

TISSUE PERFUSION ANALYSIS THROUGH
PHOTOPLETHYSMIC METHODS

by

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ABSTRACT

Most present day methods to diagnosis vascular disease evaluate arterial blood flow or pressure, although indications show that blood perfusion in the skin is a better predictor of limb health. A device based on the use of photoplethysmography was constructed to assist in evaluating skin blood pressure.

By illuminating the skin with an infra-red light source, sensitive photodetectors can record blood volume changes in vascular beds beneath the skin. If an increasing external pressure is simultaneously applied to this area, the signals received by the photodetectors will decrease and eventually vanish. The applied pressure which causes the signals to vanish can be equated to skin blood pressure. A unit which contained a light source and four detectors to monitor signals, a rounded plexiglass bottom to apply force, and a spring and LVDT arrangement to measure force was constructed to test this principle.

The limbs of 10 normal subjects without vascular disease, and 3 patients with vascular disease were used to test the instrument. The signals from the diseased limbs were not as clear as those obtained from healthy limbs; differences noted in hyperemic reactions and forces required for signal extinction, however, indicate the future value of this device as a diagnostic tool.

CHAPTER 1

INTRODUCTION

The distribution of nutrients to all areas of the body is carried out by the circulation, which is comprised of the blood and the cardiovascular system. The tubes through which the blood flows originate at the heart; leaving it through a single large aorta, they divide into progressively smaller branches, ultimately branching into a large number of tiny vessels called capillaries. Although only about 5% of the total blood circulating is flowing through the capillaries at any one time, this is the only blood which is carrying out the exchange of nutrients. All other parts of the vascular system support the aim of getting adequate blood flow to the capillaries, which are no more than .005 inches from any cell (Vander 1975, p. 254).

When the blood supply to any area is insufficient to deliver adequate nutrients, the tissue dies. If the area in question is the heart, a painful possibly fatal "heart attack" results. If the area receiving insufficient blood is a limb, local tissue may die resulting in gangrene, in which case the limb must be amputated. The decision to amputate is not always easily reached, and once decided upon, the site of amputation is another decision made with some uncertainty. Studies indicate that rehabilitation potential decreases from excellent to fair as the amputation site increases from the ankle to above the knee;

there is also significant likelihood that with above the knee amputation a patient will never adapt to a prosthesis (Rutherford 1977, p. 1326).

Physicians are divided as to what means of measurement will give an accurate indication of whether a limb is receiving a sufficient blood supply. Most of the methods used to assist the physician in diagnosing the condition of the peripheal vascular system concern the measuring of blood flow or blood pressure. The major techniques used to assess these parameters and thus limb health are briefly reviewed below.

Major Techniques Used in Vascular Evaluation

The major measurement methods used by physicians to gauge the health of the vascular system are presented here to provide some idea of the current data gathering techniques employed. This list is not extensive, but covers only those which are deemed as fairly reliable, though different physicians have their preferences. Usually more than one of these methods are used to form an accurate picture of patient health.

Doppler-Ultrasound

The use of ultrasound is a convenient non-invasive way to measure blood flow. An ultrasound device consists of a small piezo-electric crystal which emits a high frequency signal, and a receiver which detects any differences between the emitted frequency and received frequencies. When a light or sound wave is reflected by a moving object, there is a change in frequency of the wave which is

dependent on the velocity of the object; this is the Doppler effect. With the ultrasound device placed over an artery the signal will be reflected from red blood cells, and flow measurements can be obtained. This signal can be demodulated and connected to an audio system thus enabling the user to "hear" changes in flow.

This method is also applied to help measure blood pressure. A pneumatic cuff is placed around the limb being studied and the ultrasound unit is placed over the artery of interest. With the cuff inflated to a pressure high enough to stop blood flow, the ultrasound unit will not provide any signal to the audio system. When the cuff pressure is decreased and blood flows, the sound will again begin; a recording of cuff pressure can then be equated to systolic arterial pressure.

Drawbacks to this system are that low flow velocities may not be detected. In addition, the complete safety of ultrasound is being examined.

Isotope Clearance

Xenon 133 or a comparable isotope tracer is injected into tissue under the skin, and the speed of removal from the site is recorded with a scintillation detector coupled to a ratemeter. Blood flow determines the speed of removal from the local area. This test is performed with the patient at rest and after exercise. The rate of disappearance of the tracer gives indications of a patient's vascular health.

This method can also be used to detect blood pressure in the skin. With a pneumatic cuff proximal to the injection site, pressure is increased until flow is observed to stop; systolic pressure is the value obtained when this occurs.

Plethysmography

This method has different variations, all of which concern the recording of volume changes. Digital plethysmography uses a mercury in silastic strain gauge placed around a toe (or finger). When the digit's volume expands as a result of blood entering the area with each pulse, the rubber gauge stretches and increases its resistance. These changes are amplified and recorded. From pulse contours, information about arterial occlusions can be obtained. Venous occlusion plethysmography is used to study larger sections of a limb. A water filled container is enclosed around the area to be studied. A pressure cuff distal to the device is inflated to give venous occlusion. Since blood can enter but not leave the area, the limb expands slightly and causes a change in the water volume. This change of volume with time is observed and total inflow to the limb is calculated by measuring the change of volume over a period of time. Photoplethysmography uses a light source and detector usually attached to a digit. Light illuminates small blood vessels which reflect or absorb the light in relation to the amount of blood in the area; a photo detector records these changes and a volume wave is obtained. This method will be covered in detail in the following chapter.

Pulse Volume Recorder (PVR)

A blood pressure cuff is placed on a limb or digit and inflated until a preset pressure is reached. The PVR measures and records cuff pressure changes which correspond to changes in limb volume. Comparison with normal readings confirm or dispute vascular problems.

Many of these reviewed techniques are awkward, lengthy and painful. Admittedly, better methods are needed in trying to assess the condition of the vascular system (Holstein 1973).

Except for the isotope clearance method, which is time consuming and difficult to repeat immediately, the above techniques tend to measure blood pressure or flow within the larger arteries. A clot or obstruction in any of these main vessels will surely impede blood flow to the arterioles and capillaries, but the actual effect in these smaller vessels, which perfuse muscle tissue and skin, is what needs to be measured.

Moore reports (Rutherford 1977, p. 1311) that it is the perfusion level of the skin which is the important indicator of the condition of deeper tissue. As in the larger vessels, flow and pressure measurements are the two ways of measuring circulation beneath the skin. In vascular disease however, it is important to measure circulation at several locations to accurately form a picture of overall limb health. As multiple flow measurements are lengthy and cumbersome, pressure measurements are more convenient for the clinical environment (Gundersen 1972). In addition, studies indicate (Gundersen 1972) that when local peripheral blood pressure drops below some critical value, capillary

perfusion becomes inadequate and the risk of gangrene increases. A measure then, of blood pressure characteristics just beneath the skin appears to be a valuable tool in aiding in the diagnosis of vascular disease and in extreme cases would also aid in the determining amputation site selection (Holstein and Lassen 1973).

Goals and Objectives

The purpose of this thesis is to investigate the feasibility of using a simple hand held non-invasive device to evaluate local skin blood pressure and to assess tissue perfusion levels. With such a device, physicians would have a means to obtain easily that which current methods fail to provide -- a measure of local tissue health which would aid in diagnosing the severity of vascular disease.

CHAPTER 2

UNIT DESIGN

As blood is pumped through the vessels its pressure rhythmically increases and decreases; in turn the volume of blood flowing through an area increases and decreases. Plethysmography is the name given to methods which measure this volume pulse and as mentioned in the review of diagnostic techniques, it is one of the methods used to assess vascular disease.

Photoplethysmography

Photoplethysmography, as used in my device, measures volume changes in an area by detecting the amount of light reflected from or absorbed by the pulsating blood. This technique was first used in 1938 (Hertzman 1938). Basically, as the heart contracts, and blood enters an area, the number of red blood cells increases. By illuminating the skin with a light source, these changes in blood volume below the skin can be detected by measuring the changes in the amount of light reflected. Before the increase in blood volume, some light would be reflected by the skin, some would be absorbed by red blood cells and some would be scattered by tissue. When more blood is forced into the area, however, the population of red blood cells increases greatly, causing some light which was previously reflected to be absorbed by the blood.

Therefore, a decrease in the amount of blood under the skin surface results in an increase in the amount of reflected radiation. In the study of peripheral circulation, photoplethysmography traditionally has been used to monitor the pulse in a limb. With a light source and detector attached to a toe or finger, a pneumatic cuff is placed proximal to the device. When the cuff is inflated to a pressure high enough to stop blood flow, the pulse was observed to vanish in the extremities. This is simply a variation of the auscultatory method where the cuff is inflated and one listens to blood flow noting the pressures at which the sound vanishes and returns.

Uretzky and Palti (1971a) have demonstrated that blood volume changes observed by a photodetector are a result of changes which take place in the vascular bed immediately adjacent to the photo cell. When a pneumatic cuff is used to stop arterial blood flow as described above, the photoplethysmographic device records the effects on the local vascular bed. Since local and not deep arterial volume changes are being observed with photoplethysmography, if blood flow is halted in capillaries right beneath the surface of the skin, this change should be noticed by a photoplethysmic device. Thus, if instead of a pneumatic cuff, which stops arterial circulation, a small external force is applied so as to only stop blood flow beneath the skin, the applied pressure at which this flow stops could be equated to local skin blood pressure. This is in effect using the same method to measure arterial pressure but on a much smaller scale. Unlike pressure applied with a cuff, the pressure would be applied only to a local area and of a

magnitude to only inhibit blood flow to vessels in the adjacent skin and tissue.

The above idea is the basis of the instrument designed for this project. Wood, Knutson and Taylor (1950) used a similar method to determine ear systolic pressure. More recently, Nielsen, Poulsen and Gyntelberg (1973) used a photoelectric probe beneath a pressure cuff to measure skin blood pressure and correlated their findings to systolic blood pressure.

Design Goals

The instrument to be designed, then, was to detect vascular pulse changes through photoplethysmography and also provide a means to apply a measureable force to the observed area. When the pulse recorded has disappeared in response to this force, the pressure being applied will be noted and equated to skin blood pressure. Many of the devices used to study peripheral circulation incorporate pneumatic cuffs. Since cuff size must be selected to be compatible with patient limb size and with the site to be studied (Geddes and Baker 1975) (Gundersen 1972), an alternate method which was independent of these factors was attempted.

The final instrument which was constructed consisted of a light source to illuminate the vascular bed, photodarlington devices to detect light changes and a plexiglass spacer which enabled pressure to be applied to the skin. Pressure was applied by hand to the spacer through a spring mounted above these components. Spring movement was monitored by an LVDT and equated to a force. Figures 4 and 5 (pages 18,19) show the completed device with an external and internal view respectively.

Light Source and Detectors

From research done by Hardy and Muschenheim (1934), high skin transmittance of radiation was found to occur at wavelengths around 900 nm. This wavelength, which is in the infra-red range, is also absorbed readily by red blood cells. This is ideal for the intended purpose. A Texas Instrument TIL31 Gallium arsenide light source and a General Electric (ZN5779) NPN planar silicon photodarlington detector were arranged as shown in Figure 1; this configuration of source and detector was chosen to decrease random noise and increase sensitivity. Except in areas with numerous capillaries, the signal to noise ratio is poor. This is basically due to the high noise characteristics of the photodetectors and small signals being recorded. At the capillary or arteriole level, volume change is slight; the resulting signal is small and in many cases tends to be masked by noise. By using four photo-devices connected in parallel, it was intended to increase signal size while decreasing noise. Since the noise from each detector was random, the positive and negative fluctuations of the individual noise signals would combine to cause some cancellation of the unwanted signal. This same connection however, would benefit the detection of the desired signal. Since each photodiode receives the same signal, the combination of the four would produce a signal four times as big. Thus, an overall greater signal to noise ratio would be achieved by connecting all the detectors in parallel.

The detectors are situated to receive light from an area right beneath the surface of the skin and to avoid reflections off deeper

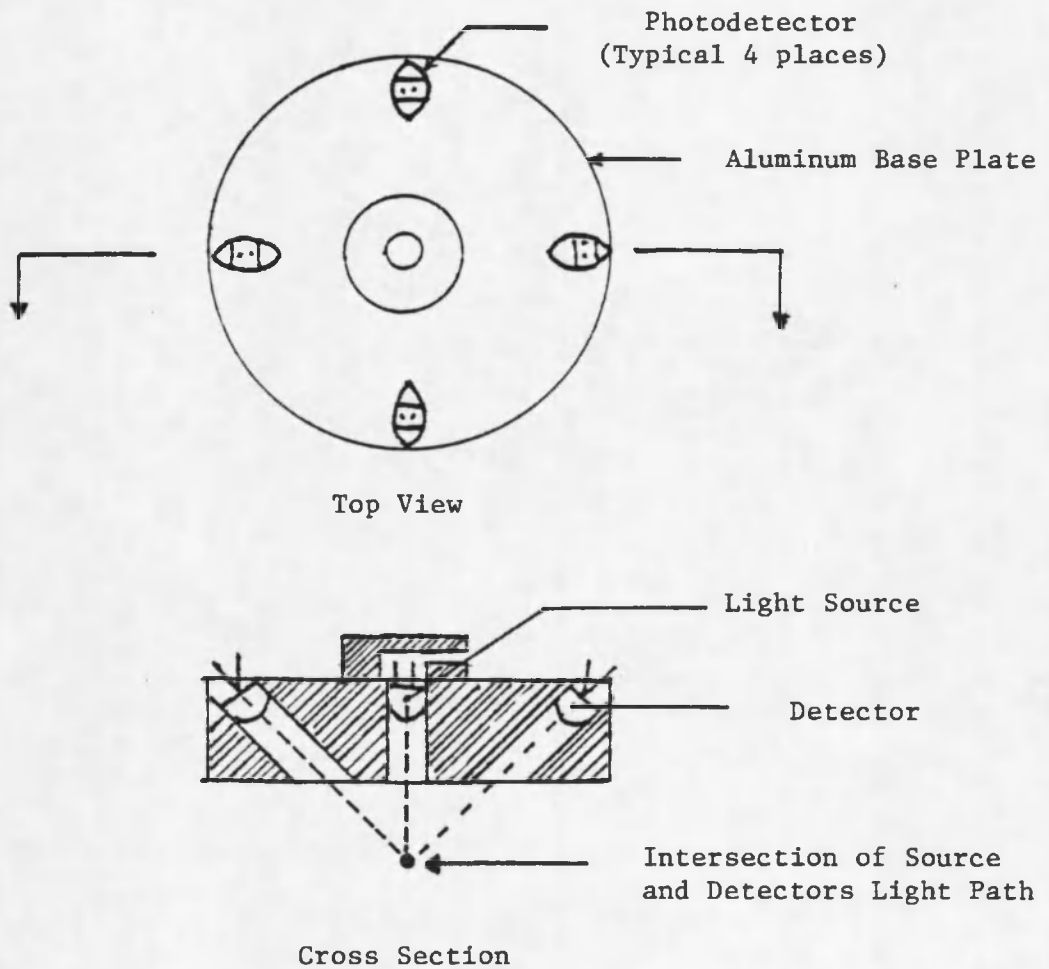


Figure 1. Light Source and Photodetector Arrangement.

layers of tissue. Although it was mentioned that vascular beds adjacent to a photoplethysmic instrument are the source of signals received, this area actually extends to about three millimeters beneath the skin, which is the depth of infra-red light penetration (Hardy and Muschenheim 1934). As light is directed into the skin it is reflected from the different layers of tissue beneath the skin. Since I was interested in the layer closest to the skin, the detectors were situated so the intersection of the incident light path and a return light path would be on the skin's surface. The angle between the incident and reflected light was chosen to keep the size of the device from becoming inconveniently large (Fig. 2).

The Plexiglass Spacer

Since pressure had to be applied to the area, a plexiglass, coneshaped spacer was placed between the light source and detectors and the skin (Fig. 2). This shape was chosen after experimentation revealed that the rounded bottom permitted good signal reception while only requiring moderate force to close the blood vessels and cause the signal to vanish. The rounded vertex also avoids blood entrapment which was observed when a flat bottomed spacer was used. The outer edge of a flat object tends to trap blood in the center of the piece and blood pooling develops. This can be demonstrated by placing a flat object, say a coin, on the arm and applying pressure. Skin blanching will be noticed around the circumference when the coin is removed, yet the center, filled with blood, will remain red. Pressure applied with one's

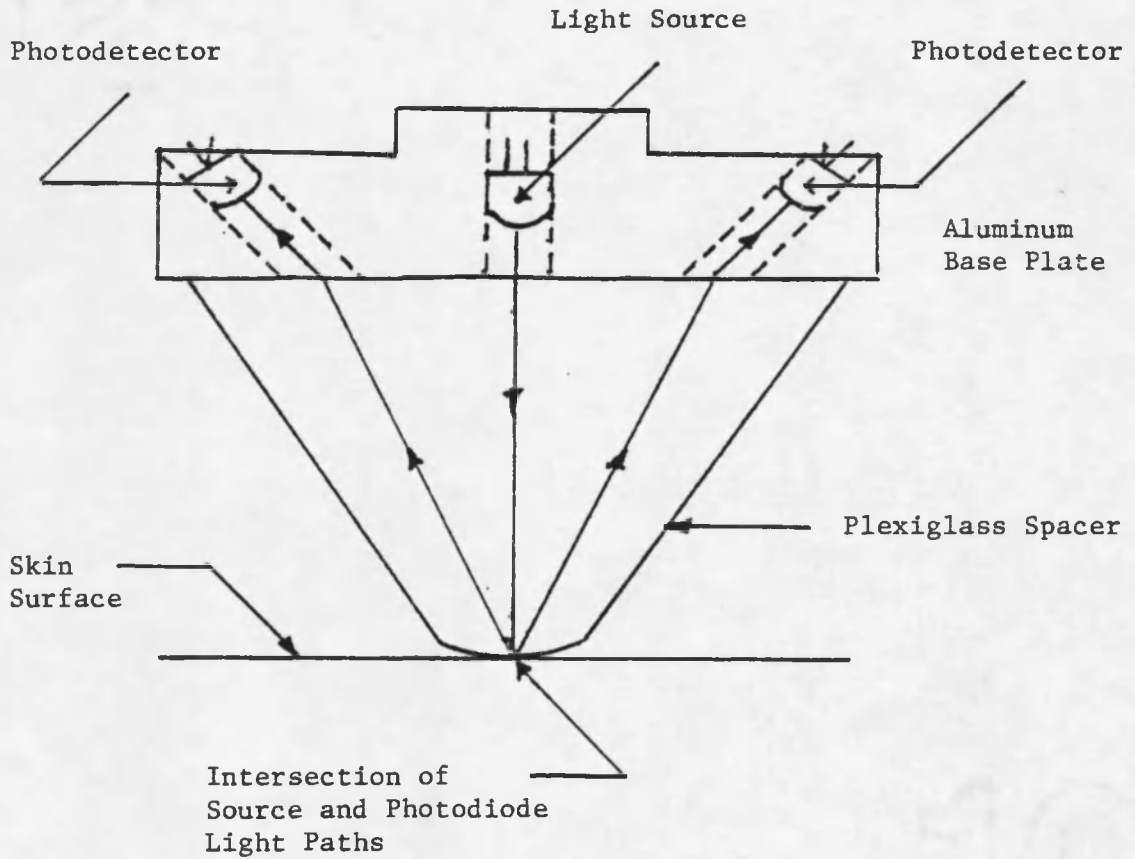


Figure 2. Plexiglass Spacer beneath the Light Source and Photodetectors Showing the Interception of Incident and Returning Light.

finger however (a rounded object), will force blood from the center of the area and cause a more complete uniform blanching.

Without the spacer, the intersection of the light path from the source and a line from the center of the detectors was about 1/2 inch beneath the aluminum base plate (Fig. 1). The position of the diode and the refraction properties of plexiglass were used to determine the height of the spacer. The height was chosen to enable the intersection of the light path from the source and a path to the diodes to be at about the surface of the skin (Fig. 2).

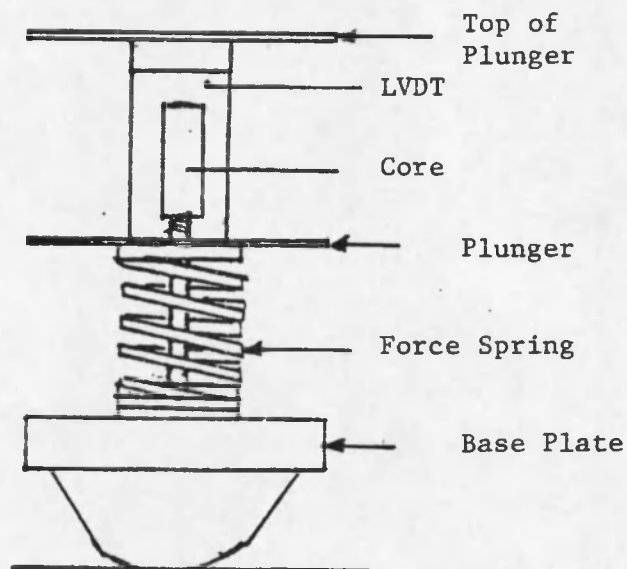
If the spacer were omitted and the device raised slightly above the skin, skin pulsations rather than blood flow would cause changes in light reflections. If the same device were lowered to the skin, the light received by the detectors would be from an area deeper than the surface vessels. Commercial photoplethysmic devices used to monitor pulses in the fingers or toes operate in this way. Substantial pressure on these devices is required to cause received signals to vanish, since deeper tissue is being observed. The major difference in the device constructed in this project is that the surface tissue in particular is being observed and a means to apply pressure to the skin is provided.

Alternate methods could be devised to apply pressure to the skin which would omit the plexiglass spacer, but the device which contains the detectors would have to be different in width or height from the design used here. The spacer provides a convenient way to refract the light and keep the physical size of the unit small while also providing a rounded bottom which could be used to apply pressure to the skin.

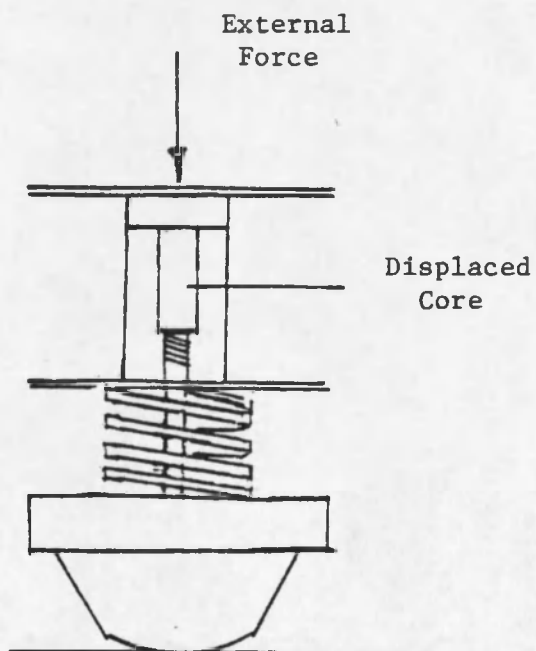
Force Application

The design goals indicated the need for a system able to apply a measurable force to the skin. After exploring different ideas it was decided to use either a small bellows or spring placed above the spacer to accomplish this task. Because of cost and simplicity, a spring arrangement above the spacer was chosen; with a known spring constant, any measurement of spring displacement could be translated into a known force.

To apply a force to the spacer and ultimately the skin, the force spring (Barnes Inc. Associated Spring Co., Bristol, Conn., # 1100-05-1500M) was mounted as shown in Figure 3. At the top end of the spring, a hollow plastic "plunger" with a small hole in its base was attached so that any force applied to the plunger would compress the spring. In order to measure spring displacement, a Model E100 Linear Variable Differential Transformer (LVDT) (Schapvitz Co.) was placed in the hollow plunger, and the core was attached by a threaded rod to the same base as the spring (Fig. 3). The LVDT is basically a transformer with a primary and two secondary coils in addition to a moveable core. Any displacement of the core between the coils, produces a voltage output from the transformer which is proportional to the linear displacement of the core. Thus, with the core anchored in the aluminum base and the LVDT cylinder contained in the plunger, any force which compresses the spring will move the LVDT down in relation to the core (Fig. 3). Since the maximum range of the LVDT is $\pm .1$ inch, a large



Without any force applied, the LVDT output is zero.



When force is applied, the spring is compressed, and the LVDT moves down. Translation between the core causes a voltage output proportional to force.

Figure 3. Internal Spring and LVDT Showing Core Movement.

k factor of 50.4 lb/inch, thus enabling small displacements to be recorded while allowing moderate force to be applied.

To keep the weight of the unit from resting on the skin before a measurement is made, a threaded aluminum shield was screwed on to the outside of the device (Fig. 4). This piece could be raised or lowered and enabled the lends to be placed so as to just touch the skin. With the plunger depressed, the force spring will not be compressed until the spacer is in contact with the skin or meets other resistance. Without an opposing resistance, a force applied to the spring will move the spacer down, but since both the LVDT cylinder and core move the same distance, no voltage output will be recorded. A second spring was installed on the external portion of the LVDT housing (Fig. 1,5). This external spring (Barnes Inc. Associated Spring Co., Bristol, Conn. # C1225-096-1500-s) returned the plunger to the zero position when force was not applied to the device.

Force System Calibration

Calibration of the force system was accomplished by applying a known force and observing voltage output. By constructing a plot of applied force versus LVDT voltage out, future voltage recordings from the LVDT could easily be translated into a value for applied force. Periodic recalibration verified the repeatability and linearity of the system (Fig. 6).

Although the force level delivered to the skin was easy to measure, it is a pressure reading which is desired. The odd shape of the plexiglass however, inhibited an accurate pressure calculation.

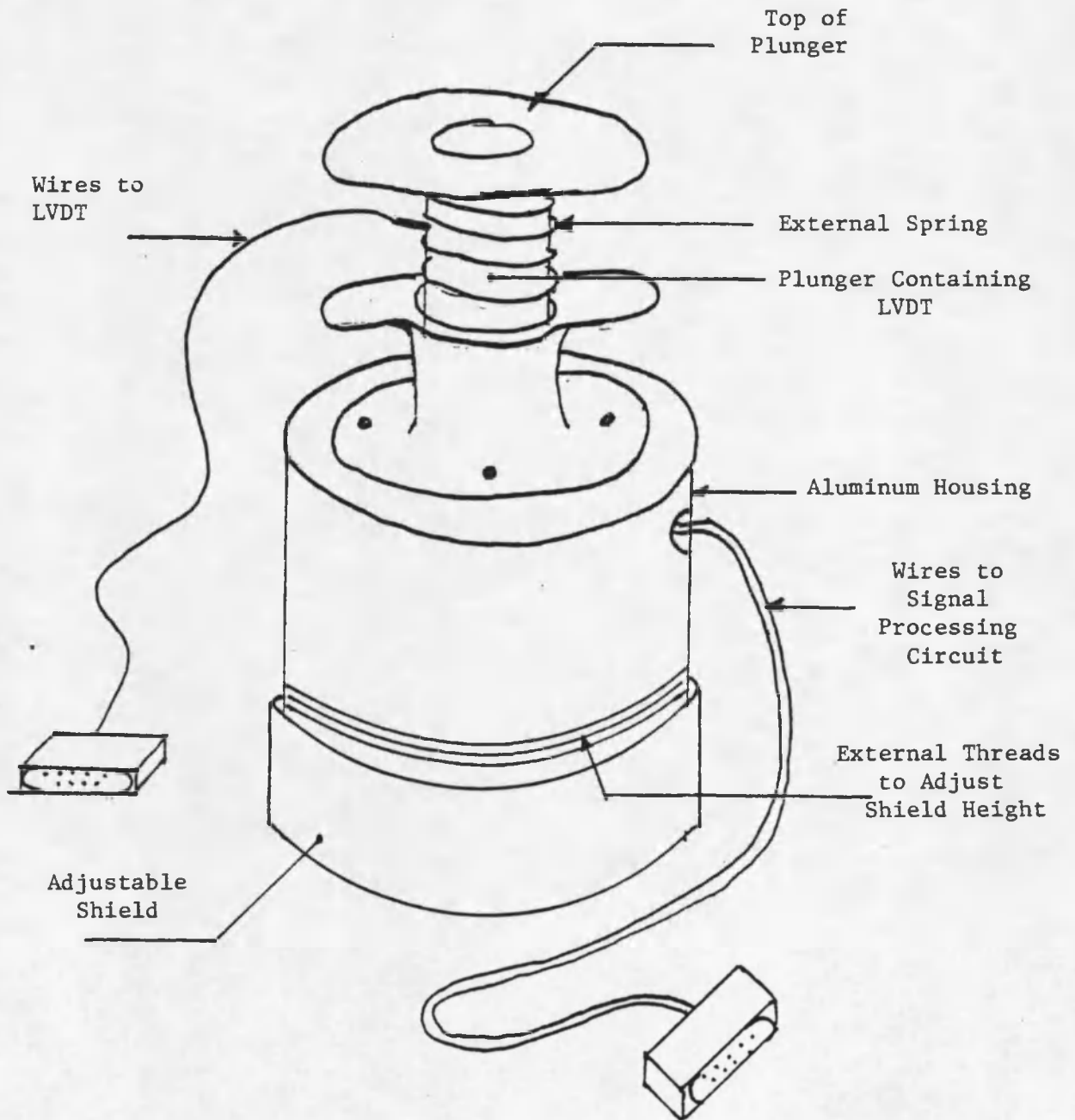


Figure 4. External View of Analyzer.

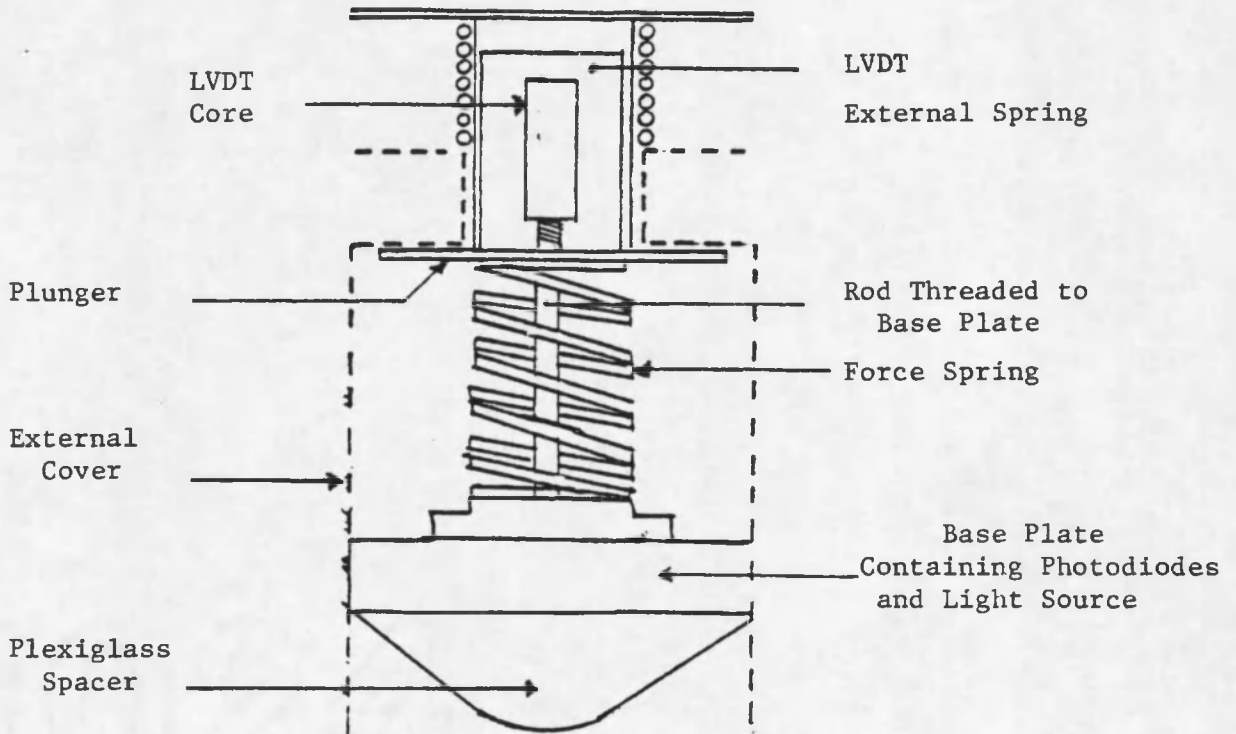


Figure 5. Internal View of Analyzer.

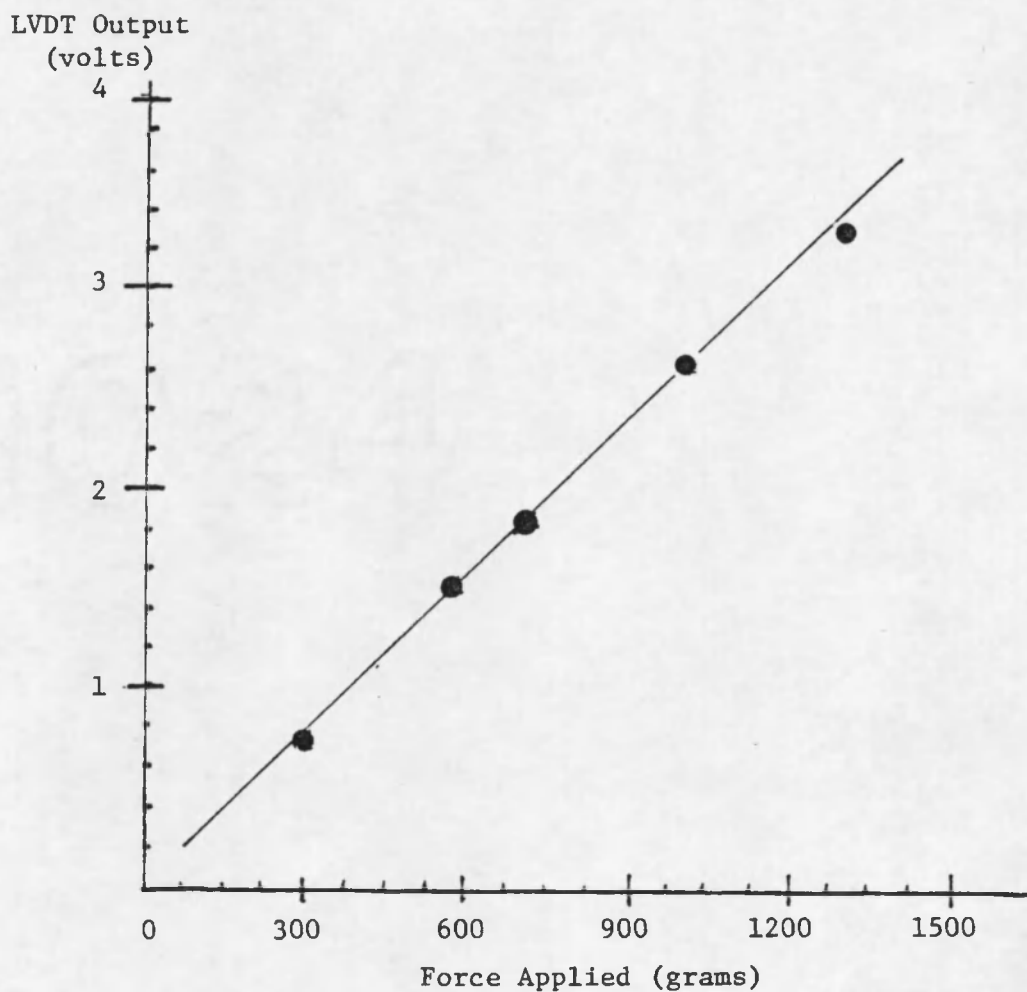


Figure 6. LVDT Calibration Plot: Force Applied Versus LVDT Voltage Out.

Since the spacer is curved and the skin flexible, an increasing force tends to stretch the skin and cause an increase in the area of the plexiglass over which the force is distributed.

In an attempt to measure pressure, the plunger was removed from a 100cc syringe and, in an attempt to approximate skin resiliency, the large open end was covered with a varying number of rubber finger cots (Fig. 7). The small end of the syringe was attached through a stop-cock to a sphygmomanometer and to a rubber bulb, the type used to inflate blood pressure cuffs. With my photoplethysmographic device seated on the rubber top of the syringe, pressure was increased in the syringe. It was hoped that in this manner the pressure within the syringe would push against the spacer of the unit and produce a voltage output which would correlate to pressure applied. Readings proved unreliable, however, and an alternate analysis method was attempted.

By knowing the area of the spacer through which the signal is received, a force distribution over this area could be assumed and an estimate of pressure could be obtained. The following experiment was attempted in order to calculate the portion of the spacer through which the signal was received.

By covering the entire plexiglass surface with black tape, no noticeable signal was recorded, as would be expected. If all the tape was removed, however, except for a circular place $1/2$ inch in diameter, again no noticeable signal was able to be recorded. Through applying various sized circular pieces of tape to the bottom of the spacer, it was observed that the amplitude of the signal returned to the

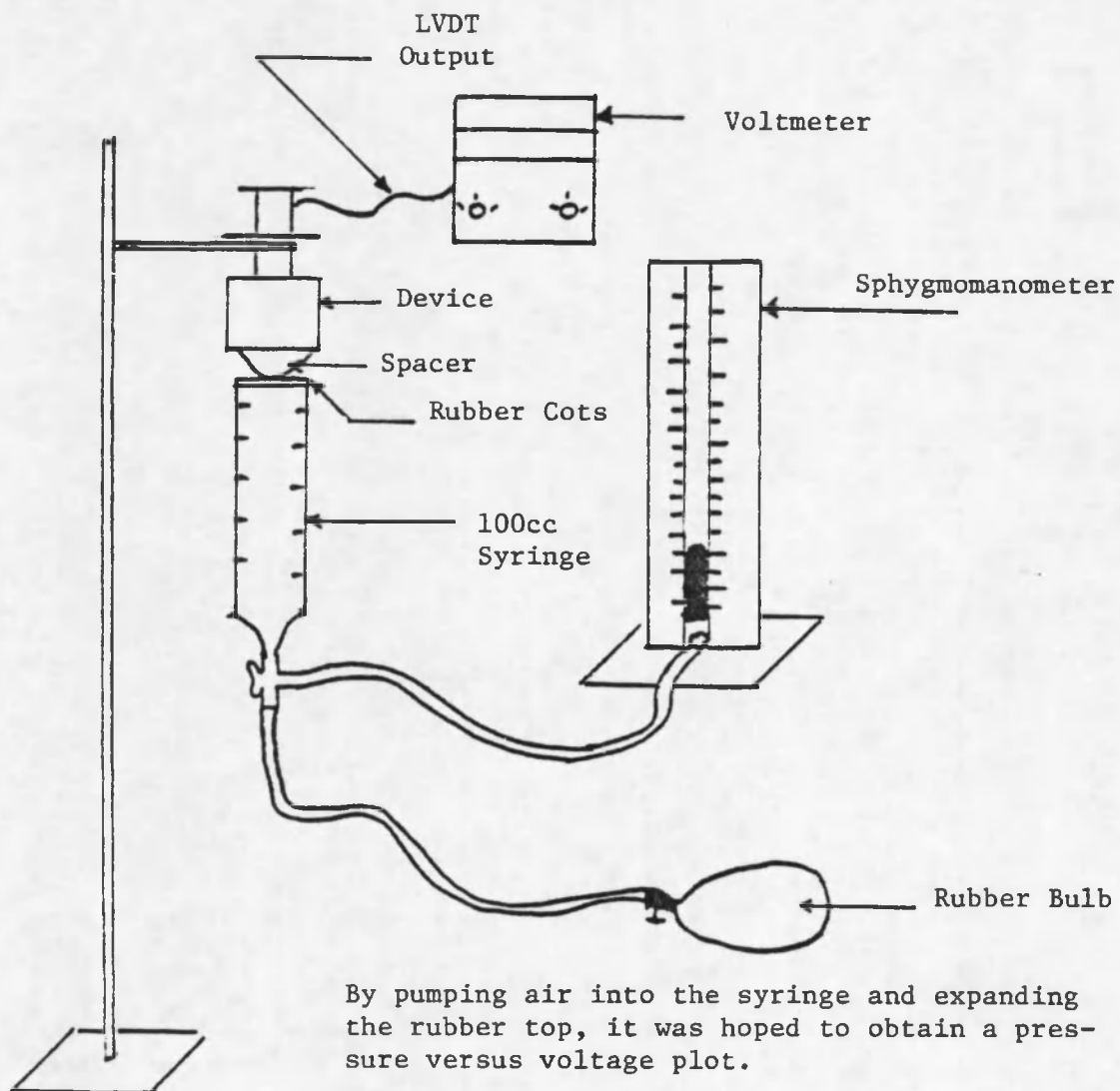
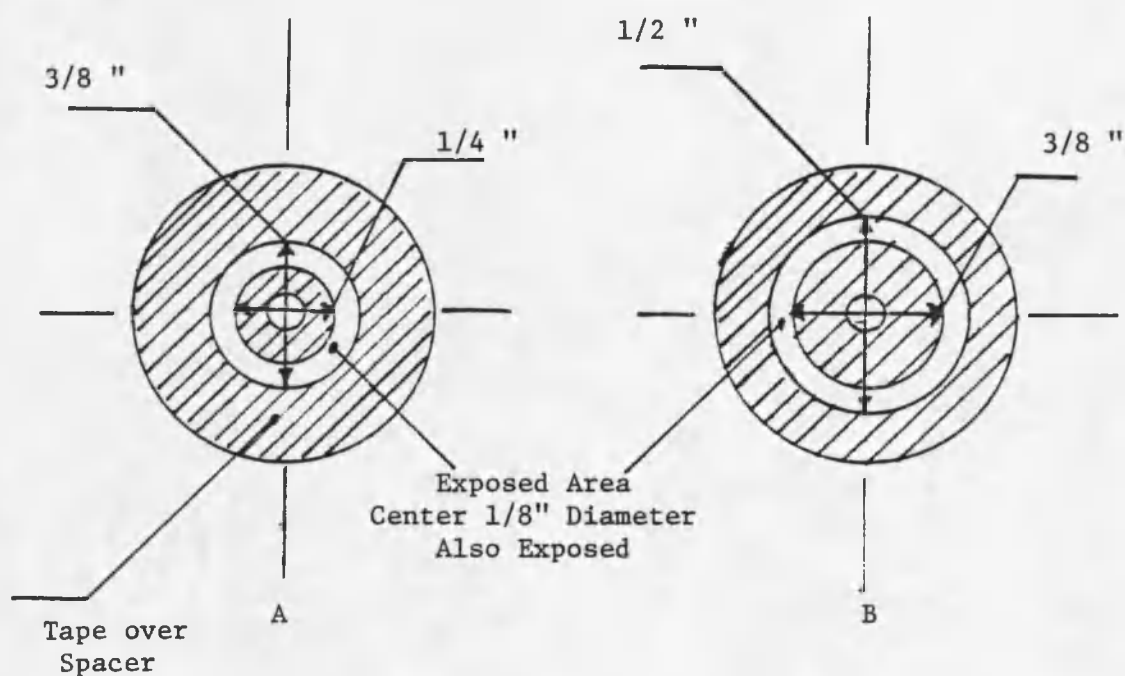


Figure 7. Test Equipment Setup for Pressure Calibration Experiment.

photodiodes was a function of the amount of area exposed and radial distance from the center of the spacer's vertex. A larger exposed area did not necessarily yield a greater signal but the location of the area exposed proved important. For example, if all but a small ring on the bottom of the plexiglass was covered with black tape, the amount of signal returned to the diodes depended not only on the area of the ring but also on its distance from the center of the plexiglass (Fig. 8). A ring created by covering the center of a $3/8$ inch diameter hole with $1/4$ inch diameter piece of tape (Fig. 8a) returns more signal than a ring created by a $1/2$ inch diameter hole with a $3/8$ inch diameter center covering (Fig. 8b), although the second ring has more area exposed.

With different tape configurations, signals were obtained from above the knee of my right leg. A plot of signal obtained per area exposed versus mean radius from the center of the spacer is shown in Figure 9. From the results it became obvious that most of the signal returned was between $1/8$ inch and $3/16$ inch radius. Thus of the total force applied, only a portion was actually being used toward signal extinction. Since more signal was being returned through some areas, a larger force would be needed in those areas for Signal Cancellation. Because an accurate estimation of the pressure could not be obtained, it was decided to abandon the idea of an absolute reading but instead to collect comparative readings of the force required for signal extinction and evaluate the worth of the device.



Although B has a larger area exposed,
A returns a greater signal.

Figure 8. Examples of Tape Placement for Testing Signal Strength from Various Areas of the Plexiglass Spacer.

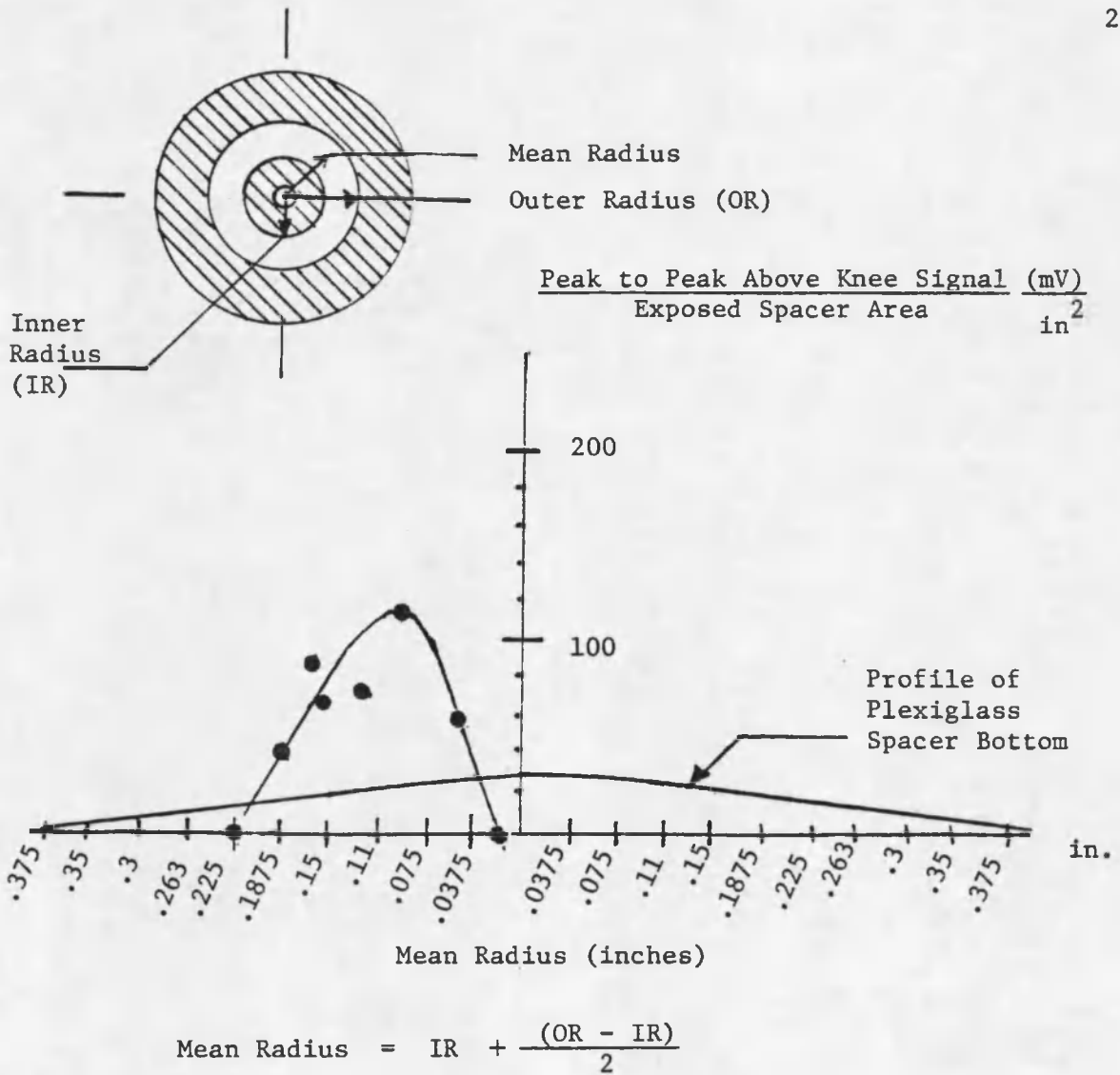


Figure 9. Signal/Area Versus Mean Radius Curve Superimposed on the Bottom of the Plexiglass Spacer to Show the Area where Peak Signal is Received.

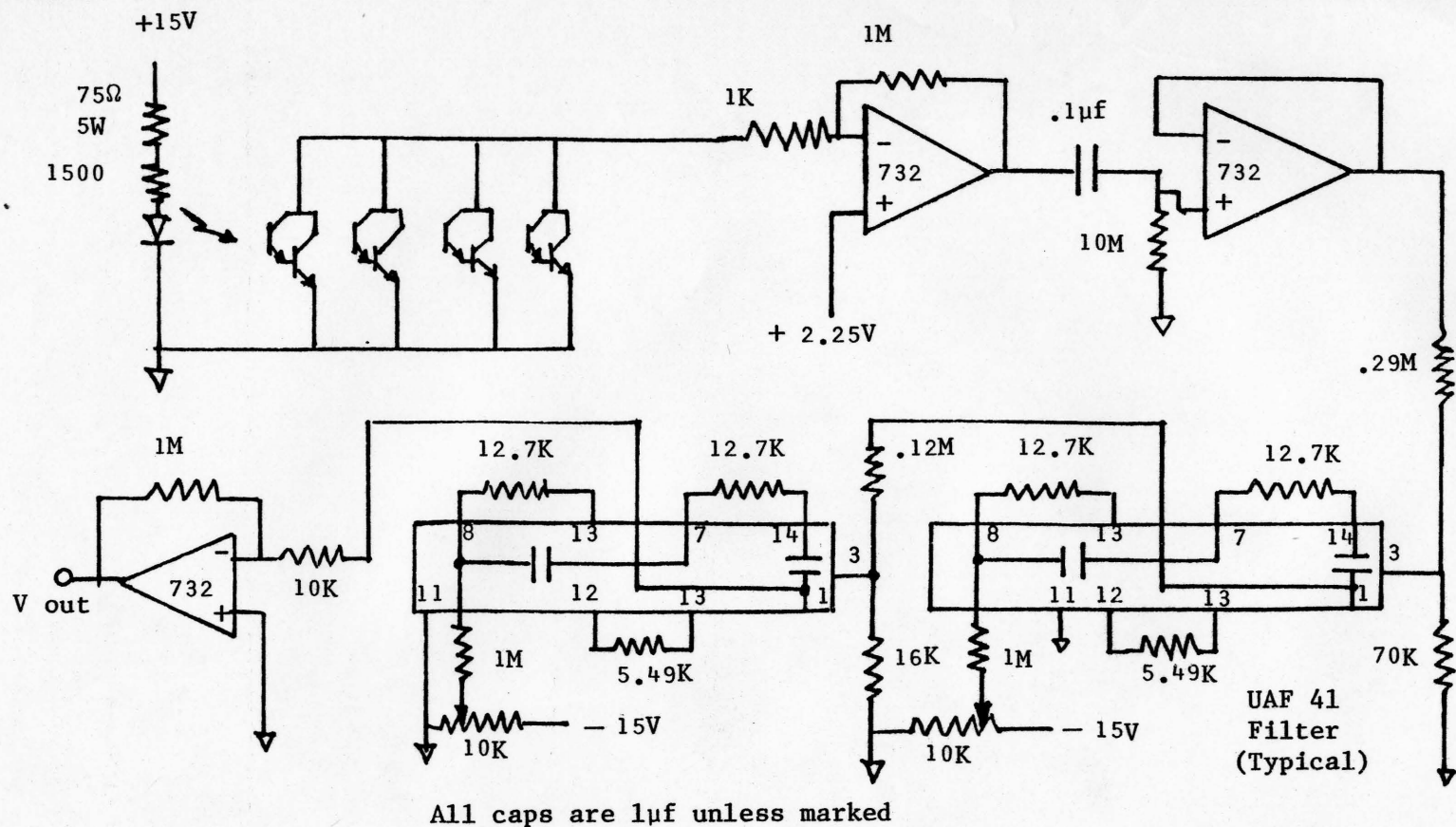
Electronics

The circuit used to process the pulse signals is shown in Figure 10. The main sections of the circuit are a light source and detector, current to voltage converter, filter and amplifier.

As the changes in reflected radiation are received by the photodarlington detectors, the current through them varies almost linearly with light flux; this current fluctuation is converted to a voltage through the first inverting op-amp in Figure 10. The frequency response of the system was limited from .1 Hz to 4 Hz to decrease noise and eliminate DC changes while still passing the desired signal. Much of the noise, however, is in the same frequency range of the signal. Filtering was accomplished by two Burr Brown UAF 41 filters each producing 2 poles of a low pass Butterworth response resulting in a 4 pole filter with all poles at about 4 Hz.

A potentiometer is available to change the gain of the first op-amp and the intensity of the infra-red light source. If the light intensity is too high, the circuit gain must be reduced to avoid amplifier saturation. The light intensity needs to be sufficient to illuminate the vascular bed. A bright source with small signal gain or vice versa did not seem to influence the quality of the signal received. The ability to balance signal gain and source brightness was included in the controls to determine this fact; light source current was maintained at a moderate level of about 60 ma.

The circuit was constructed on a Proto Board and covered with a plastic protective top. In the signal collection unit, all



All caps are 1μF unless marked

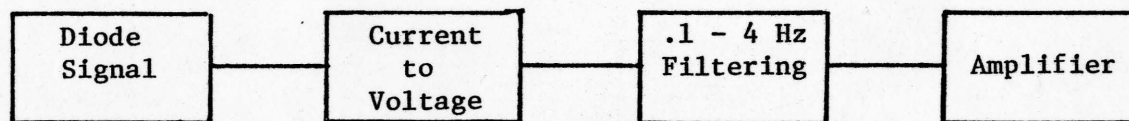


Figure 10. Signal Processing Circuit and Block Diagram.

photodarlington collectors were joined together, as were all the emitters. These two wires, along with those from the light source, were common in a shielded cable. A hole in the side of the aluminum case enabled the wire to leave the device and be connected to the circuit box (Fig. 4). Both the collection unit and cable were grounded. Another group of wires leaving the LVDT were braided and connected to another circuit which changed the AC emitted signal to DC. This second circuit was constructed as explained in application literature (# 7202) from the LVDT manufacturer (Schaevitz Engin. Co., Camden, N. J.). The output of this circuit was connected to one channel of an Hewlett Packard model 7402A recorder while the output from the photoplethysmographic signal processing circuit was connected to the second channel. In this way, force applied and signal obtained could be monitored simultaneously.

All equipment used was grounded and safety checked for resistance to ground and current leakage; readings obtained were all within standard safety limits. Retesting by the University of Arizona Health Science Center Biomedical Engineering Division verified equipment safety prior to use on human subjects.

CHAPTER 3

DATA COLLECTION

Ten subjects, six female and four male between the ages of 19 and 27 and asymptomatic of any vascular disease, were examined with the tissue perfusion analysis device. Recordings were taken from above and below the elbow of the left arm and above and below the knee of the right leg. These areas were chosen since most vascular disease takes place in the extremities and readings could be compared among different locations.

Method

Each subject was instructed to lie on a cot. Brachial blood pressure was taken and the device was placed over pre-selected test regions -- approximately four to six inches above or below the joint. The bottom shield was adjusted so that the spacer was right above the skin, thus preventing any weight from resting on the skin. After a stable signal was obtained, gradual increasing pressure was applied to verify the previous attained level. The force was finally released and the magnitude of the hyperemic pulse was noted. Reactive hyperemia is the phenomenon whereby an area receives an increase in blood flow following a period of blood deprivation. This local reaction is in response to an excess of metabolic waste in the region, which stimulates

the walls of the blood vessels to open up and facilitate the blood flow to the area.

Only three patients with known vascular disease were available for a comparative study. All patients suffered discomfort or pain in at least one leg. For comparison purposes measurements were taken on both legs using the same method as described for the asymptomatic group. Because these tests were performed at a clinic where patients had a set schedule, time prohibited testing any areas on the arms.

Results

Figures 11 through 14 are a sample of signals taken from the asymptomatic subjects while Figures 15 through 19 shows signals obtained from symptomatic patients. Table 1 shows the measurements taken from data from normal subjects while Table 2 shows the available data measured from the symptomatic patients. Figures 20 through 23 are plots of the various data from Table 1 while data from Table 2 is plotted in Figure 24.

The second column in Table 1 records upper arm blood pressure while the next column, labeled initial amplitude is the peak to peak voltage obtained from the pulsatile waves before the application of any force. AE, BE, AK and BK are abbreviations for above and below the elbow and above and below the knee. The fourth column lists the voltage output of the LVDT when sufficient force was applied to cause pulsatile signals to vanish. As this force was reduced, the signal was observed for a return of a periodic wave and the LVDT output was again noted (column 5). After removal of all pressure following a high force

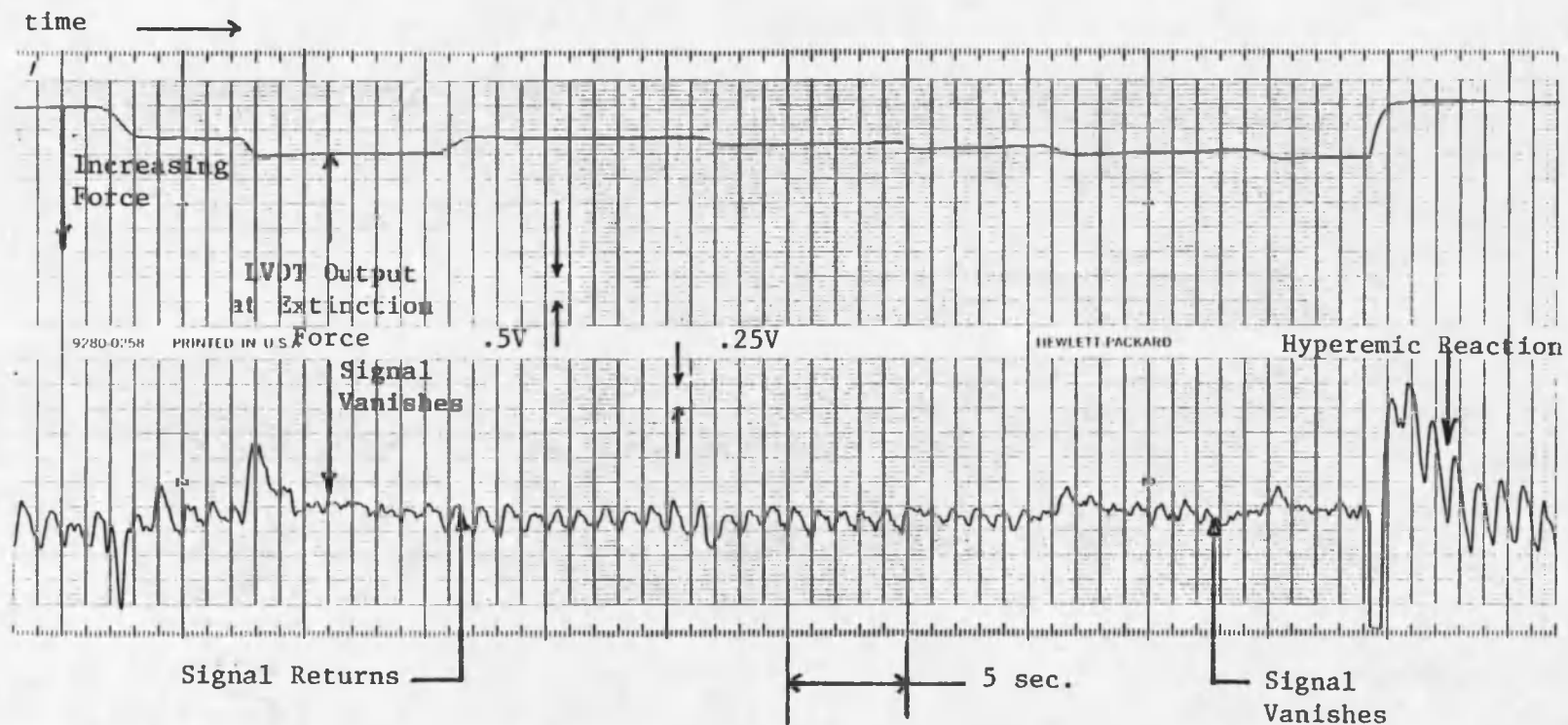


Figure 11. Sample Recording of Force and Volume Pulses from Below the Elbow of Normal Subject Number 7.

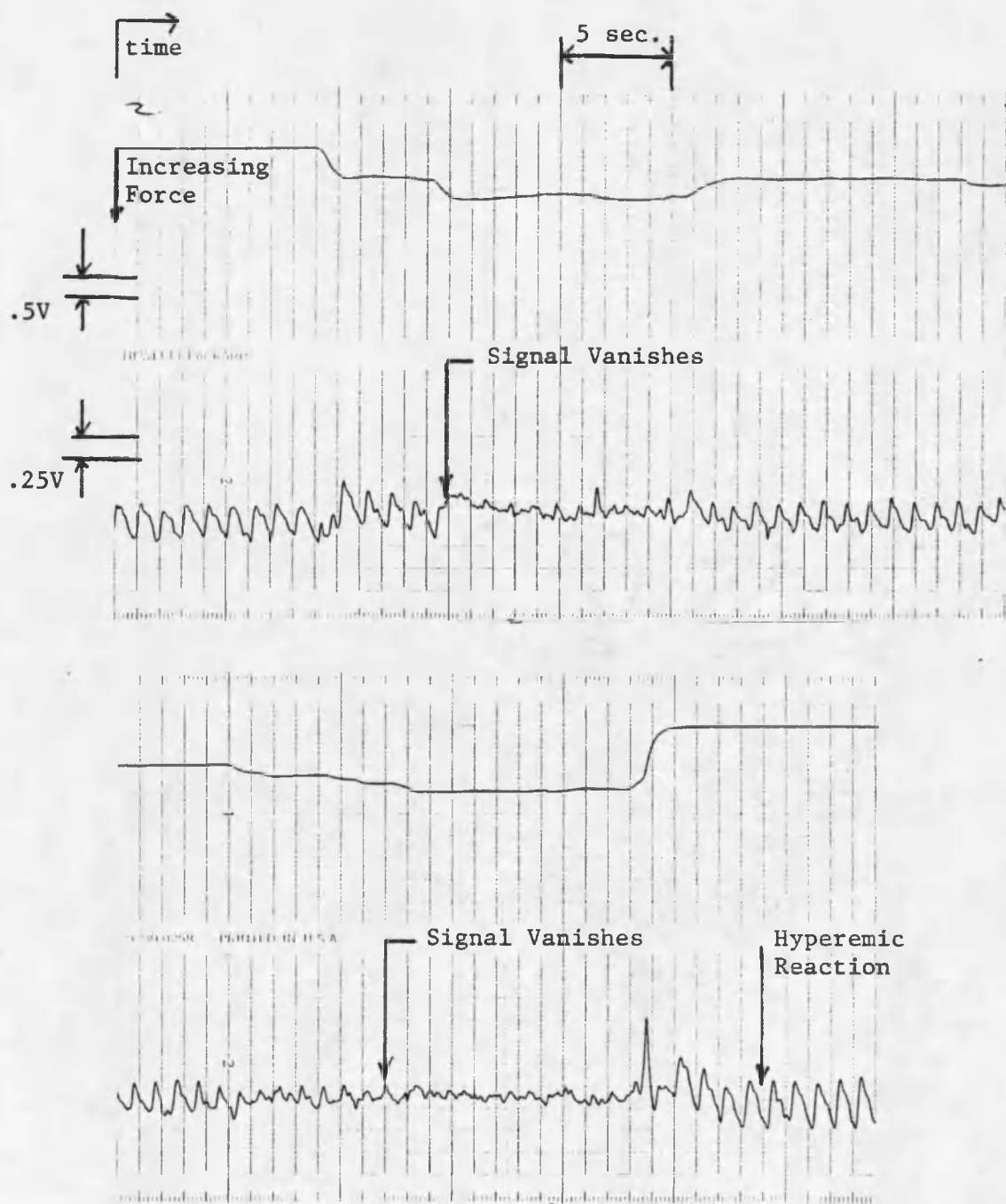


Figure 12. Continuous Recording of Force and Volume Pulses from Above the Elbow of Normal Subject Number 5.

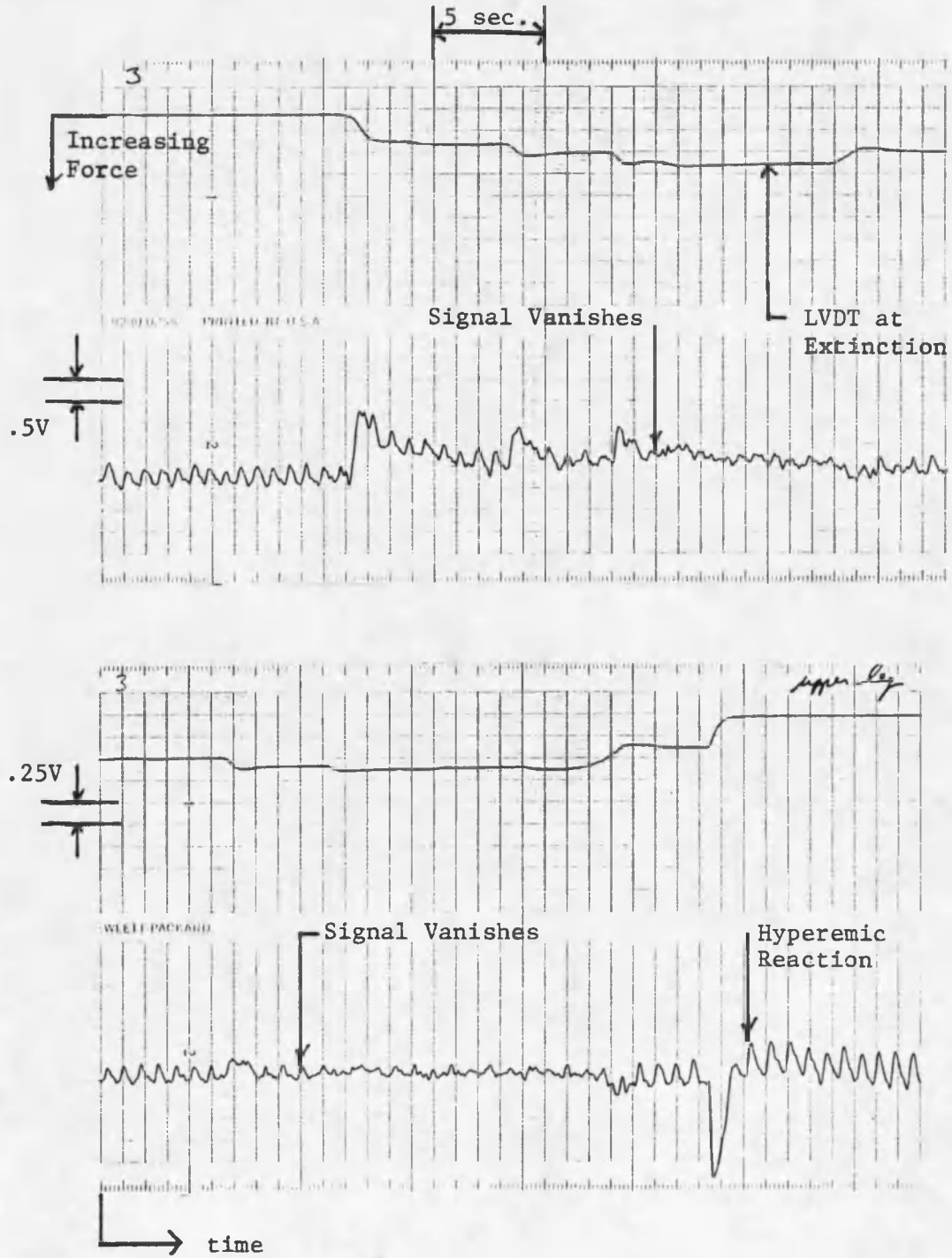


Figure 13. Continuous Recording of Force and Volume Pulses from Above the Knee of Normal Subject Number 10.

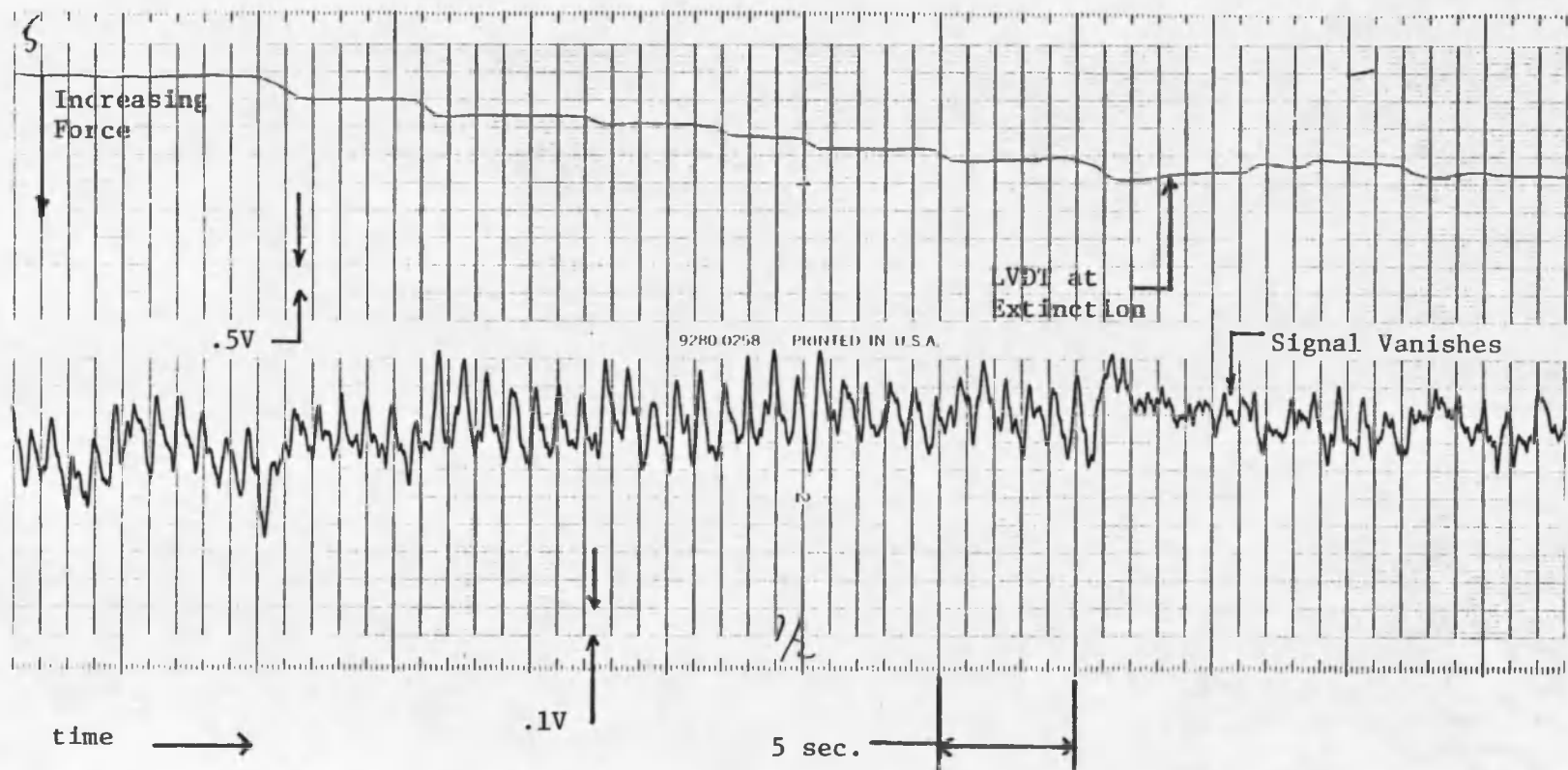


Figure 14. Recording of Force and Volume Pulses from Below the Knee of Normal Subject Number 2.

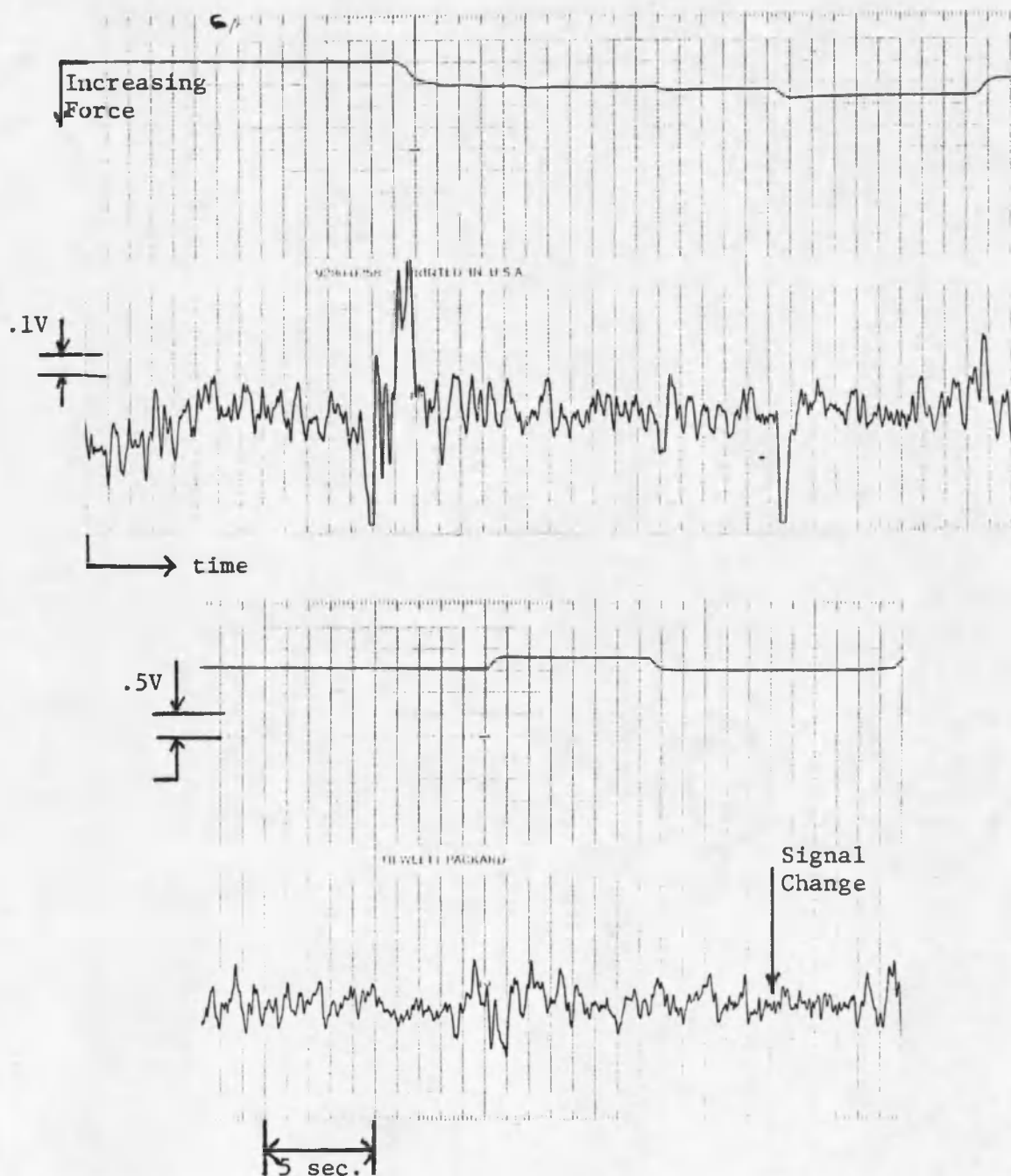


Figure 15. Continuous Recording of Force and Volume Pulses from the Left (Asymptomatic) Leg, Below the Knee, of Patient Number 2.

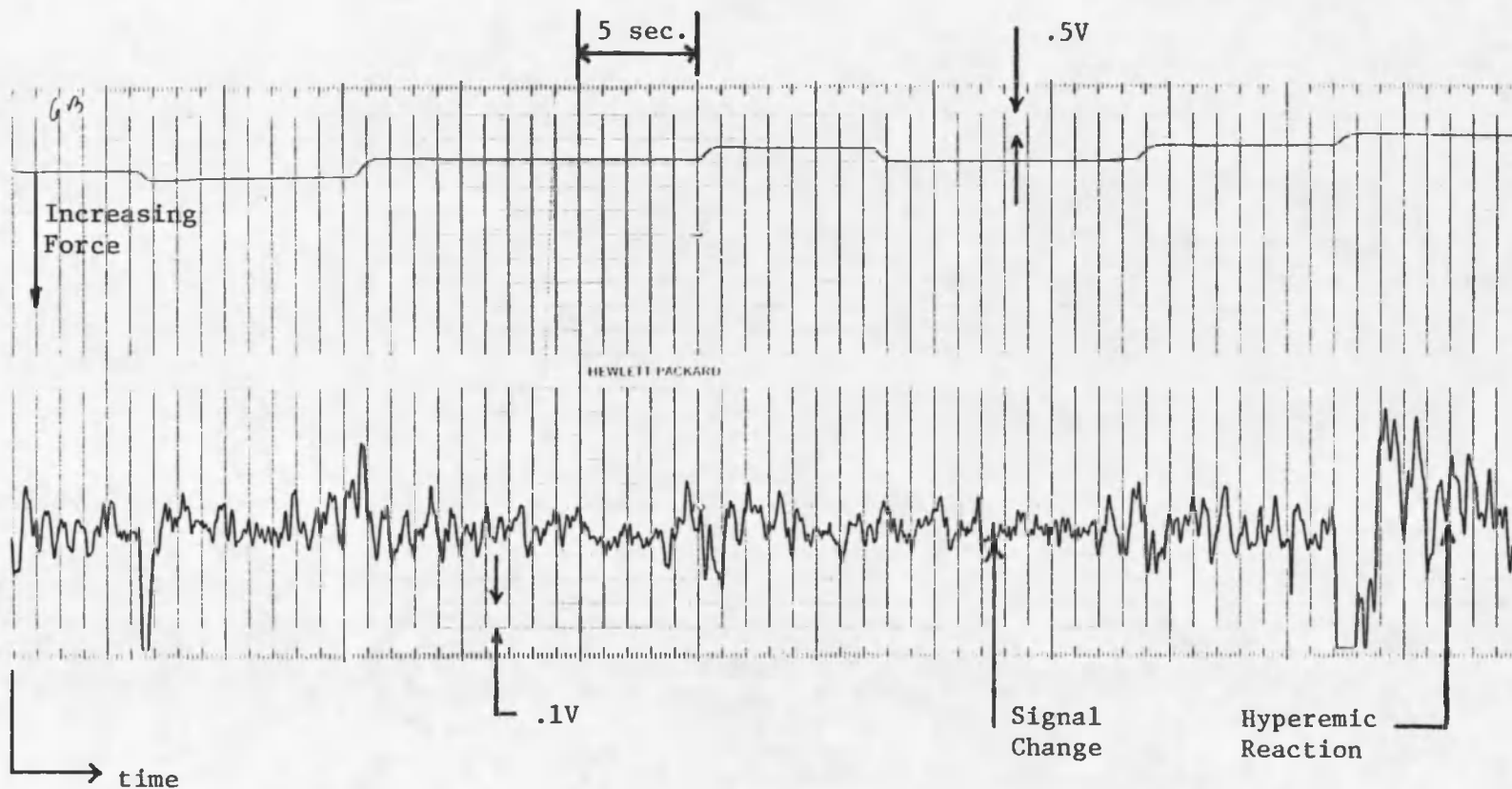


Figure 16. Recording of Force and Volume Pulses from Left (Asymptomatic) Leg Below the Knee of Patient Number 2 Showing a Hyperemic Reaction.

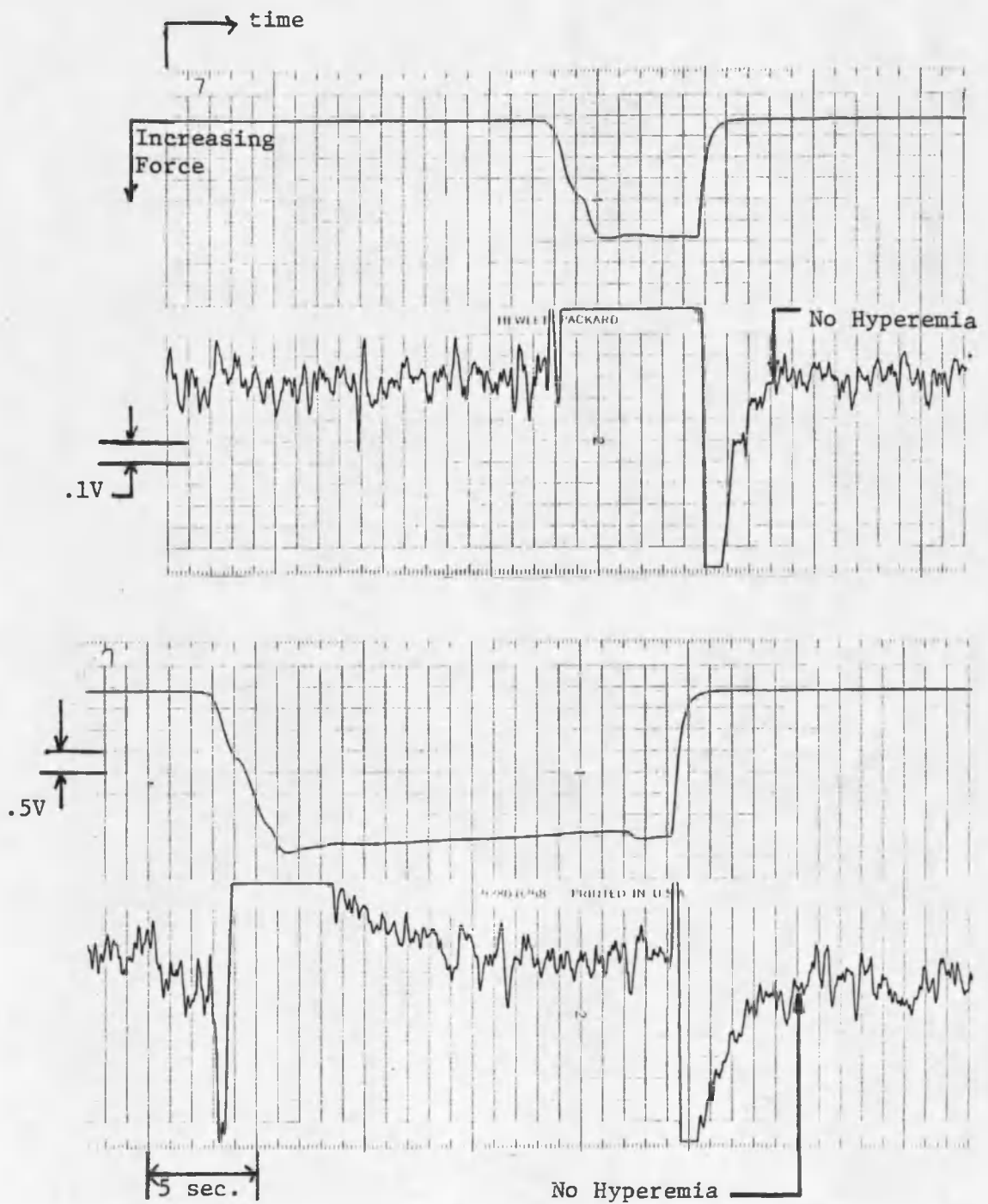


Figure 17. Continuous Recording of Force and Volume Pulses from the Right (Symptomatic) Leg Below the Knee of Patient Number 2.

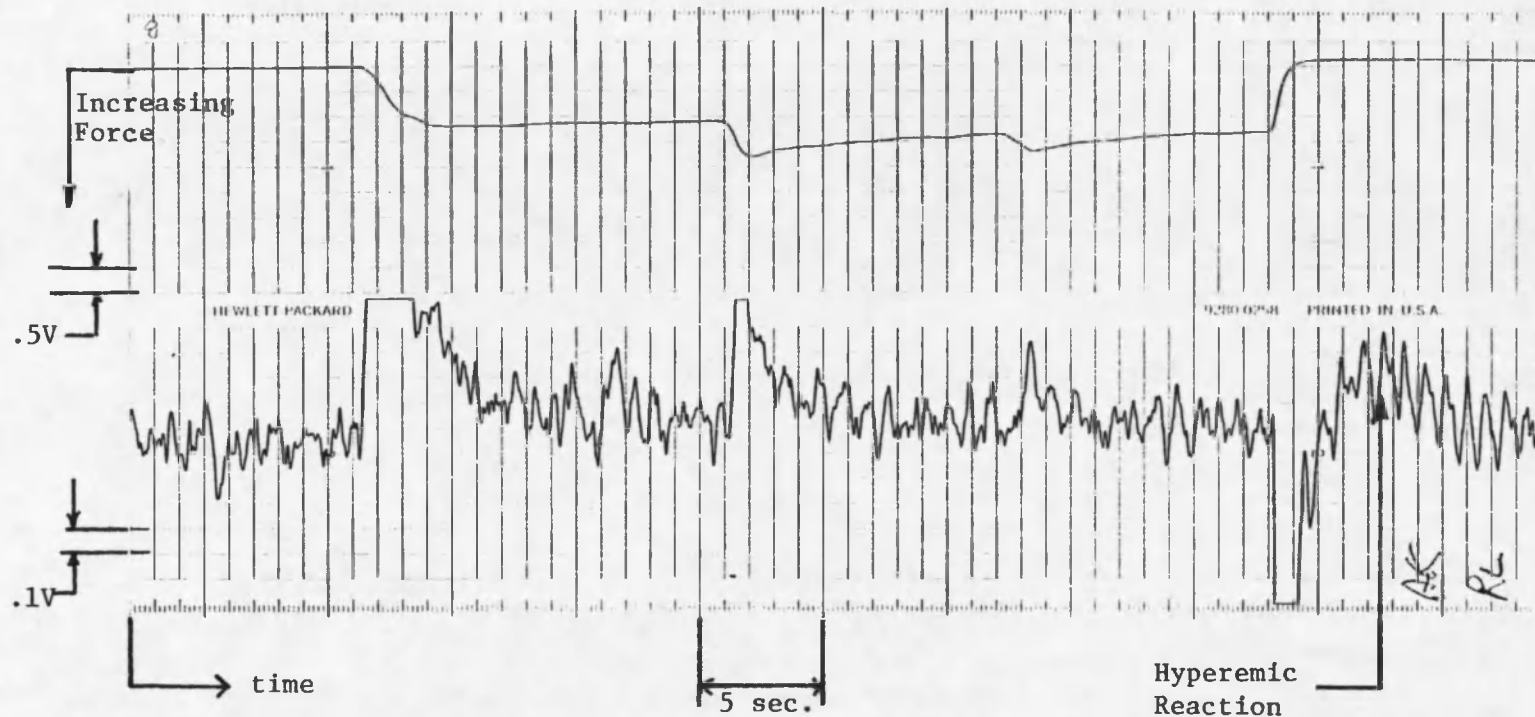


Figure 18. Recording of Force and Volume Pulses from the Right (Asymptomatic) Leg Below the Knee of Patient Number 1.

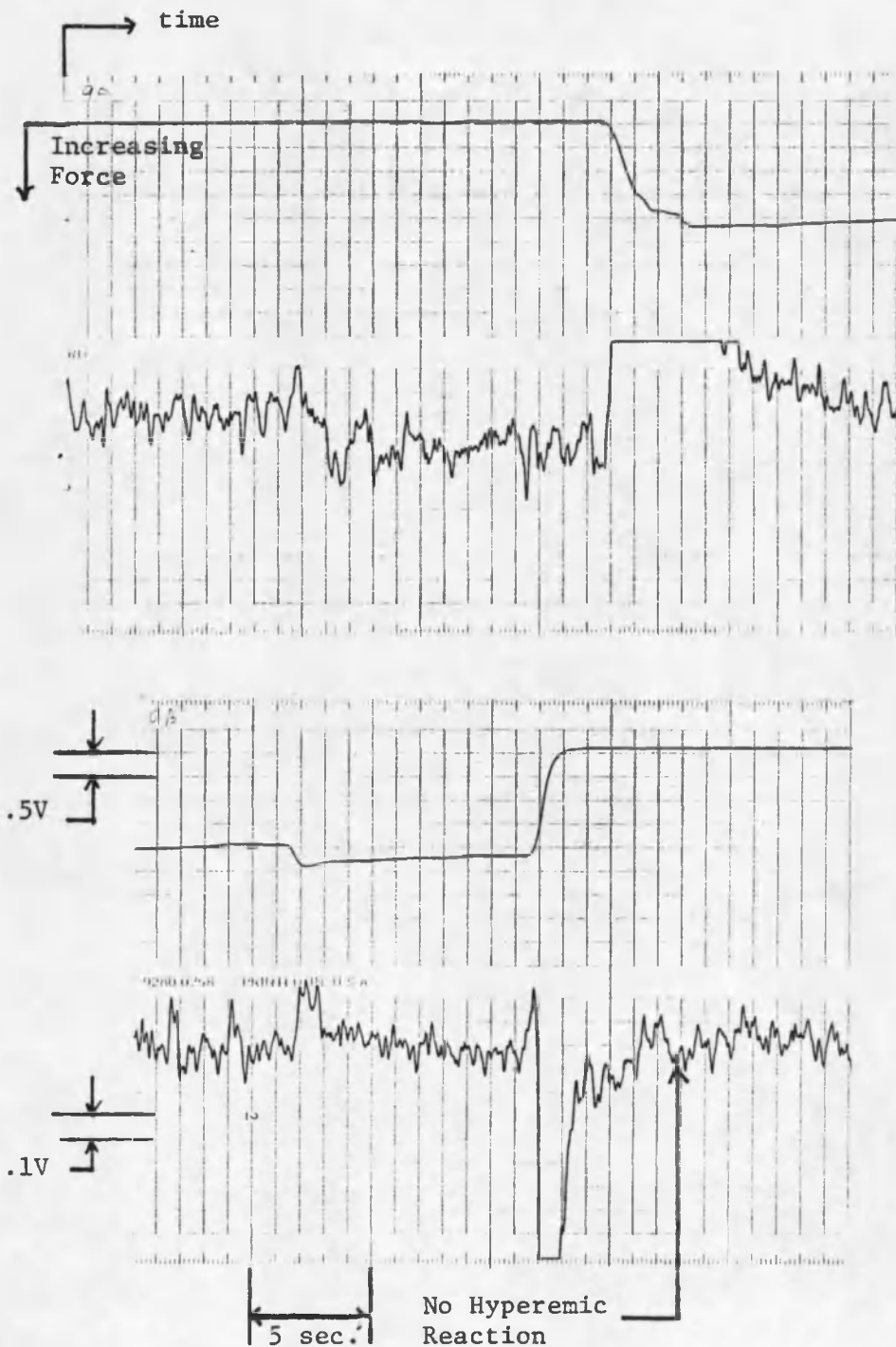


Figure 19. Continuous Recording of Force and Volume Pulses from the Left (Symptomatic) Leg, Below the Knee, of Patient Number 1.

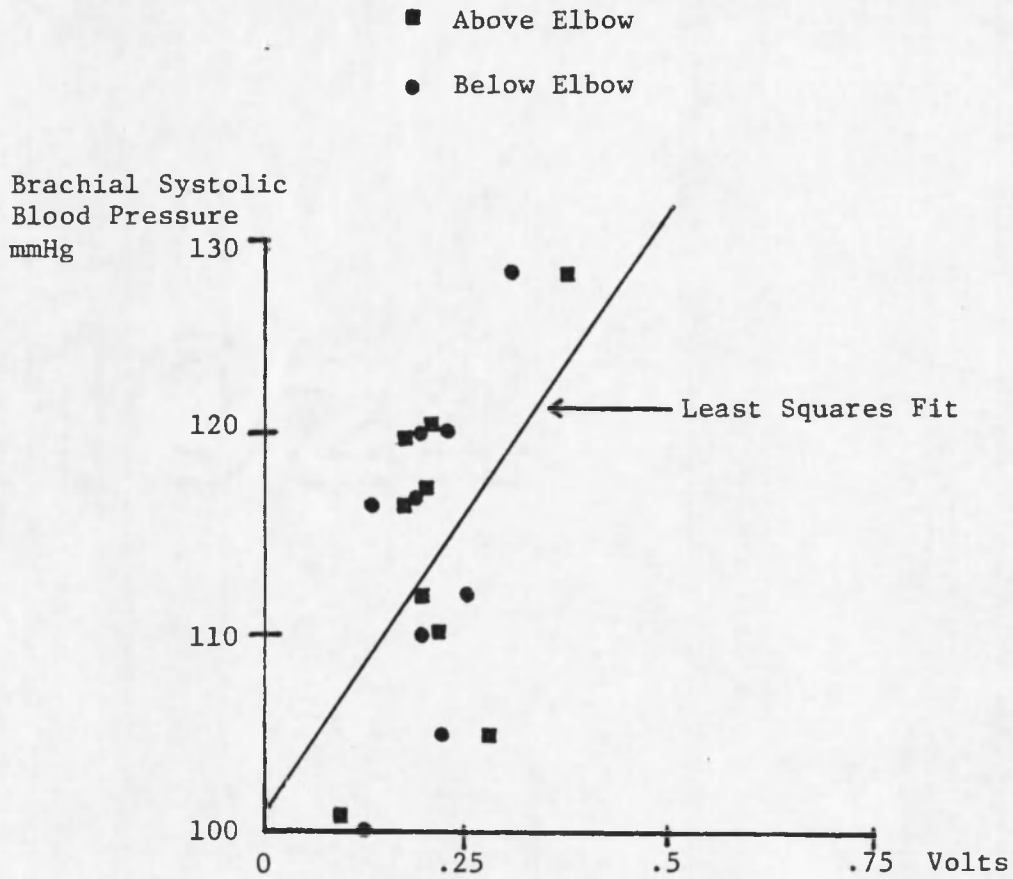
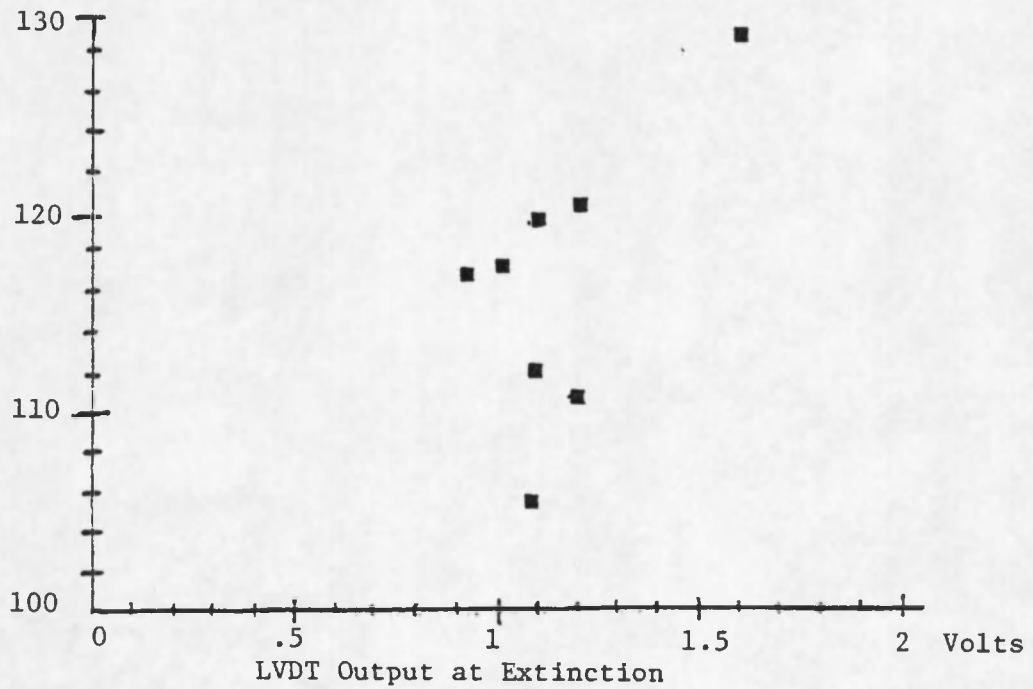


Figure 20. Initial Volume Pulse Amplitude of Normal Arms Versus Systolic Blood Pressure.

Brachial Systolic
Blood Pressure
mmHg



Brachial Systolic
Blood Pressure
mmHg

Below Elbow

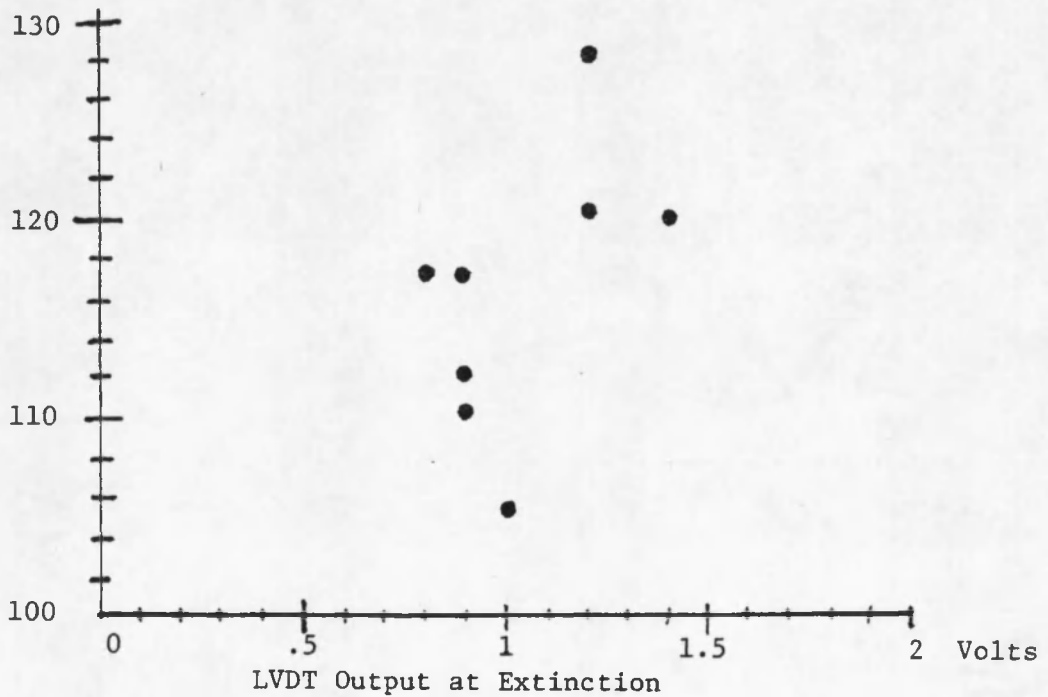


Figure 21. LVDT Output at Extinction Versus Systolic Blood Pressure for Normal Subject's Arms.

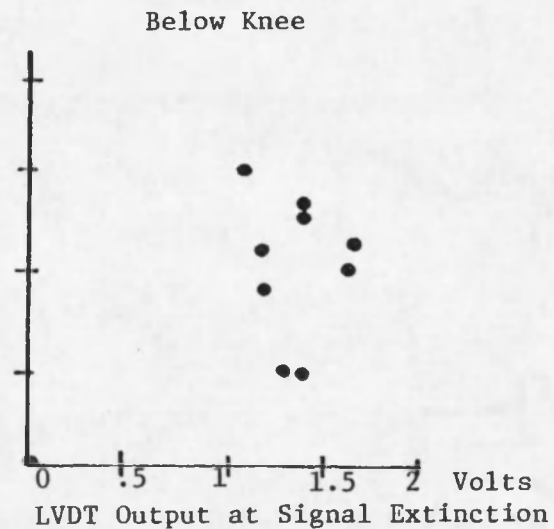
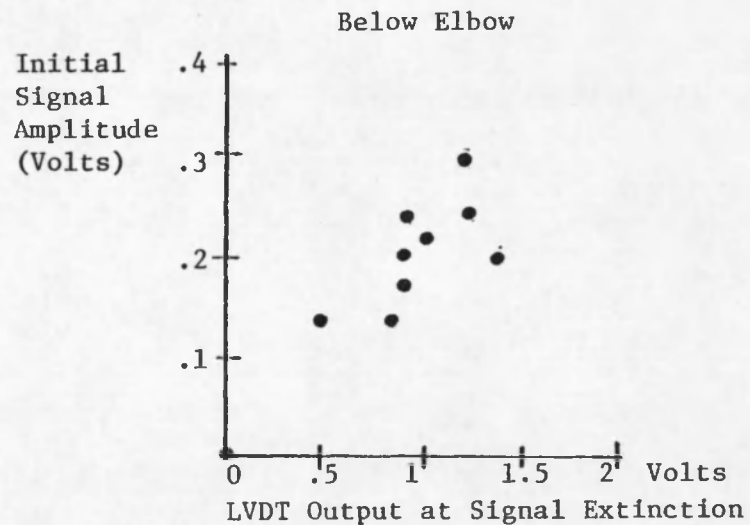
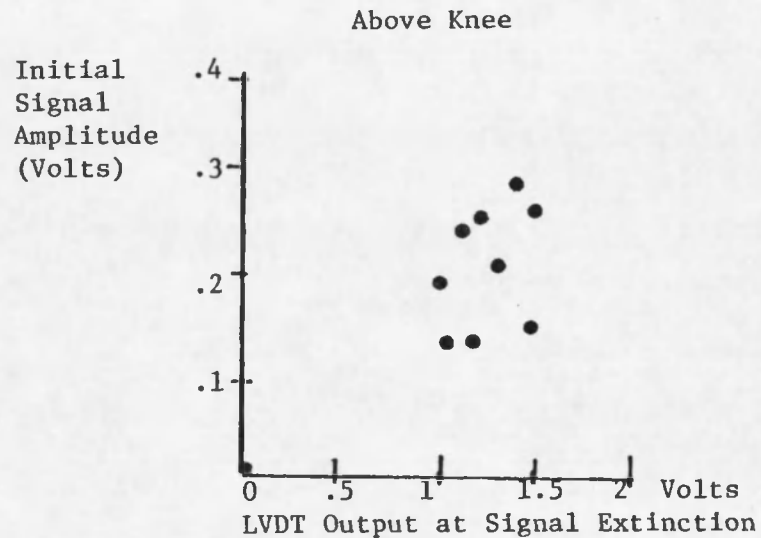
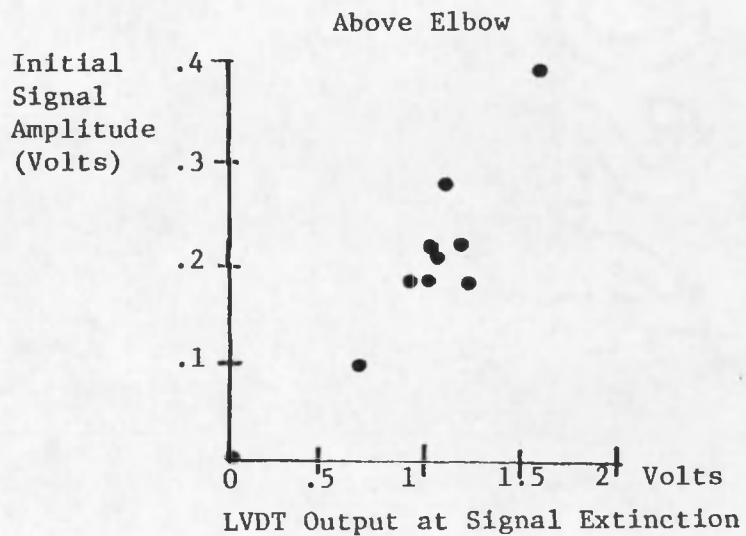


Figure 22. Initial Signal Amplitude Versus LVDT Output at Extinction for Different Locations on Normal Subjects.

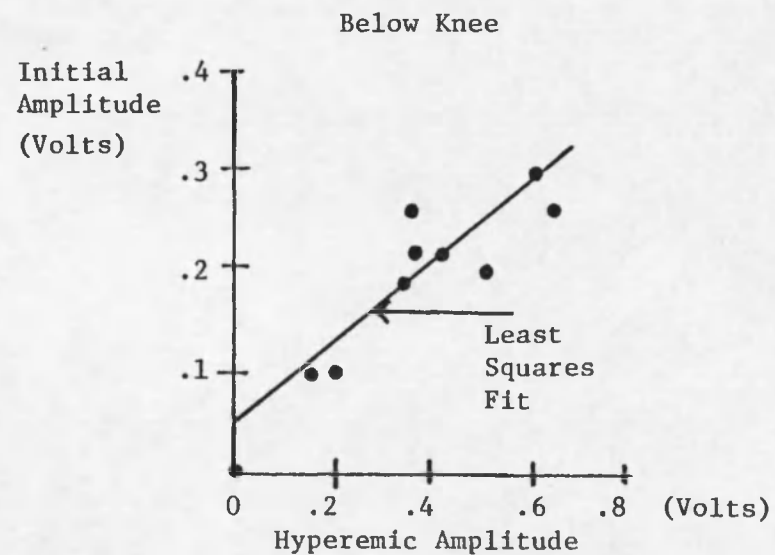
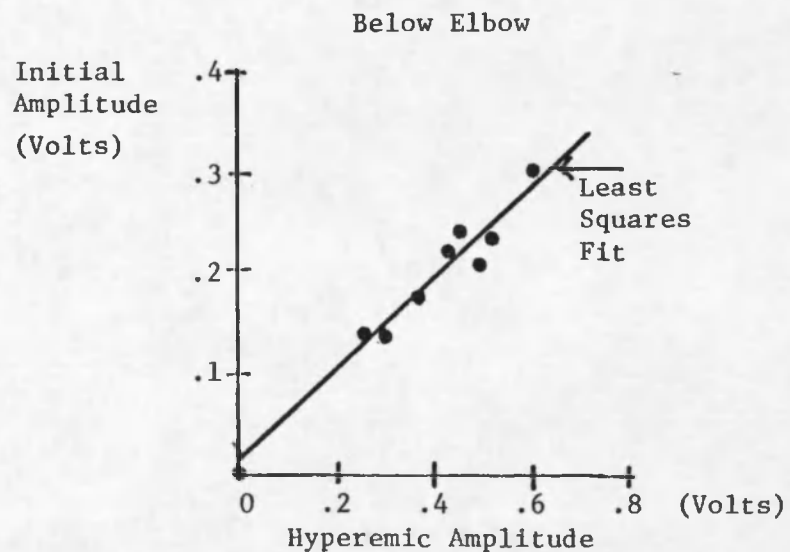
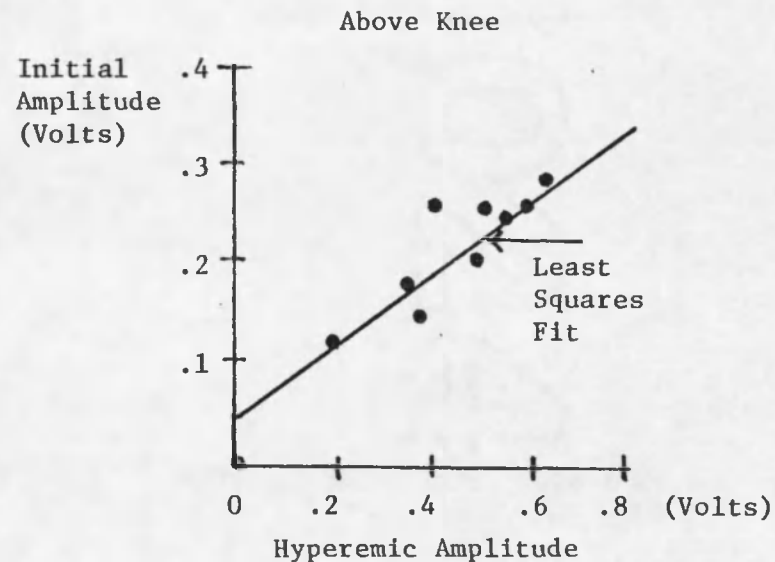
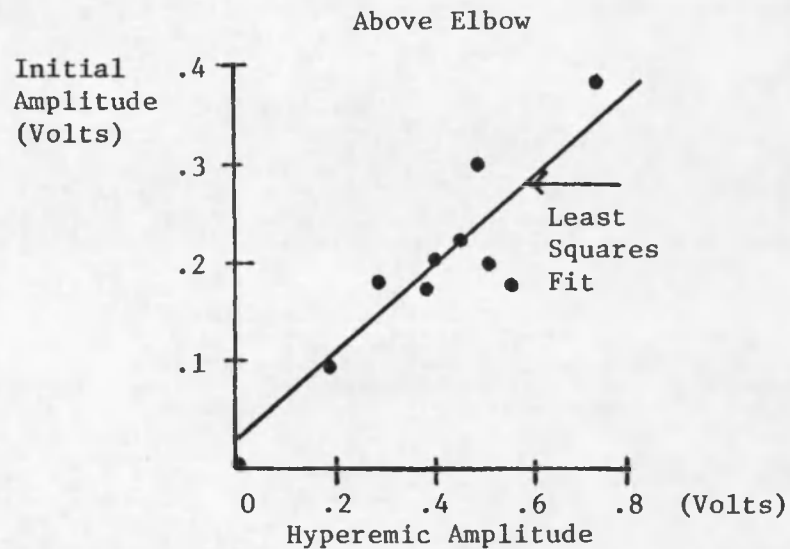


Figure 23. Initial Versus Hyperemic Volume Pulse Amplitude for Normal Patients with Least Square Fit Displayed.

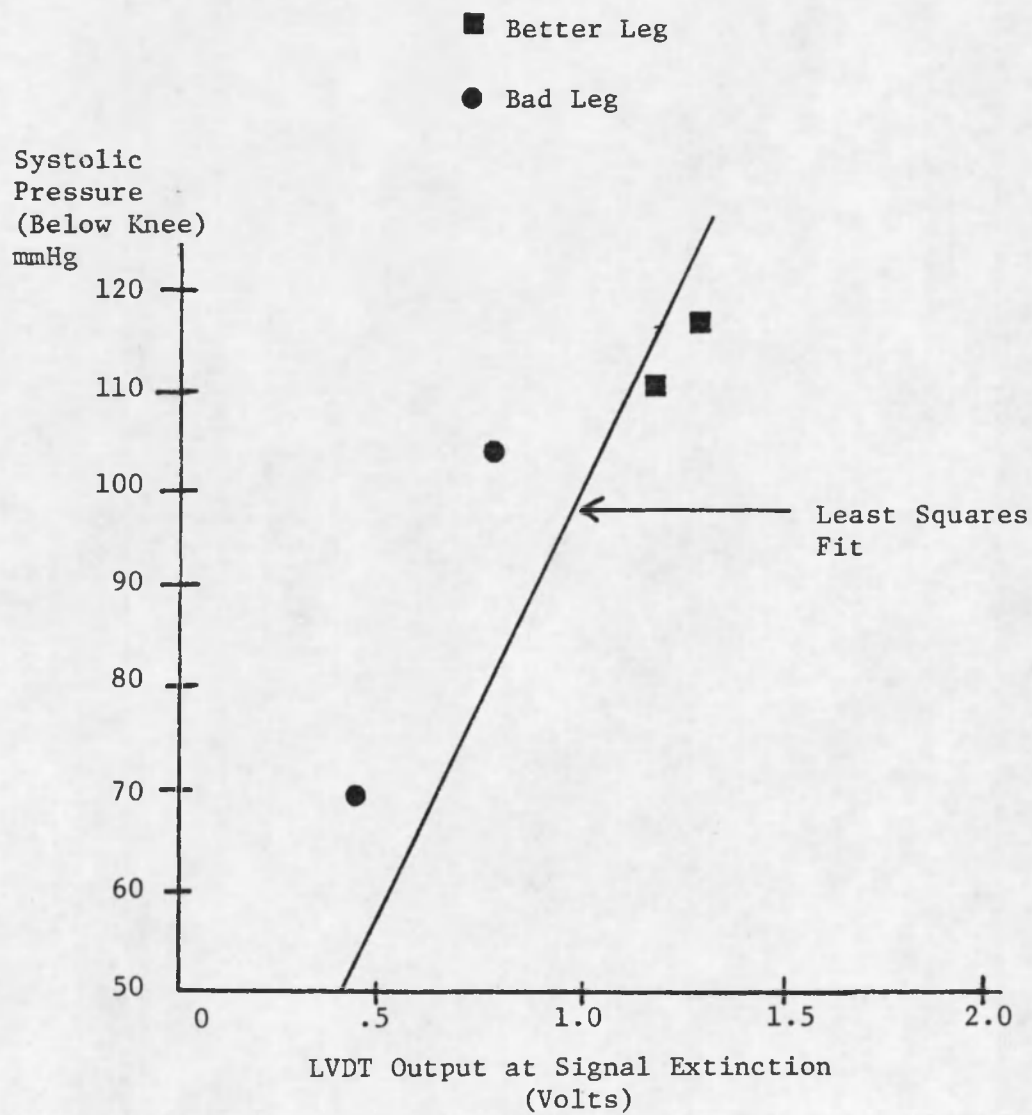


Figure 24. Systolic Pressure Versus LVDT Output at Signal Extinction for Symptomatic Patients, with Least Squares Fit Displayed.

Table 1. Data Obtained from Signals of Asymptomatic Subjects.

Subject Number	Blood Pressure Brachial (mm Hg)	Initial Amplitude Peak to Peak (Volts)				LVDT Output at Extinction Force (Volts)				Signal Return Voltage (Volts)				Maximum Hyperemia Amplitude (Volts)				Ratio Hyper/Initial				hT Before Decrease (Volts)							
		AE	BE	AK	BK	AE	BE	AK	BK	AE	BE	AK	BK	AE	BE	AK	BK	AE	BE	AK	BK	AE	BE	AK	BK				
1	128/75	.38	.3	.28	.3	1.6	1.2	1.4	1.1	1.5	1.1	1.3	1.0	.72	.60	.64	.62	1.89	2	2.28	2.06	.2	.3	.4	.38				
2	117/75	.17	.18	.18	.22	1.0	.9	1.0	1.7	.9	.8	.9	1.6	.38	.38	.36	.41	2.23	2.11	2	1.63	.28	.18	.24	.22				
3	117/80	.18	.14	.14	.1	.9	.8	1.5	1.3	.8	.8	1.5	1.2	.28	.3	.34	.2	1.55	2.14	2.42	2	.18	.14	.3	.1				
4	100/70	.1	.14	.12	.1	.7	.5	1.1	1.4	.7	.5	1.0	1.4	.2	.26	.2	.18	2	1.05	1.66	1.8	.1	.14	.12	.1				
5	105/65	.28	.22	--	--	1.1	1.0	--	--	1.0	.9	--	--	.48	.44	--	--	1.71	2	--	--	.4	.26						
6	110/68	.22	.2	.25	.26	1.2	.9	1.0	1.4	1.1	.9	1.0	1.3	.46	.48	.6	.65	2.09	2.4	2.4	2.5	.22	.2	.3	.5				
7	112/60	.2	.25	.25	.25	1.1	.9	1.5	1.4	1.0	.8	1.4	1.3	.5	.5	.5	.35	2.5	2.5	2.5	1.4	.2	.25	.25	.25				
8	117/65	--	--	.24	.18	--	--	1.1	1.2					--	--	.56	.3	--	--	2.33	1.66	--	--	.2	.24				
9	120/72	.18	.24	.12	.22	1.2	1.2	1.3	1.2	1.1	1.1	1.2	1.1	.56	.45	.5	.36	3.1	1.87	2.5	1.63	.18	.5	.22	.56				
10	120/75	.2	.2	.25	.2	1.1	1.4	1.2	1.6	1.0	1.3	1.1	1.4	.4	--	.4	.5	2	--	1.6	2.5	.2	.32	.25	.16				
Average		.212	.207	.212	.203	1.1	.97	1.24	1.43	1.0	.91	1.04	1.14	.44	.43	.45	.4	2.11	2.11	2.19	1.91	.22	.25	.25	.28				
AE -- Above Elbow		BE -- Below Elbow				AK -- Above Knee				BK -- Below Knee																			

Table 2. Data Obtained from Signals of Symptomatic Patients.

Patient Number	Systolic Pressure in the Leg (mm Hg)		Initial Signal Amplitude Peak to Peak (Volts)		LVDT Output when Signal Vanishes (Volts)		Hyperemic Signal Amplitude (Volts)		Hyperemic Amplitude	
	RL	LL	RL	LL	RL	LL	RL	LL	RL	LL
1	114	72 ^a	.2	.14	1.3	*	.32	*	1.6	*
2	60 ^a	70	.1	.2	*	.45	*	.3	*	1.5
3	110	102 ¹	.16	.16	1.2	.8	.2	.2	1.25	1.25
Average									1.42	1.38

^a Indicates leg in which patient experienced discomfort or pain.

* Indicates that data could not be obtained.

application, the maximum peak to peak amplitude of the hyperemic signal was recorded (column 6). A ratio of this hyperemic signal to initial amplitude (column 6 to column 3) is listed in the 7th column. The last column, height before decrease, was included because of a phenomenon noticed in a few cases: while pressure was being increased, the signal increased in amplitude before exhibiting a decrease. Figure 20 is a plot of initial signal amplitude versus systolic blood pressure. Since only brachial blood pressure was recorded, readings taken on the arm are plotted in the graph. Figure 21 displays this same systolic blood pressure versus the voltage of the LVDT at time of extinction. Figure 22 plots initial amplitude versus LVDT voltage corresponding to the extinction force while Figure 23 displays initial amplitude versus hyperemic signal amplitude. Because of the small data base for the subjects with vascular disease the only plot made of the data is shown in Figure 24. This displays systolic pressure versus LVDT output at the applied extinction force.

CHAPTER 4

DISCUSSION

During the collection of data, signal strength and shape varied from each individual and from each test site. This verifies literature reports that capillary population can vary in different regions and from one person to another (Jarrett 1973, p. 619).

Figure 20 indicates there is a possible linear relationship between initial pulse amplitude and systolic blood pressure while Figure 21 indicates there may be some relationship between systolic blood pressure and external force required for signal extinction. The range of blood pressure was too small as was the sample size, however, to draw any valid conclusions. Perhaps more significant is the indication shown in Figure 24 which is a plot of these same variables for the symptomatic patients. These few data points indicate a possible linear relationship between systolic pressure and local tissue pressure. The plots of Figure 23 display an interesting linear behavior between initial signal amplitude and the hyperemic signal amplitude in normals, which could be used as an important measurement of limb health. Also, the average initial signal to hyperemic signal amplitude ratio for symptomatic patients was only about 1.40 while for the asymptomatic subjects this same ratio was around 2.0. This again reinforces the value of this measurement to help assess vascular problems.

Examining the signal recordings (Figures 11 through 19) it is obvious that noise is more evident in the signals of the symptomatic patients. Comparing these signals with a noise recording (Figure 25) however reveals a periodic signal in the occluded limb which is not evident in the pure noise recording. Thus it seems that weak signals are being sensed by the instrument.

A comparison between the signals of a symptomatic patient's right leg with left leg reveals that the more occluded leg lacked a hyperemic reaction. Figures 15 and 16 are a continuous sample of a signal from a patient's "good" leg; though the signal was noisy there is some periodic signal which vanishes when slight pressure was applied. Figure 17 shows that in the more occluded leg no hyperemic reaction was evident. Likewise, the asymptomatic and symptomatic limbs of the patient in Figures 18 and 19 respectively show a hyperemic reaction is obtained from the asymptomatic limb only.

It is interesting to note that a hyperemic signal was obtained from a patient with a 70mm Hg systolic pressure reading while the other patients leg which had a systolic pressure of 72mm Hg showed no such reaction. The 70mm reading was from the first patient's painless leg while the second patient experienced pain in the leg with a 72mm reading. Thus, this is one indication that perhaps the presence of hyperemic reaction is a better indication of limb health than systolic pressure measurements.

The range of LVDT outputs at the force required for signal extinction varied in normal subjects, although of the 36 readings taken

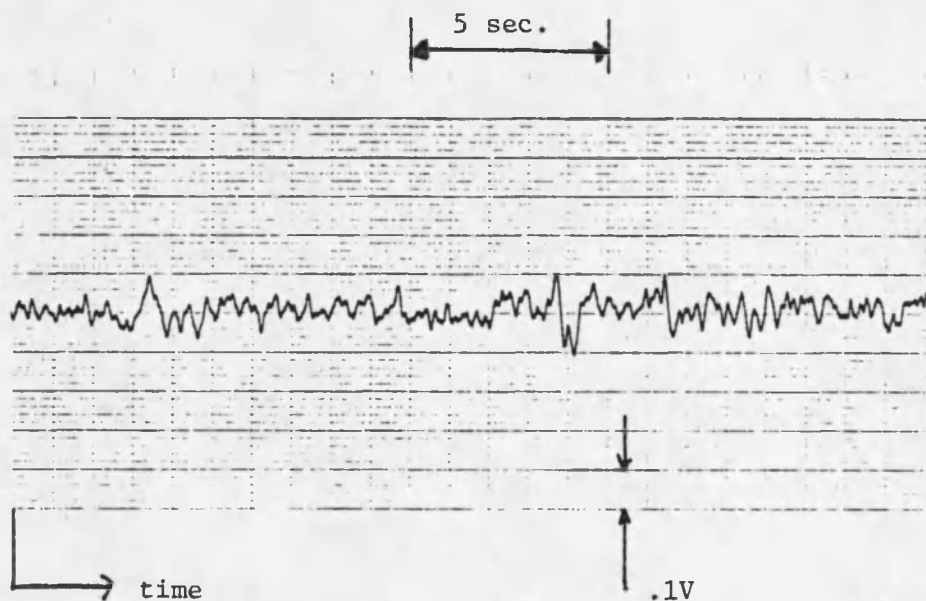


Figure 25. Noise Recording of Photodiode Output Obtained by Light Reflected from a Stable Inert Object.

only 7 were under one volt and only 3 were under .9 volts. For the symptomatic limbs of the 3 patients studied, readings of .8 volts and .45 volts were the recorded LVDT outputs at signal cancellation. For other symptomatic limbs, lack of a clear signal prohibited correct identification of voltage output at extinction force.

These figures seem to indicate that tissue perfusion pressure can be gauged by the method of testing used in this study; an accurate assessment of minimum pressure required for a limb to be considered normal still has to be ascertained but differences between normal and symptomatic patients seem evident.

CHAPTER 5

CONCLUSIONS

The use of a photoplethysmic device as described in this report appears to have potential for being a diagnostic tool in future vascular disease studies. From the recordings shown in this report, the following measurements are possible: initial volume pulse amplitude, force required for signal extinction, time required for onset of a hyperemic reaction, if any, the amplitude of a hyperemic reaction and the study of pulse contours from various locations.

The hyperemic response of skin tissue to local pressure applications and the pressures required to cause signal cancellation seem to be able to provide information on tissue health. Although absolute skin blood pressure measurements could not be obtained, as was the hope at the beginning of this project, the comparison of forces required for signal cancellation between normal and diseased limbs still may provide valuable information. Noise reduction would improve the signal to noise ratio and enable more accurate readings to be obtained from signal recordings. The use of an optically ground lens in place of the plexiglass spacer and photodiode arrangement may be able to assure that surface capillaries are being observed. Since current photoplethysmographic devices are not able to receive signals from diseased limbs, the signals received with this instrument are an indication that

arranging photodiodes so as to observe surface vessels is a step in the right direction.

Regrettably, the symptomatic group studied was small, and positive conclusions can not be stated at this point. Future studies, however, will give more information.

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