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JOURNAL OF THE AMERICAN HEART ASSOCIATION

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TRAVIS WINSOR

*Circulation* 1951;3;830-836

Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 72514

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# Simplified Determination of Arterial Insufficiency

## Plethysmographic Observation of Reactive Hyperemia following Fifteen Minute Arterial Occlusion at the Ankle

By TRAVIS WINSOR, M.D.

Reactive hyperemia following 15 minute arterial occlusion at the ankle was studied in plethysmographic tracings using the venous occlusion technic. The resulting curves present an essentially different pattern in normal subjects and patients with various types of peripheral arterial disease. Several characteristic features can be distinguished, notably the level of highest blood flow after release of arterial occlusion, the time required until the highest blood flow is reached, and the degree of secondary vasoconstriction. Evaluation of these factors permits an estimate of the therapeutic value of lumbar sympathectomy.

**P**LETHYSMOGRAPHIC observation of transient reactive hyperemia elicited through arterial occlusion has for many years been employed to determine the degree of vascular response and to estimate the therapeutic effect which may be expected from various medical and surgical procedures. The method was greatly improved by the development of the technic of venous occlusion.<sup>1</sup> Other technics proposed include injection of vasodilating drugs,<sup>2</sup> lumbar sympathetic block, posterior nerve block, spinal,<sup>3</sup> sacral, or paravertebral anesthesia.

Many of these procedures require the personal supervision of a physician, and in some cases the element of hazard cannot be entirely excluded. With the introduction of the pneumoplethysmograph<sup>4</sup> it has become possible to devise a standardized, simple and safe method for the determination of arterial insufficiency, which can be entrusted to a well-trained tech-

nician without requiring the immediate attention of a physician. Five minute arterial occlusion with the cuff applied above the knee is essentially satisfactory,<sup>3</sup> but produces submaximal vasodilatation, and the vascular response is in some cases appreciably influenced by pain at the site of the occluding cuff. It was therefore decided to test a modified technic employing arterial occlusion for a period of 15 minutes with the cuff at the ankle, a site at which pain is much less frequently observed.

### METHOD AND MATERIALS

In a comfortable environment<sup>6</sup> with a mean room temperature of 26 C.  $\pm$  1.5 C., determinations were carried out on 156 individuals (table 1) who had been made to rest for a period of 45 minutes, covered with wool blankets. The arterial cuff at the ankle was inflated to 100 mm. Hg above the arterial systolic pressure as ascertained by the plethysmographic technic.<sup>7</sup> Occlusion was maintained for 15 minutes and the string shadow frequently checked for any sign of drift indicating arterial leakage. The skin temperature was measured simultaneously with an electronic recorder. A fall of 2 C. was ordinarily observed in individuals with a resting skin temperature distinctly above room temperature, and was taken to mean that no gross leaks of arterial blood had occurred.

Following release of arterial occlusion the relative blood flow was measured by applying a venous collecting cuff at the ankle. The cuff was rapidly inflated for two to three seconds to a pressure of 60 mm. Hg in subjects without arterial disease,

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From the Department of Medicine, University of Southern California Medical School, and the Nash Cardiovascular Foundation, Hospital of the Good Samaritan, Los Angeles, California.

These studies were supported in part by grants from the A. M. Roberts Memorial Fund of the Los Angeles Heart Association, and the Los Angeles County Tuberculosis and Health Association.

Read in part before the Twenty-third Annual Scientific Sessions of the American Heart Association, June 23, 1950, San Francisco, Calif.

while in patients with arterial disease lower pressures were employed (not less than 35 mm. Hg) for longer periods of time. Volume changes of the digit were recorded at intervals of from 15 seconds to 1 minute for a period of 10 minutes. The rate of filling of the digit was calculated from the slant of the base line in cu. mm. per 5 cc. of tissue per second. Prior to the test, the volume of the toe was carefully measured and the instrument accurately standardized.

TABLE 1.—*Number and Ages of Subjects Studied Employing 15 Minute Arterial Occlusion at the Ankle for Production of Reactive Hyperemia.*

	Number of Determinations	Age of Subjects
Normal Individuals	26	18-54 Average: 30 20-65
Arteriosclerosis Obliterans	100	Average: 45
Vasoneurosis	5	18-30 Average: 22
Raynaud's Phenomenon due to Thromboangiitis Obliterans	5	27-51 Average: 36
Arteriosclerosis Obliterans Treated by Lumbar Sympathectomy	20	30-60 Average: 39
Total.....	156	

RESULTS

*Maximum Rate of Toe Flow*

The changes in the blood flow to the toe before and after arterial occlusion (fig. 1B) in a normal individual are correlated with the changes in amplitude of the pulse wave and in the total volume of the digit (fig. 1A). It should be mentioned that diastolic periods appear in the plethysmographic curves, in which the pulse recorder is running horizontally, denoting absence of blood flow; but this well known "standard error" may be neglected for the purpose of clinical evaluation. After release of occlusion the volume of the digit increased rapidly, while the amplitude of pulse waves reached a maximum about two minutes later. Blood flow to the toe arrived at a peak of 32 cu. mm. per second after forty-five seconds; it decreased gradually to 7 cu. mm. per second, rising again to 9 cu. mm. per second after four minutes. This phase of decline of the flow rate below the resting level is probably due to

vasoconstriction—an assumption confirmed by the finding that in a representative group of patients with arteriosclerosis obliterans treated by lumbar sympathectomy, blood flow to the toe never declined during reactive hyperemia below the resting level (fig. 2). Throughout the four minute period following release of occlusion, respiration, alpha and beta waves appeared in the plethysmogram of normal patients, suggesting vasomotor activity due to sympathetic activity.

Fifteen-minute arterial occlusion was performed five days in succession and under uniform conditions in healthy individuals and patients with arteriosclerosis obliterans without ulceration of the toes. The daily variations in each case were comparatively small, thus demonstrating the reproducibility of the technic.

The characteristic features of reactive hyperemia in *normal subjects*, following 15 minute arterial occlusion at the ankle are presented in a group of 5 typical cases, with ages ranging from 18 to 34 years (fig. 3). The mean resting blood flow was 7.8 cu. mm. per 5 cc. per second, the maximum toe flow amounted on the average to 20.8 cu. mm. (19.0 to 24.2 cu. mm.), and was reached after 0.68 minute (0.38 to 1.0 minute). During the vasoconstrictive phase the toe flow declined on the average to 4.1 cu. mm. (2.0 to 6.0 cu. mm.).

These values represent normal blood flow through normally patent vessels under normal nervous vascular control. Curves of unusual configuration can be produced by deep breathing or breath holding, a startling sound, a disturbing light, or application of cold, or painful heat to the body during the phase of reactive hyperemia. Higher readings are generally obtained a few hours after a heavy protein meal; unusually low values result when the test is performed without preceding rest, during pain, anxiety, or soon after smoking.

During the period of occlusion the toe presented a cyanotic appearance, but erythema developed rapidly with reactive hyperemia and a palpable increase in temperature was noted. Continuous recordings showed that the skin temperature returned to the resting level six minutes after release of occlusion and then proceeded to rise gradually to a highest value,

approximately 2 C. above the control temperature.

Reactive hyperemia in patients with *arteriosclerosis obliterans without demonstrable tissue changes of the toes* is presented in a group of 4 typical cases (fig. 4). In these patients blood flow to the toe rises slowly to a comparatively

in patients with advanced arterial disease and is associated with an unusually small rate of arterial inflow as well as with a low maximum rate of toe flow. Anemocydia, however, is also observed in the plethysmogram of subjects without organic arterial disease, but suffering from pronounced vasospasm of the toes. In the

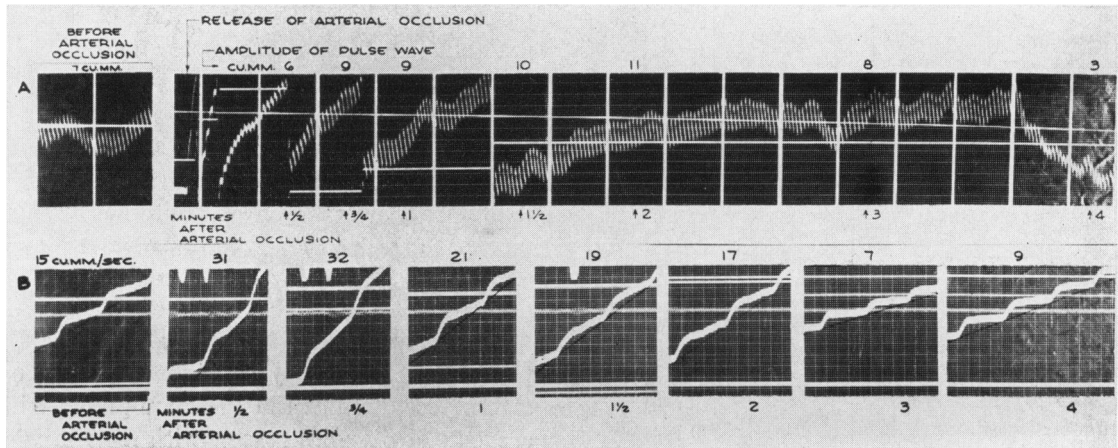


FIG. 1. Reactive hyperemia in a normal individual, following 15 minute arterial occlusion at the ankle. A. Changes in the amplitude of the pulse wave and in the total volume of the digit, before and after arterial occlusion. B. Changes in the blood flow to the toe, before and after arterial occlusion.

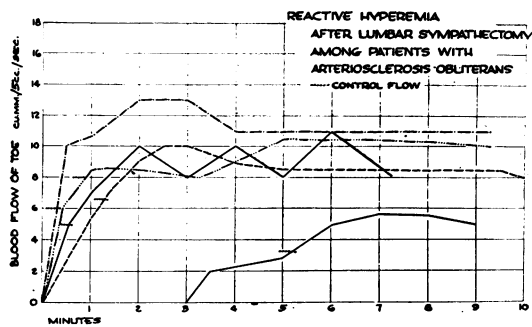


FIG. 2. Reactive hyperemia following 15 minute arterial occlusion at the ankle, in a group of 15 patients with arteriosclerosis obliterans, three months to three years subsequent to lumbar sympathectomy.

low maximum rate, and the vasoconstrictive phase is somewhat less pronounced than in normal individuals.

Fifteen minute arterial occlusion at the ankle was also produced in 50 other patients with arteriosclerosis obliterans. In many cases blood flow to the toe following release of the arterial cuff became apparent only after an interval of seconds or even minutes. This condition, called "anemocydia"<sup>8</sup> is encountered

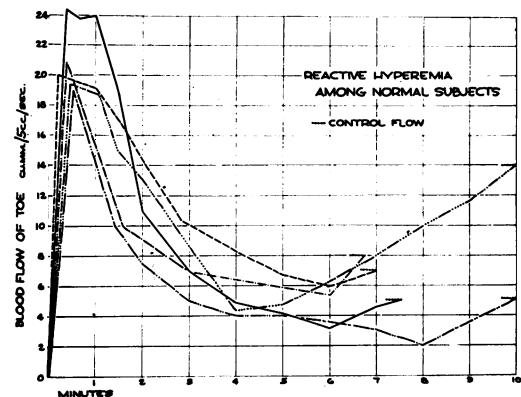


FIG. 3. Reactive hyperemia following 15 minute arterial occlusion at the ankle, in a group of 5 normal subjects.

latter group the plethysmographic curve returns to almost normal following intense body heating (fig. 5E), while in arteriosclerosis obliterans the degree of anemocydia is only slightly modified.

Clinically the appearance of erythema following release of the cuff was delayed. Measurements of the skin temperature taken in all

54 patients showed that the rate of cooling of the digit during arterial occlusion did not differ significantly from that observed in normal individuals. On the average, however, the skin temperature rose in this group after release of the cuff 0.2 C. above the control level as compared to 2.1 C. in normal subjects with similar control temperatures (32 to 33 C.). Due to the subnormal rate of blood flow<sup>9</sup> the control level was reached in patients with peripheral arterial disease in 12.8 minutes, as against 6.2 minutes in normal subjects.

Following lumbar sympathectomy patients with arteriosclerosis obliterans present a fairly elevated resting blood flow. After 15 minute

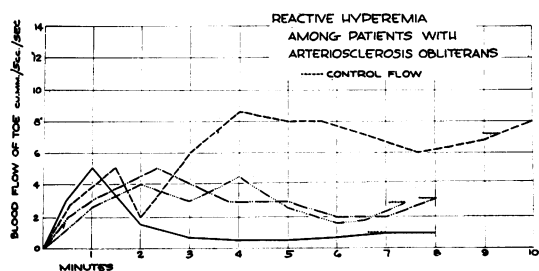


FIG. 4. Reactive hyperemia following 15 minute arterial occlusion at the ankle, in a group of 4 patients with arteriosclerosis obliterans without demonstrable tissue changes of the toes.

arterial occlusion at the ankle blood flow to the toe rises slowly to a comparatively high maximum rate, while secondary vasoconstriction is entirely absent (fig. 2).

The maximum rate of blood flow reached during reactive hyperemia represents the net effect of the interaction between vasodilating influences, probably due to the release of a humoral substance of histamine-like character, and vasoconstricting influences traceable to sympathetic nervous activity. In normal subjects the rate of blood flow to the toe rises immediately, culminates quickly, and secondary vasoconstriction occurs four to six minutes after release of arterial occlusion. The characteristic pattern in patients with arteriosclerosis obliterans shows slow filling of the vascular bed and a low maximum rate of blood flow; in individual cases the configuration of the plethysmographic curve depends mainly on two factors: the caliber of the large

arteries supplying the digit, and the degree of vasodilatation produced by release of arterial occlusion.<sup>10</sup> The curve is furthermore modified by the degree of tissue distensibility as well as the amount of hyperemia existing as a result of disease prior to 15 minute arterial occlusion.

The highest rate of blood flow to the toe during reactive hyperemia differs considerably in patients with arteriosclerosis obliterans *without* and *with* tissue changes of the toes. In the first group the highest rate amounted on the average to 12.2 cu. mm. per 5 cc. per second (limits: 5.0 to 17.0), while in the latter group the average was 1.9 cu. mm. per 5 cc. per second (limits: 0.1 to 6.0). Any relation

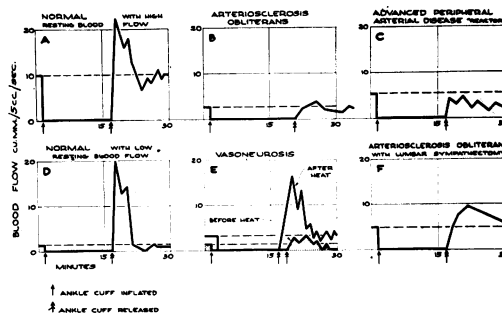


FIG. 5. Blood flow debt and repayment following 15 minute arterial occlusion at the ankle in normal individuals with high resting blood flow (A); normal individuals with low resting blood flow (D); patients with arteriosclerosis obliterans (B); patients with vasoneurosis (E); patients with advanced peripheral arterial disease: "reactors" (C); and patients with arteriosclerosis obliterans treated by lumbar sympathectomy (F).

between clinical appearance and degree of reactive hyperemia, however, must be cautiously evaluated. The state of the tissues does not depend exclusively upon the maximum rate of blood flow possible following release of arterial occlusion; many other factors have to be considered, especially the amount of exercise which the patient has taken, previous application of heat, prolonged foot soaks, infection, trauma, the presence or absence of metabolic changes and the duration of vasoconstriction.

Among patients with arteriosclerosis obliterans *without* tissue changes the rate of highest blood flow varied considerably. Tissue changes were sometimes absent even though a flow as low as 5.0 cu. mm. per 5 cc. per second was

observed following release of arterial occlusion. The peak flow was never reached in less than one minute, and sometimes only after an interval of four minutes.

*Tissue changes* accompanying arteriosclerosis obliterans consisted mostly of erythema with diapedesis of red cells into the subcutaneous layers which did not blanch on pressure. If this was the result of arterial insufficiency and not of external causes, the highest blood flow was always lower than 6 cu. mm. per 5 cc. per second and was reached in a very slow rise. Occasionally, transition from normal clinical appearance of the toes to demonstrable changes in the tissues of the digit is observed without variation in the level of the highest flow rate.

#### *Blood Flow Debt and Repayment*

Hyperemia following arterial occlusion at the ankle was also studied in order to ascertain whether the net effect of the technic amounted to an increase or a decrease of blood flow to the digit. Bier reported that the net effect of this entire procedure is an increase in the blood flow, and built a therapeutic procedure upon that premise.<sup>11</sup>

If, indeed, an actual increase in blood flow would take place, the rise above the control level in the period of reactive hyperemia (repayment) would have to be in excess of the amount of blood withheld during arterial occlusion (blood flow debt). A rough estimate of this ratio is possible through graphic representation of the plethysmographic values obtained.

Among 5 normal individuals with high resting blood flow, age 23 to 33 years (fig. 5A), the debt exceeded the repayment. The deficit would be still more accentuated and the repayment even less significant if, in estimating the blood flow debt, one were also to take into consideration the phase of secondary vasoconstriction. Among 5 normal subjects with low resting blood flow, age 31 to 35 (fig. 5D), the debt was small and the repayment large, owing to the low control level. Among 10 patients with arteriosclerosis obliterans, age 35 to 60 (fig. 5B), the blood flow debt was often increased due to anemocyelia. Repayment was consistently small, probably because the effect of acute ischemia induced through arterial

occlusion must remain marginal in the presence of chronic ischemia due to pathologic processes. Among 5 individuals, age 18 to 30 years (fig. 5E) with intense vasoneurosis (originating from a pathologic state of anxiety) whose hands and feet were characteristically cold and clammy, the reactive hyperemia curve was often identical with that of patients with organic peripheral disease. However, after prolonged rest and application of heat to the body the curve in the former group was transformed into one resembling the normal. Blood flow debt and repayment in this group of patients vary considerably, depending on the level of the resting blood flow, the degree of spasm, and the conditions under which the test is performed. Another group of cases presents unusually pronounced vasoconstriction after release of the arterial cuff; it is mainly composed of patients with Raynaud's phenomenon due to thromboangiitis obliterans, but probably also includes subjects with advanced arterial disease of any type. Among 5 "reactors," ages 27 to 51 years (fig. 5C), blood flow following release of arterial occlusion did not reach the control level during the test period, which in other groups is characterized by reactive hyperemia of varying degrees; thus no repayment occurred and the blood flow debt was still increased after release of occlusion. Patients of this type are often hypersensitive to emotional disturbances or touch, and vasoconstriction may well represent an abnormal response to pressure applied at the ankle. In this group, vasospasm was much less pronounced following lumbar sympathetic block or posterior tibial nerve block using Novocain, a finding suggesting that vasoconstriction is at least partly of nervous origin. Vasospasm was, on the other hand, accentuated when the occluding cuff was placed at the base of the toe instead of the ankle; this is probably due to direct pressure on the smaller vessels close to the recording cup. Among 20 patients, ages 30 to 60 years (fig. 5F), with arteriosclerosis obliterans treated by lumbar sympathectomy, the control level was high and repayment proportionately small.

The different theories brought forward in an attempt to account for the variations in blood

flow debt and repayment have been discussed at length by Abramson.<sup>1</sup> It seems probable that in the presence of a blood flow debt there occurs also a metabolic debt, but in none of the 156 cases in this series were clinically demonstrable ill effects from this procedure observed.

#### DISCUSSION AND SUMMARY

The technic of 15 minute arterial occlusion at the ankle combined with intermittent venous occlusion following release of the arterial cuff has proved to be a simple, rapid, and reliably reproducible laboratory procedure. It can be carried out by a well trained technician without supervision of the physician. Reactive hyperemia produced by this technic results in plethysmographic data which are characteristically different for normal individuals, patients with arteriosclerosis obliterans, subjects with vasoneurosis, and patients with arteriosclerosis obliterans treated by lumbar sympathectomy. The curves of patients with arteriosclerosis obliterans and of subjects with vasoneurosis without arterial disease are under ordinary circumstances very similar, but can be differentiated through application of heat to the body prior to repeated performance of the test.

Reactive hyperemia following 15 minute arterial occlusion at the ankle leads essentially to identical results when the test is reproduced on successive days under standard conditions in normal individuals or patients with peripheral arterial disease. If, on the other hand, tests are performed in patients at regular intervals, the change in the hyperemia curve will furnish an indication as to progression or regression of the disease. For instance, in the case of a 48 year old man with popliteal embolism due to posterior myocardial infarct of three months' duration, no reactive hyperemia was recorded. Subsequent to lumbar sympathectomy there occurred first a two minute period of anemocyclia, followed by a rise of blood flow to a highest rate of 8 cu. mm. per 5 cc. per second, reached after three minutes. One year later anemocyclia was reduced to one minute and a maximum flow of 10 cu. mm. per 5 cc. per second was attained after 2.2 more

minutes. The patient lived with a useful limb until he succumbed to a myocardial infarct two years postoperatively.

The configuration of the reactive hyperemia curves thus indicates the state of peripheral circulation and makes it possible to choose between the various therapeutic agents and procedures available. This applies in particular to an estimate of the probable outcome of sympathetic surgery.<sup>12</sup> The method, furthermore, proves of value in establishing the degree of dilatation which may be elicited in patients previously treated by sympathectomy.

When anemocyclia fails to disappear following body heating or medication with ganglionic blocking agents, the disease process is far advanced and only relatively poor results can be expected from sympathectomy. The same applies to cases with a highest flow rate below 4 or 5 cu. mm. per 5 cc. per second. Surgical intervention, however, is often advisable if such a low maximal flow rate represents an increase of the resting blood flow to four or five times its previous value. Absence of secondary vasoconstriction, particularly in patients in whom it coincides with a low maximal flow rate, is often followed by poor operative results. In cases of this kind the endings of the sympathetic nerves have been destroyed, as for instance in certain types of peripheral vascular disease secondary to diabetes, or in the presence of pronounced rigidity of the vessel walls. Lumbar sympathectomy, on the other hand, ordinarily leads to satisfactory results in patients without true anemocyclia and with a maximal blood flow of from 6 to 17 cu. mm. per 5 cc. per second. Pronounced vasodilatation is observed in the first few postoperative days, declining during the next few weeks; but the rate of blood flow with the patient at rest remains in almost all instances for months or years considerably higher than prior to surgery.

A comparison of the highest skin temperatures reached after release of 15 minute arterial occlusion at the ankle with the maximum reading after posterior tibial nerve block using Novocain shows that the latter technic results in considerably higher skin temperatures while the blood flow is slightly lower. This

finding suggests that arterial occlusion produces a relatively greater flow through the deeper tissues of the toe than through the superficial layers of the skin. The difference may, on the other hand, be due to the fact that the plethysmographic technic is more sensitive in recording rapid changes in blood flow than measurements of the skin temperature, as some time is required until changes in the rate of blood flow manifest themselves in an increased temperature of the tissues of the toes.

A study of blood flow debt and repayment during reactive hyperemia demonstrated that this method is not indicated in the treatment of patients with organic arterial disease. No deleterious effects were noted, on the other hand, following arterial occlusion for a period of 15 minutes, even in patients with far advanced arterial disease. This diagnostic technic may therefore be regarded as safe and effective.

#### ACKNOWLEDGMENTS

Gratitude is expressed to Dr. B. O. Raulston for the encouragement and cooperation extended during the course of this research. The valuable technical assistance of Grayce S. Fleming is sincerely acknowledged.

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