the presence of Monkeberg's disease, medial calcific sclerosis, the transmetatarsal systolic pressure is an accurate and valid measurement of a patient's forefoot systolic pressure. This finding has been substantiated by several different studies.

If this is so well documented, why would anyone measure the ankle systolic pressure and rely upon the ankle/arm ratio as *the* most important non-invasive diagnostic study for diabetic patients? There are several reasons why the ankle/arm ratio is still considered the clinical *gold standard*.

1. Portable Doppler units have enjoyed widespread acceptance everywhere.
2. PPG units, and /or other types of plethysmography units are usually found only with dedicated noninvasive lab setups.
3. One does not need a recording Doppler to determine the ankle systolic pressure and the ankle/arm ratio.
4. One does need a chart recorder for a PPG unit, and
5. Most importantly, the Doppler has a widespread clinical application whereas the PPG is useful in a limited number of clinical circumstances.

Will the forefoot and digital systolic pressure studies eventually be accepted? Absolutely. The very essence of diabetic ASO can be expressed as islands of tissue ischemia surrounded by oceans of adequate arterial flow.

The noninvasive studies must be obtained as close as possible to the area of diabetic foot being operated on. And because of distance and because of Monkeberg's medial calcific sclerosis—the ankle is too far away.

If the contemplated foot surgery is to take place at or around the toes, should the forefoot systolic pressure be measured rather than the digital systolic pressure of the toe to be operated on? No. If the toe to be operated on is adequately accessible, then we should measure the pressure at that toe. Unfortunately, many of our preoperative diabetic patients have digital deformities which make it impossible to apply both a digital blood pressure cuff and a PPG probe to the toe in question.

Even if the diabetic toe to be operated on is large enough and straight enough to apply both a PPG probe and a digital blood pressure cuff, it is still a good idea to check the forefoot systolic pressure as well as the digital systolic pressure. This is necessary because the forefoot and digital systolic pressure readings should corroborate each other. The forefoot systolic pressure may normally be 10 to 20 mm Hg higher than the digital systolic pressure. If the digital systolic pressure is 40 mm Hg (or more) lower than the forefoot systolic pressure, the patient has very significant metatarsal and digital artery (diabetic) obstructive disease.

Usually the forefoot and digital systolic pressures are within 10 mm Hg of each other.

PREDICTIVE VALUE

The forefoot systolic pressure is not as valuable as the digital systolic pressure, when it comes to predicting whether a diabetic toe will heal after surgery. But it is still very necessary. And, finally, the forefoot systolic pressure (and, therefore, the forefoot/arm ratio) is many times more accurate than the ankle systolic pressure (and the ankle/arm ratio) when it comes to determining forefoot arterial blood flow in diabetic patients.

DIGITAL SYSTOLIC PRESSURE

Definition

The digital systolic pressure is a measurement of the *cross sectional* systolic pressure of a toe. This measurement does not differentiate the relative contributions of each digital artery to the overall systolic pressure of a toe.

Technique

The digital systolic pressure may easily be determined as follows:

1. Wrap a digital blood pressure cuff around the base of the toe in question.
2. Using a piece of adhesive tape that is sticky on both sides, apply a photoplethysmographic probe to the distal plantar fat pad of the toe in question.
3. Turn the photoplethysmography (PPG) unit on and let the recording paper run at slow speed.
4. Turn up the electrical gain (size control knob) in order to increase the size of the PPG wave forms being recorded.
5. With the recording paper running at slow speed and the enlarged PPG wave forms being recorded, raise the pressure at the digital cuff.
6. Continue to raise the pressure at the digital cuff until no PPG wave forms are being recorded and the stylus falls and records in a straight line.
7. Lower the pressure at the digital cuff slowly.
8. The pressure at which the PPG wave forms begin to reappear is taken as the digital systolic pressure.

Significance

The digital systolic pressure is the single most important measurement for the diabetic toe. In fact, this measurement is so important that the perspective of this article may need to be reframed.

The clinical expression of diabetic and (nondiabetic) arterial disease has not changed over the years. What has changed is the ability to diagnose and treat these problems.

Such a heightened level of diagnostic sophistication has been reached that it is difficult to decide which tests to order. It is also difficult to determine how these test results are to be interpreted, and extremely difficult to decide on the relative clinical significance of each test result.

In addition, there is the added problem of financial compensation. More tests mean more money and this ugly truth cannot be ignored.

So clinically the lowest common denominator is needed that will allow quick and inexpensive evaluation of preoperative arterial inflow to a patient's foot. The digital systolic pressure is the cornerstone measurement for the diabetic foot. In fact, the result of a digital systolic pressure determination combined with the findings of a digital artery Doppler examination, for a single toe, gives enough information to decide whether that diabetic toe will heal after the trauma of surgery.

When Should This Test Be Used?

Ideally, all diabetic patients undergoing digital surgical procedures should have the digital systolic pressure of the toe or toes to be operated on measured preoperatively. The digital systolic pressure of one toe can not be measured and assumed to be the same for the adjacent toes.

The segmental nature of diabetic ASO means that one toe can be very ischemic while the adjacent toes are normal. This tells us that most surgeons will recognize the desirability of measuring the systolic pressure of each of the diabetic toes.

The Toe/Arm Ratio

Definition

The toe/arm ratio (or toe/arm index) is a number obtained by dividing the systolic pressure of the toe by the systolic pressure of the arm.

Calculation

If the systolic pressure of the toe is measured at 80 mm Hg and the patient's blood pressure is recorded as 120/84—what is the patient's toe/arm index? After you have calculated the toe/arm index, look below where the solution to the problem may be found.

When the Toe/Arm Ratio Should Be Used

Ideally, the toe/arm ratio should be calculated any time a digital systolic pressure study is performed. And a digital systolic pressure study should be done on any diabetic toe to be operated on.

Alternative Measurements

What if the patient's toe is too deformed to allow for placement of either the digital cuff and/or the PPG sensor? In that case the patient's forefoot systolic pressure should be measured instead, being careful to place the PPG probe at the base of the toe to be operated on.

By combining the forefoot systolic pressure (and the forefoot/arm ratio) with the information obtained from a digital artery Doppler study, the arterial status of the toe in question may be evaluated.

Answer to the previous problem:

The patient's blood pressure is 120/84
The patient's digital systolic pressure is 80 mm Hg

80 (toe systolic)/120 (arm systolic)
80/120 = .75
the patient's toe/arm ratio is .75

Digital Artery Doppler Examination

Purpose

The digital artery Doppler examination is designed to answer two questions. The first question is objective and asks which of the four digital arteries of a toe are open? The second question is subjective and asks how much blood flows through each of the digital arteries of the toe in question?

Although the two questions may seem very straight forward in principle, they are difficult to answer. In fact, of all the arterial tests discussed in this chapter, the digital artery Doppler examination is the most difficult to perform. It is also the easiest of the arterial tests to cheat on.

Why is the digital Doppler examination difficult to perform? Because the examiner must learn to patiently move the Doppler probe very slight distances through each of the four digital artery areas of the toe.

Why is it so easy to cheat on the exam? Because of our desire to find all four digital arteries, it is very easy to move the Doppler probe from the area of one digital artery into the area of an adjacent digital artery. As a result, one may conclude both arteries are open when, in fact, only one of the arteries is patent. If this does not seem plausible, remember the toes are small and the four digital artery areas are even smaller.

CHOICE OF EQUIPMENT

Before discussing technique of finding and assessing digital artery blood flow by Doppler exam, a word is in order regarding the choice of Doppler equipment.

Doppler equipment varies greatly. Here are some basic recommendations. First, the Doppler unit purchased must have an 8 to 10 mega Hertz output. The constant wave (CW) Doppler suitable for podiatric use, should emit 8 million to 10 million ultrasound waves per second from the head of the Doppler probe. Second, and more important, the Doppler unit should be used for a trial period. Use the Doppler unit to examine the digital arteries of several different patients over a 2-3 day time period.

Many similarly priced units are of dissimilar quality. The need to select Doppler equipment should be on the basis of a digital artery exam. Because any Doppler unit will enable one to hear blood flow through a dorsalis pedis or posterior tibial artery. But only a few of the units are sensitive enough to reliably pick up blood flow through the digital arteries.

Finally, the Doppler is the workhorse of any non-invasive vascular lab set-up. As such, the quality of the Doppler should determine the choice of equipment when it comes time for buying vascular diagnostic equipment.

TECHNIQUE

The technique for performing a digital artery Doppler examination is theoretically simple and may be described as follows:

Hold the Doppler probe:
at a 90 degree angle to the skin,
at the midshaft level of the proximal phalanx and,
over the dorsal medial digital artery (DMDA).

Determine whether the blood flow can be heard through the DMDA. The potential answers to this question are yes, no, or maybe.

A *yes* answer implies the DMDA is patent and that the nearby upstream arteries (feeding into the DMDA) are patent.

A *no* answer implies the DMDA and/or its upstream feeding arteries are blocked.

A *maybe* answer implies: the sound at the DMDA is so indistinct, that it is questionable if the sound is due to flow through the artery or,

the batteries of your portable unit are weak, or,

an inferior quality Doppler unit is being used.

Determine how loud the arterial sound is at the DMDA. Admittedly, this calls for a completely subjective conclusion. However, by keeping the volume control knob at the same setting for every study, one quickly develops a discriminating ear that will allow one to grade *loudness*.

In practical terms, a louder arterial sound implies more blood flow (through the DMDA) and a quieter arterial sound implies less blood flow.

An easy grading system for loudness is as follows.

0 = inaudible arterial sound
= = questionably audible arterial sound
+1 = weak but definitely audible arterial sound
+2 = moderate to strongly audible arterial sound
+3 = unusually loud arterial sound

Perform the digital artery Doppler examination only on the toe or toes in question.

The quality of this examination falls off rapidly when listening to too many toes because this examination is boringly repetitive and, at any rate, time is wasted to listen to and grade all 40 digital arteries.

Perform the digital artery Doppler examination in the same order each time. By listening to the digital arteries in exactly the same sequence every time, recording errors may be avoided when writing the grading number for each artery. The author listens to the dorsal medial digital artery first, the dorsal lateral digital artery second, the plantar medial digital artery third, and the plantar lateral digital artery fourth. It obviously makes no difference which order one selects. But the same order must be kept each time.

THE DISTAL PLANTAR PULP DOPPLER EXAMINATION

Purpose

The distal plantar pulp (DPP) Doppler examination is a 10 second test that allows for immediate assessment of over-all arterial inflow into a toe. This is the test the author uses and is willing to share. The DPP Doppler exam findings should corroborate the combined results of the digital systolic pressure study and the digital artery Doppler examination.

Principle

There are no named arteries along the distal, midline, plantar surface of the toes. The only arterial components present are the smallest arterial branches of the medial and lateral plantar digital arteries. These small arterial branches anastomose with each other at the distal plantar pad of the toe and this rete-like network of small arteries is called the distal plantar arterial tuft.

Because the toes are the last areas to receive a piece of each systolic bolus, it stands to reason that a quick test of digital arterial inflow is actually a quick peek at the systemic arteries—all the way from the abdominal aorta to the tips of the toes. If the toes are okay, the upstream arteries are okay.

Technique

The technique for the DPP doppler examination may be broken down as follows:

1. Dilate the patient by heating the exam room and covering the patient with a blanket.
2. Hold the Doppler probe at 90 degrees to the skin, over the central (midline) plantar pulp of the toe. It should be held distally at the point on the distal plantar fat pad where the skin begins to curve dorsally towards the nail bed.
3. The same grading system is used for the DPP arterial sound as is used for the digital artery Doppler exam.

Comment

The author feels that this new diagnostic sign (within the toes) is a direct reflection of arterial flow through the smallest and most distal end arteries of the toes. And, this sign of arterial adequacy can easily be elicited by listening to and grading the loudness of the arterial sound at the tip of the toe.

Perhaps inappropriately, this sign is referred to as the Maximum Ultravascular Linearly Labile Endodigital Neodiagnostic Sign.

CLINICAL PEARL

Every diabetic toe the author has examined, and at which a strong distal plantar pulp arterial sound has been present has healed without amputation.

Many of these patients have required extensive resection of infected bone and many have had large, purulent diabetic ulcers requiring extensive and prolonged local surgical care. But a loud distal plantar pulp arterial sound, meant adequate arterial inflow for healing.

THE NON-INVASIVE FLOW SHEET

The following non-invasive flow sheet for elective foot surgery, applies to both diabetic and non-diabetic patients. All of the tests listed on the flow sheet have been discussed in this chapter and the total amount of time required to perform this presurgical exam should not exceed ten minutes.

In order to be in agreement as to the use and interpretation of the flowsheet, an imaginary presurgical patient will be used.

The first test listed is the ankle/arm index. If the patient's ankle/arm index is less than .75, no elective surgery will be performed. If the ankle/arm index is equal to or greater than .75 we will next determine the toe/arm index for the toe or toes on which surgery is to be performed.

If the patient's ankle/arm index is equal to or greater than .75, but the toe/arm index is less than .65, elective surgery will not be performed on the toe or toes in question. If the patient's ankle/arm index is equal to or greater than .75 and the toe/arm index is equal to or greater than .65, a digital artery Doppler examination will be performed (on the toe or toes to be operated on).

It is important to remember that if a presurgical toe in question is too deformed or too short or too whatever to allow for direct measurement of the digital systolic pressure, the thing to do is to measure the forefoot systolic pressure and to use the forefoot/arm index in place of the toe/arm index.

When the forefoot/arm index is substituted for the toe/arm index, our flowsheet progression would read as follows: If the patient's ankle/arm index is equal to or greater than .75, and the patient's forefoot/arm index is equal to or greater than .65, a digital artery Doppler exam would be performed next.

If the hallux is the toe to be operated on and the patient has an ankle/arm index of .75 or greater, and has a toe/arm (or forefoot/arm) index of 0.65 or greater, the patient is okay for surgery, if two out of four digital arteries of the hallux can be heard. Remember, the dorsal digital arteries of the hallux go all the way out to the tip of the toe—as do the plantar digital arteries of the hallux. Therefore, adequate arterial perfusion of the hallux will occur if any two out of the four digital arteries of the hallux are intact.

If any of the lesser toes, 2, 3, 4, or 5 are to be operated on, and the patient has an ankle/arm index of .75 or greater and has a toe/arm or forefoot/arm index of .65 or greater, the patient is okay for surgery. If either or both dorsal arteries, and one plantar artery can be heard, or if both plantar arteries can be heard, then surgery is acceptable. The anatomical differences are being acknowledged between the dorsal digital arteries which stop at the level of the pip joint and the plantar digital arteries which extend to the tips of the lesser toes.

Finally, an arterial sound should be definitely audible at the distal plantar pulp of any toe to be operated on. If a patient is covered with blankets and still there is difficulty hearing a distal plantar pulp arterial sound, consider the use of arterial occlusion at the ankle for five minutes. This can be accomplished by wrapping a blood pressure cuff around the ankle, just above the malleoli, and inflating the cuff. In order to make this easy, raise the cuff pressure to a value 50 mm Hg higher than the measured ankle systolic pressure. This way, any loss of cuff pressure during the five minutes of arterial occlusion, can be corrected before the pressure drops below the systolic pressure level.

Maximum blood flow through the dilated digital vessels will occur during the first minute after dropping the cuff pressure. It is during this initial period of profound dilation and maximum blood flow that the distal plantar pulp of the toe or toes to be operated on should be re-examined.

SUMMARY OF THE NON-INVASIVE EXAMINATION

In summary, the preoperative, non-invasive arterial examination should take approximately ten minutes to perform, from start to finish. The exam should consist of the following:

1. determination of the ankle/arm index
2. determination of the toe/arm index (or the forefoot/arm index if necessary)
3. a digital artery Doppler examination
4. and a determination of the presence or absence of a distal plantar pulp arterial sound.

If these guidelines are followed there should be no problems. In fact, by current standards, these rules are somewhat more conservative than is necessary. However when performing completely elective foot surgery, a greater margin of safety should be observed than would be the case for semi-elective or non-elective foot surgery.

A copy of the author's vascular evaluation worksheet used in the office is included. Please, feel free to copy it for your own use.

ARTERIAL INFLOW AND CHARCOT ARTHROPATHY

The relationship between angiopathy and neuropathy in the development and course of Charcot arthropathy is important.

Although there may be some controversy as to the exact etiology of Charcot arthropathy, there is no question that the natural history of this diabetic disease process unfolds as follows:

1. The foot becomes *numb*.
2. The bones become *soft*.
3. The patient walks on the numb foot with soft bones.
4. The soft bones fracture.
5. The fractures heal with malposition of the fragments and deposition of bone debris in the adjacent capsule.
6. The process repeats.
7. The foot becomes shorter and wider and develops angular bony prominences.
8. The foot becomes ulcerated and infected as the diabetic patient walks on the angular bony prominences.

Underlying the pathophysiology of Charcot arthropathy are two clinical findings which must be present in order for this disease to occur. First, the patient must have diabetic neuropathy and second, the patient must have adequate arterial inflow to support the sustained increased level of metabolic activity in the areas of bone fracture and repair.

Due to the diabetic neuropathy, the patient is at least partially unaware of the injury to the neuropathic joint. Concomitantly, the diabetic neuropathy involves the autonomic nerve fibers.

Because there are no parasympathetic nerve fibers to the foot, the term *autonomic neuropathy* means the sympathetic nerve fibers to the foot are not working. These post ganglionic adrenergic sympathetic nerve fibers normally innervate the smooth muscles in the walls of the blood vessels and innervate the sweat glands. When stimulated, these sympathetic nerves normally produce widespread vasoconstriction in the foot along with sweating.

As a result of diabetic autonomic neuropathy, the foot with Charcot arthropathy is dry and there is widespread vasodilation throughout all the tissues of the foot. The foot is warm to the touch and the cutaneous veins are engorged. The arterial inflow through the bones of the foot is increased—and this is very likely responsible for the *softening* of the diabetic bones.

Certainly, there are some obvious questions regarding Charcot arthropathy which have not been adequately answered. The most striking example would be: if the diabetic neuropathy continues and the arterial inflow remains adequate, why would the arthropathy ever become quiescent?

For the purpose of this paper, it is only important to state unequivocally that by all of the following studies, using all of the listed techniques, arterial inflow to the diabetic foot with Charcot arthropathy is at least normal and in many cases, greater than normal:

Doppler

1. Scarpello 1980
2. Edmonds 1982

Venous occlusion plethysmography

1. Archer 1984
2. Partsch 1977
3. Skmitizky 1977

Skin temperature studies

1. Ward 1983
2. Archer 1984

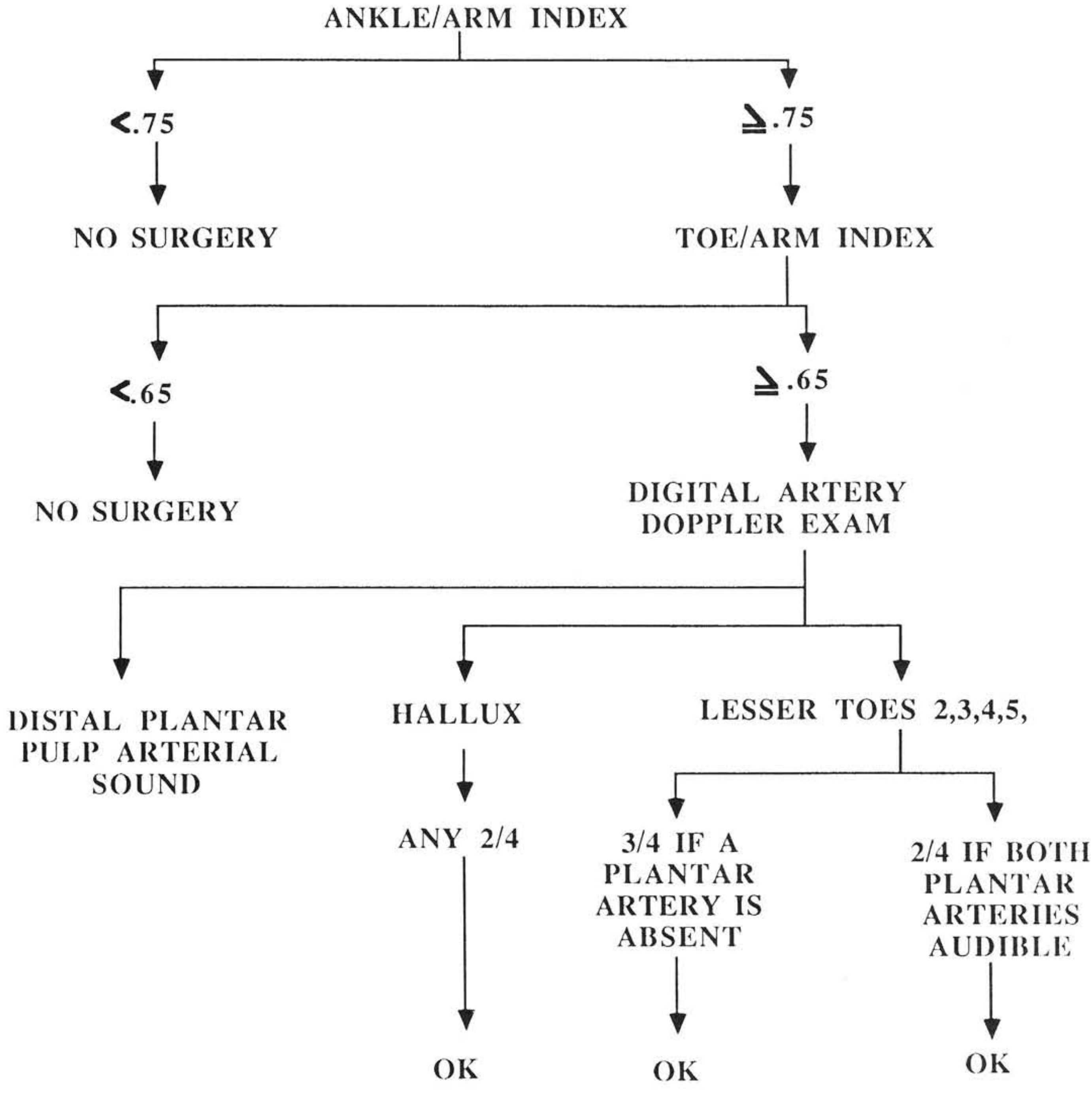
Bone Scan

1. Edmonds 1985

Arteriography

1. Seignon 1974

ELECTIVE FOOT SURGERY



DAVID D. MULLENS, D.P.M., M.S. 1101 WELCH ROAD, SUITE C-6 • PALO ALTO, CALIFORNIA 94304 • (415) 324-2091

PATIENT'S NAME ______________________ **CHART#** ________ **AGE** ____ **SEX** ____ **DATE** ____________

CLINICAL PROBLEM/LESIONS: ____

____

BP ______________ **ARM SUPINE · PULSE** ______

SUBPAPILLARY VENOUS PLEXUS FILLING TIME (NORMAL = 2–3 SEC)

L ______________

R ______________

ANKLE ARM INDEX

L ________ =

R ________ =

PULSES:	**L**	**R**
CAROTID		
RADIAL		
ULNAR		
AORTA		
FEMORAL		
POPLITEAL		
D. PEDIS		
POST. TIB.		

0 = ABSENT (NOT PALPABLE)
± = QUESTIONABLY PALPABLE
1 = WEAK BUT DEFINITELY PALPABLE
2 = MODERATE TO STRONGLY PALPABLE

SEGMENTAL SYSTOLIC PRESSURE (mm Hg)

	L	**R**
HT		
AK		
BK		
ANKLE		
MET		
TOE		

SEGMENTAL SYSTOLIC PRESSURES OF PEDAL ARTERIES (mm Hg)

	L	**R**
DORS. PEDIS		
POST. TIBIAL		
PERONEAL		

DOPPLER EVALUATION OF DIGITAL BLOOD FLOW:

	DMDA	DLDA	PMDA	PLDA	DPP
L1T					
L2T					
L3T					
L4T					
L5T					
R1T					
R2T					
R3T					
R4T					
R5T					

0 = ARTERIAL SOUND ABSENT
± = QUESTIONABLY AUDIBLE
1 = WEAK BUT DEFINITELY AUDIBLE
2 = MODERATE TO STRONGLY AUDIBLE
3 = UNUSUALLY LOUD

SEGMENTAL SYSTOLIC PRESSURE OF THE TOES (mm Hg)

L1T	R1T
L2T	R2T
L3T	R3T
L4T	R4T
L5T	R5T

CONCLUSIONS: ____