A Peripheral Vascular Insufficiency Test Using Photocell Plethysmography

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A preliminary laboratory study seeking an objective test for vascular insufficiency of the fingertips (Raynaud's syndrome) is described. In a limited number of subjects, circulatory changes in the vascular bed of one hand were examined by photocell plethysmography while the opposite hand was immersed in ice water. The time to complete recovery after cessation of the cold stimulus was significantly longer with primary Raynaud's patients than with the control subjects ($p = 0.0045$). The analysis of another parameter, the relative change in pulse amplitude during cold immersion, was confounded by age and sex differences between the Raynaud's and the control group. A follow-up investigation of the application of this technique to a population of vibration-exposed chipper and grinder and control workers is in progress.

Vibration white finger syndrome (VWF), or Raynaud's phenomenon of occupational origin, is a frequently occurring peripheral vascular disorder among workers using vibrating tools.[1,2] Although it has yet to be explained how vibration exerts its deleterious effect on the vascular bed of the fingers, the clinical features of gradually developing vascular insufficiency have been repeatedly described by many investigators since the original work of Dr. Maurice Raynaud in 1862. The diagnosis of the VWF syndrome[12] in its initial stage is based principally on subjective evidence from an occupational history and complaints of intermittent attacks of tingling and numbness of one or more fingertips, usually during exposure to cold. Objective clinical signs appear in later stages of the disease when episodes of coldness, pallor, blanching, and insensitivity of the fingers develop. Clinical tests used thus far to assess the peripheral circulation have generally proved disappointing in providing objective evidence of peripheral vascular insufficiency, particularly in the early stages of VWF. Although skin temperature measurements,[3,4,5] direct and indirect hand-cooling tests,[6,7,8] and plethysmography[9-12] have been useful for distinguishing normal subjects from patients having vascular disorders, the variability and group overlap are great and individual predictability is poor. Volume plethysmography has been used in studies of blood flow in fingers exposed to segmental (hand-arm) vibration,[11] but the method is time-consuming, exacting, and suitable mainly for experimental laboratory conditions.

The photocell plethysmography test described in the present study is simple, easily applied, and noninvasive, and appears promising for use in field surveys as well as in the clinic. Furthermore, this test has the advantage that subtle changes in the peripheral vascular bed can be identified. The main difference between this test and other plethysmographic tests is that while the finger(s) to be assessed is (are) inserted in the photocell plethysmograph the *opposite hand* is immersed in cold water. This procedure is based on the assumption that functional vascular insufficiency can be best disclosed by observing the reactivity of the vascular bed in a vasomotor reflex elicited by a stressful thermal stimulus. The magnitude of the induced vasoconstriction and the time to recovery following removal of the immersed hand from the cold water bath are indicative of the functional integrity of the neural and vascular elements of the vascular bed. Thus, the major purpose of this preliminary study was to investigate the use of photocell plethysmography as a potential diagnostic test of Raynaud's syndrome. If this test proved promising (recognizing the limitations of such a laboratory study), it would be used in a follow-up field study of workers exposed to pneumatic chipping and grinding hand tools. In effect, the field study would allow

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Table 1. — Clinical Characteristics of Raynaud's Disease Patients.			
Subject	Age	Sex	
RC	40	F	Primary Raynaud's disease. Onset age 35. Slowly progressive bilateral symptoms, occurring only in winter. Feet occasionally affected. No visible changes on extremites.
MC	58	F	Primary Raynaud's disease. Onset age 38. Progressive symptoms affecting both hands. Early atrophic changes of fingertip skin present.
RC	37	M	Primary Raynaud's disease. Onset age 36. Bilateral triphasic color changes with blanching from DIP joint of fingertip. Chemical engineer — no known vinyl chloride exposure. No visible changes on extremities.
JC	46	F	Secondary Raynaud's phenomenon associated with hypothyroidism. Onset of vascular symptoms age 41. Episodic blanching occurring on either hand, usually affecting only T finger, precipitated by cold. Appearance of extremities normal.
MM	47	F	Primary Raynaud's disease. Onset age 43. Bilateral triphasic attacks affecting all fingers, precipitated by cold. Her father was affected by rheumatoid arthritis. Normal extremities on examination.
RC	45	M	Secondary Raynaud's phenomenon. Onset age 20 following cold injury to hands. Digital pain induced by cold predominates as symptom. Normal extremities on examination.
DW	20	M	Secondary Raynaud's phenomenon. Onset age 16. Associated myotonia dystrophica. Classic symptoms of vascular spasm affecting all fingers to base. Occasional symptoms in toes. Bilateral cataract; myotonia of both upper extremities.
DR	38	M	Primary Raynaud's disease. Symptoms affect both hands and occasionally feet in winter only. Occasional morning stiffness of fingers. Normal extremities on examination.

for a more exhaustive evaluation of such a potential Raynaud's test.

Materials and Methods

The photocell plethysmography instrumentation consisted of a light source and a photocell detector mounted on opposite sides of a spring-held holder. The fingertip to be examined was slipped between the light source and the detector such that the light source was applied to the nail bed surface with the photocell detector located directly opposite on the fingertip pad. The light source consisted of a single #1816 incandescent lamp enclosed in a small, ventilated aluminum box. A regulated DC power supply (Power Designs Model 4010) maintained a constant 10 vdc to the lamp. Light was transmitted to the finger holder by a fiber-optic bundle (Olson XM0 806), thus avoiding localized heating of the examined finger. The photocell detector was a cadmium selenide photoconductive cell (Clairex CL707L) having a peak sensitivity at 700-750 nm, hermetically closed in a metal container to avoid humidity effects due to contact with the finger pad skin.

The photocell plethysmography test is a qualitative approach for validating changes in blood flow and distribution which affect tissue transparency. Since tissue is much more transparent than whole blood at the wavelength used, the variations in tissue opacity due to blood flow are depicted by the photocell detector as pulsatile variations, the signal being amplified and displayed on a strip chart recorder. The root mean square (RMS) of the pulse amplitude was simultaneously measured by a RMS voltmeter with output displayed on a second channel of the recorder. Vasoconstriction or vasodilatation in the fingertip's vascular bed could be readily observed from the corresponding changes in both pulse wave amplitude and the RMS tracing.

This study was conducted using two groups of subjects. The control group consisted of 17 normal white males ages 19 to 41 (mean age, 22), all nonsmokers. Routine clinical examinations revealed no cardiovascular or neurological disease. The second group of subjects consisted of four males (mean age, 35) and four females (mean age, 48) who had a previous clinical diagnosis of Raynaud's disease.* Three patients had associated clinical conditions: hypothyroidism, early myotonia dystrophica, and past history of frostbite of the digits. None of the subjects, control or patients, had been exposed to any form of hand-arm vibration. All patients had good peripheral pulses and only one patient showed evidence of organic peripheral vascular disease, a mild skin atrophy of the fingertip. A brief summary of the clinical characteristics of the Raynaud's patients is given in Table 1.

The testing was performed in a temperature-controlled room (24 to 25°C) with the subject recumbent on a table. The photocell plethysmography test was carried out in the control subjects on the tip of the index finger of the left hand. In the patient group, the photocell plethysmography test was performed on the finger of either hand most affected by symptoms or cold-induced vascular spasm. Arterial blood pressure was automatically and noninvasively monitored using a Hoffmann-La Roche 1216 Arteriosonde Doppler unit. Although the blood pressure measurements were discontinued during the plethysmography test per se, arterial pressures during cold immersion were measured on each subject in a preliminary session to identify any extreme reaction to cold.

The experimental procedure was as follows: prior to testing, the subjects were familiarized with the equipment and procedure. After the tip of the examined finger was placed in the plethysmograph, subjects were asked to rest recumbent for approximately 30 minutes. During this period photocell plethysmography was continuously recorded and occasional blood pressure measurements were taken. After this rest period, the opposite hand was passively immersed to wrist level in an ice water bath (3 to 5°C) for one minute. The hand was then immediately and gently removed from the cold water and gently covered with a dry paper towel. Blood pressure measurements were resumed only after complete recovery of the photo-

*Although the age and sex distributions of the two groups studied obviously are different, the investigators were limited by the availability of suitable, matched subjects. Because of the preliminary nature of this investigation, it was felt prudent to conduct the study with the available Raynaud patients and controls.

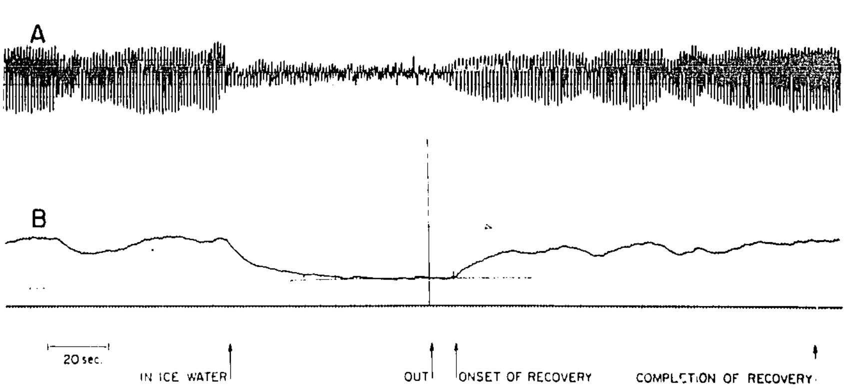

Fig 1. — Finger tip photocell plethysmography record (A) and tracing of the changes in root mean square measurements of pulse amplitude (B) before, during and after immersion of the opposite hand in ice water.

cell plethysmographic record indicated it had arrived at its pre-immersion amplitude level. During testing the examinee was requested to remain still and relaxed. Room noise and other environmental stimuli were avoided.

Results

Immersion of one hand in ice water causes an immediate change in the blood circulation of the contralateral hand (Fig 1). The time delay to achieve this effect is two to four seconds when using ice water. This effect is sustained during the period of immersion. The strip chart record during cold stimulus shows the pulse amplitude is decreased, revealing reflex vasoconstriction in the vascular bed of the examined fingertip. The vasoconstriction continues during cold immersion, usually reaching a plateau and then subsiding after passive removal of the hand from the ice water. The primary parameters measured in the test were: (1) the relative change in pulse amplitude during immersion-induced vasoconstriction; and (2) the time from onset of recovery to completion of recovery to the pre-immersion level.

The relative change in pulse amplitude is expressed as a ratio between the amplitude averages of the peak-to-peak values of 15 consecutive pulses measured 15 to 20 seconds before and during cold immersion. The ratio values for Raynaud patients and control subjects were found to be highly correlated with age and sex. Table 2 shows the mean and range values of pulse amplitude ratios for male and female Raynaud patients and for controls. Using an analysis of covariance to adjust for the effects of age (as the covariant) and sex (only male Raynaud patients included), no significant difference was found between controls and male Raynaud patients for the ratio measurement.

Fig 1, Tracing B, shows there is a delay between the time the hand is removed from the ice water (shown as OUT on Tracing B) and the onset of recovery. The recovery time is measured from the onset of recovery to the moment when the tracing first reaches the level measured prior to the cold stimulus. Table 3 shows the mean and range values of recovery time for male and female Raynaud patients and for controls. Use of an analysis of covariance to adjust for the effects of age (as the covariant) showed that the male Raynaud patients had significantly ($p = 0.0045$) longer recovery times compared to the controls. This result suggests a sluggish recovery of the vascular bed in the fingertip of subjects with peripheral insufficiency.

Table 2. — Pulse Amplitude Ratios for Raynaud's Patients and for Controls — Means and Ranges.

	No. of Measurements	Mean Ratios	Range of Ratios
Raynaud's patients			
Males	7	2.20	1.68 - 2.74
Females	6	2.09	1.37 - 3.56
Controls	36	2.72	1.21 - 5.43

Discussion and Conclusions

The photocell plethysmography described in the present study utilizes the phenomenon of reflex-induced vasomotor reactions to evaluate the integrity of the neural and vascular elements that control the blood supply to the fingertips. Two parameters of the vascular reflex have been examined: (1) the relative change in pulse amplitude between the control pre-immersion period and that of the cold immersion-induced vasoconstriction period; and (2) the time to recovery of the finger circulation after cessation of the stimulus. Both variables have been examined by monitoring the pulse amplitude and the average RMS of the pulse deflections on the photocell plethysmography recordings. Since significant difference regarding the recovery time parameter was found in patients with peripheral vascular disorders, the procedure may be applicable as a test for peripheral vascular insufficiency. The vasoconstrictor ratio parameter and other indicators of vascular responsiveness need to be further evaluated on larger populations. Field studies using this technique are underway.

The thermal effect of cooling one hand on its symmetrical limb has been known since the classical experiments of Brown-Sequard and it has been ascribed to a vascular reflex elicited by stimulation of the skin. In

Table 3. — Recovery Times for Raynaud's Patients and for Controls — Means and Ranges.

	No. of Measurements	Mean Recovery Time (Seconds)	Range of Recovery Times (Seconds)
Raynaud's patients			
Males	5	59	27 - 92
Females	5	46	32 - 62
Controls	41	26	7 - 56

humans, Steward[8] first demonstrated that application of cold to one limb induces a decrease in blood flow in the opposite limb. In 1932, Pickering[7] showed conclusively that both the afferent and efferent pathways of the vasomotor reactions are neurally mediated and segmental. The reflex nature of the sympathetically mediated vascular reacton following cold stimulation of an opposite limb has never been questioned[13] and has most recently been applied to the monitoring of blood flow in chain saw operators.[14] Functionally, it is surprising that immersion of one hand in ice water elicits a sustained vasomotor effect in the opposite hand, as no reflex accommodation has been observed in these experiments during one- and even two-minute immersions in ice water. It appears that the reflex is potentiated by stimulation of cold and pain sensory receptors.

The clinical evaluation of the test in this study was carried out by comparing normal subjects with a limited number of available patients suffering from primary Raynaud's disease. The patients were a group of subjects with mild functional vascular disorders. The lack of objective signs of persistent digital ischemia supports the assumption that their conditions were in the early stages of Raynaud's disease. This test revealed a significant difference in the increase in the time needed for recovery following cessation of the cold stimulus. The findings in the patient group could be accounted for by a decreased "responsiveness" of the peripheral vascular bed. Apparently the examined parameters seem to be indicators of reflex vascular reactivity and functional abnormalities of the peripheral vascular bed.

Though this test is noninvasive and simple to use, it is sensitive to emotional and environmental stimuli, resulting in decreased stability of the pulse record. In order to obtain reliable data, the examination must be performed in a quiet, stable environment where the subject is made comfortable and relaxed for a minimum of five minutes before testing. However, this technique's advantages appear to outweigh the disadvantages. This study has prompted the design and implementation of a unique multi-finger photocell plethysmography system, described elsewhere.[15] The purpose of this new instrument is to implement the previously mentioned field study and facilitate the expeditious examination of a large number of control and other workers exposed to hand-arm vibration.

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