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HEADQUARTERS
QUARTERMASTER RESEARCH & ENGINEERING COMMAND
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TECHNICAL REPORT

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ENVIRONMENTAL PROTECTION RESEARCH BY MEANS OF RADIO TELEMETRY

PART II

NOX

QUARTERMASTER RESEARCH & ENGINEERING CENTER
ENVIRONMENTAL PROTECTION RESEARCH DIVISION

JULY 1961

NATICK, MASSACHUSETTS

AD- Div. 16 Accession No.

Quartermaster Research & Engineering Center, Natick, Mass. ENVIRONMENTAL PROTECTION RESEARCH BY MEANS OF RADIO TELEMETRY II. MEASUREMENT OF PULSE RATE FROM ACTIVE TEST SUBJECTS by Francis W. Botsch, James J. Powers and Michael J. Sacco, 22 pp., illus. (Technical Report EP-158), July 1961

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UNCLASSIFIED

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2. Auditory signals
3. Cardiotachometers
4. Exercise
5. Safety devices
6. Stress (Physiology)
I. Botsch, Francis W.
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Quartermaster Research & Engineering Center
Natick, Massachusetts

ENVIRONMENTAL PROTECTION RESEARCH DIVISION

Technical Report
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ENVIRONMENTAL PROTECTION RESEARCH

BY MEANS OF RADIO TELEMETRY

II. MEASUREMENT OF PULSE RATE FROM ACTIVE TEST SUBJECTS

Francis W. Botsch James J. Powers Michael J. Sacco

BIOPHYSICS BRANCH

Project Reference:
7X83-01-009

July 1961

FOREWORD

One of the most critical problems confronting a scientific investigator working with human test subjects under extreme stress conditions is that of determining when a test subject has reached a dangerous level of strain. Pulse rate and rectal temperature are accepted criteria for indicating an upper limit of tolerance; however, methods for accurately measuring pulse rate have previously been inadequate for many exercises and impossible in those which need the most careful monitoring.

This report describes new instruments for measuring pulse rate which are easy to use and eliminate most of the shortcomings of previous systems. The instruments are so designed that they can be operated with a minimum of equipment in climatic chambers where direct contact with the subject is permissible or as part of a more complicated radio system for remote recording of pulse-rate data in the field.

AUSTIN HENSCHEL, Ph.D.
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CONTENTS

ABSTRACT

Three instruments; 1) a wire telemeter used in climatic chamber studies, 2) a portable unit which delivers an audio signal suitable for either earphone monitoring or recording on magnetic tape, and 3) a radiocardiotachometer used in field studies, are described for the measurement of pulse rates from active human test subjects.

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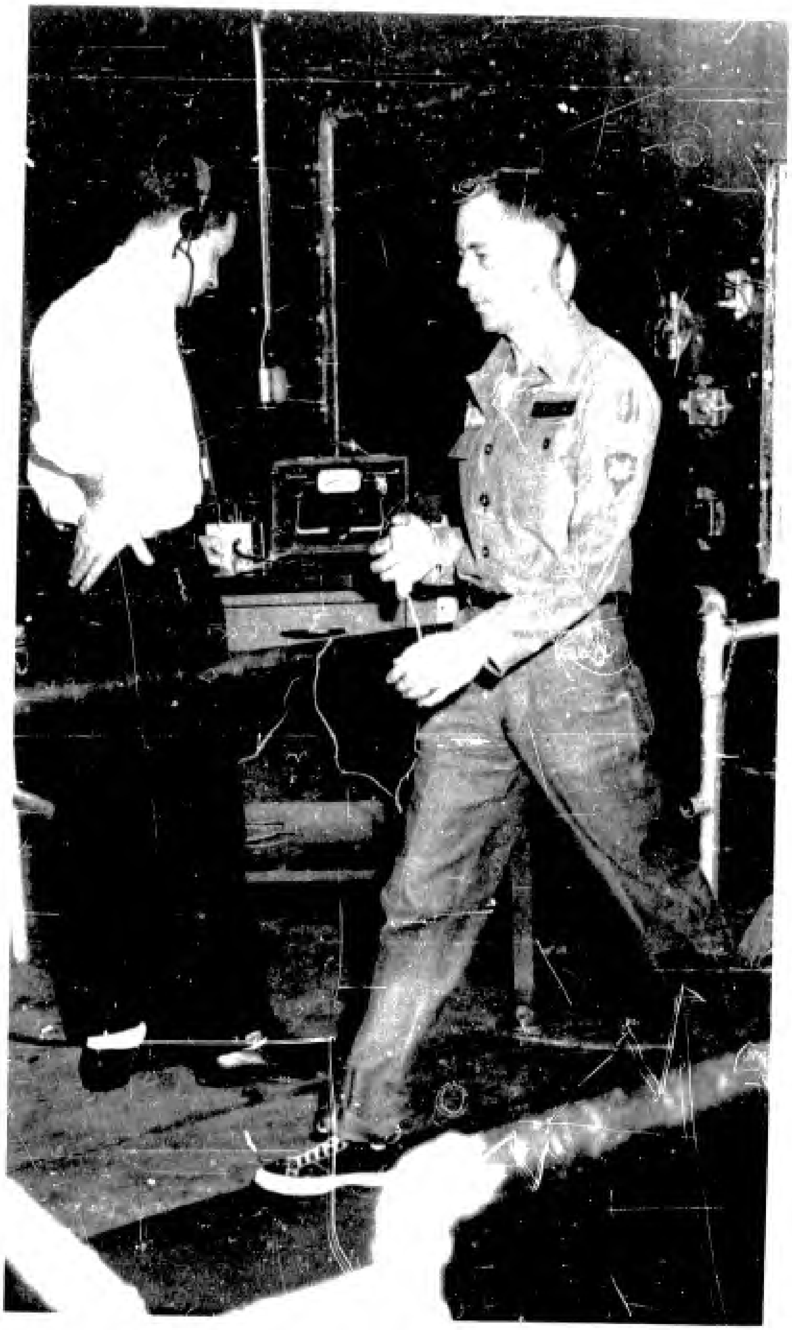

Figure 1. Measuring pulse rate during walking exercise.

ENVIRONMENTAL PROTECTION RESEARCH BY MEANS OF RADIO TELEMETRY

PART II: MEASUREMENT OF PULSE RATE FROM ACTIVE TEST SUBJECTS

1. Introduction

The telemetry of pulse rate from human test subjects during exercise has been the subject of many investigations because the frequency of heart beat is known to reflect physiological strain. Furthermore, it is generally accepted that a measure of pulse rate and rectal temperature will indicate to an investigator when his subject has reached a dangerous level of strain and should be withdrawn from the stress condition. The instruments described in this report were designed primarily as safety devices to protect men performing at high work levels under environmental extremes from being subjected to undue strain. It was therefore essential that the apparatus be reliable and that it deliver a non-ambiguous form of pulse rate measurement.

Numerous systems for detecting and recording heart beats have been described in the literature and may be classified according to the transducer used. The four general types are (a) microphone systems which sense heart sounds, (b) peripheral pressure systems (12) which sense pressure changes in the arteries (displacement type), (c) electric potential systems (6, 11) which record or count variations in the cardiac potential, and (d) photoelectric devices which sense changes in blood content in the tissue.

All of these systems work well on resting subjects but require basic modifications before they can be applied to exercising men. A microphone placed over the chest will respond to sounds generated by breathing, muscle movement, and background noise in the experimental chamber, as well as the audio signals from the heart. Pressure systems are delicate and easily upset by muscle activity and blood pressure variations. Electric potential systems require critical placement of electrodes in order to nullify the effect of higher-magnitude muscle potentials during exercise. In addition, since the test subject is not electrically isolated from the amplifying equipment, a shock hazard is created and interference is generated when other measurements such as body temperatures are being recorded concurrently. In general, the major difficulty encountered by using any one of the first three systems to measure pulse rate during exercise arises in discerning the heart beats from extraneous noise, because these systems function with an unfavorable signal-to-noise ratio. Attempts to improve this ratio by using filters and multi-channel devices with coincidence circuits (7) necessitate the use of elaborate harnesses and extensive pre-exercise instrumentation; this precludes their use with a large group of test subjects.

The fourth method of sensing pulse rate, the photoelectric technique, was adopted by the authors as the most feasible, primarily because it can operate with a favorable signal-to-noise ratio on exercising men and complete electrical isolation can be achieved. Another advantage of this system became apparent after a prototype was built: a single transducer can be used to measure the pulse rates of many test subjects. This transducer senses pulse beats by the translumination of a vascular volume; it does not require any special harnesses, electrodes or complicated instrumentation; it can easily be passed around among the test subjects. Furthermore, the application of the photoelectric method of pulse-rate measurement in a long-range radio telemeter (2) demonstrated that a suitable transducer could be constructed which would not be affected by heat, sweat, individual differences or body motion.

This report describes the application of a photoelectric transducer in 3 different measuring systems which permit investigators to monitor or record pulse beats from exercising test subjects. The basic instrument is used in treadmill studies in climatic chambers where the transducer is connected by direct wire to an analog recorder. In addition, two modifications of this apparatus are discussed: (1) a portable unit which delivers an audio signal suitable for either magnetic tape recording or aural monitoring and (2) a radiocardiotachometer used in field studies where complete freedom of movement is desired.

2. Pulse rate transducer

Photoelectric detection of heart beats is accomplished by sensing changes which occur in the optical density of vascular tissue due to variations in its blood content during the cardiac cycle. Figure 2 is a graph of the transmission spectra of flesh shown for (1) bloodless tissue, (2) tissue flushed with blood with subject breathing 100% oxygen and (3) tissue flushed with blood with the subject breathing air.

It can be seen from the graph that the intensity of the transmitted light will vary due to changes in blood content of the tissue and also to variations in the transmission characteristics of the blood itself. At the wavelength of 7500°A, however, the optical density of the blood is relatively independent of the ratio of oxyhaemoglobin concentration to haemoglobin concentration which is related to the respiratory state of the subject (3).

Figure 2 also shows the relative sensitivity of the Clairex type CL-3 cadmium selenide photocell superimposed on the graph of the transmission spectra for flesh. This cell is ideally suited for use as a sensor in the photoelectric transducer since its response is maximal near the isobestic point (7500°A) and minimal in the region between 6000°A and 6500°A where disturbances in the respiratory state of the subject (such as hyperventilation and breath-holding) have a great effect on the transmission properties

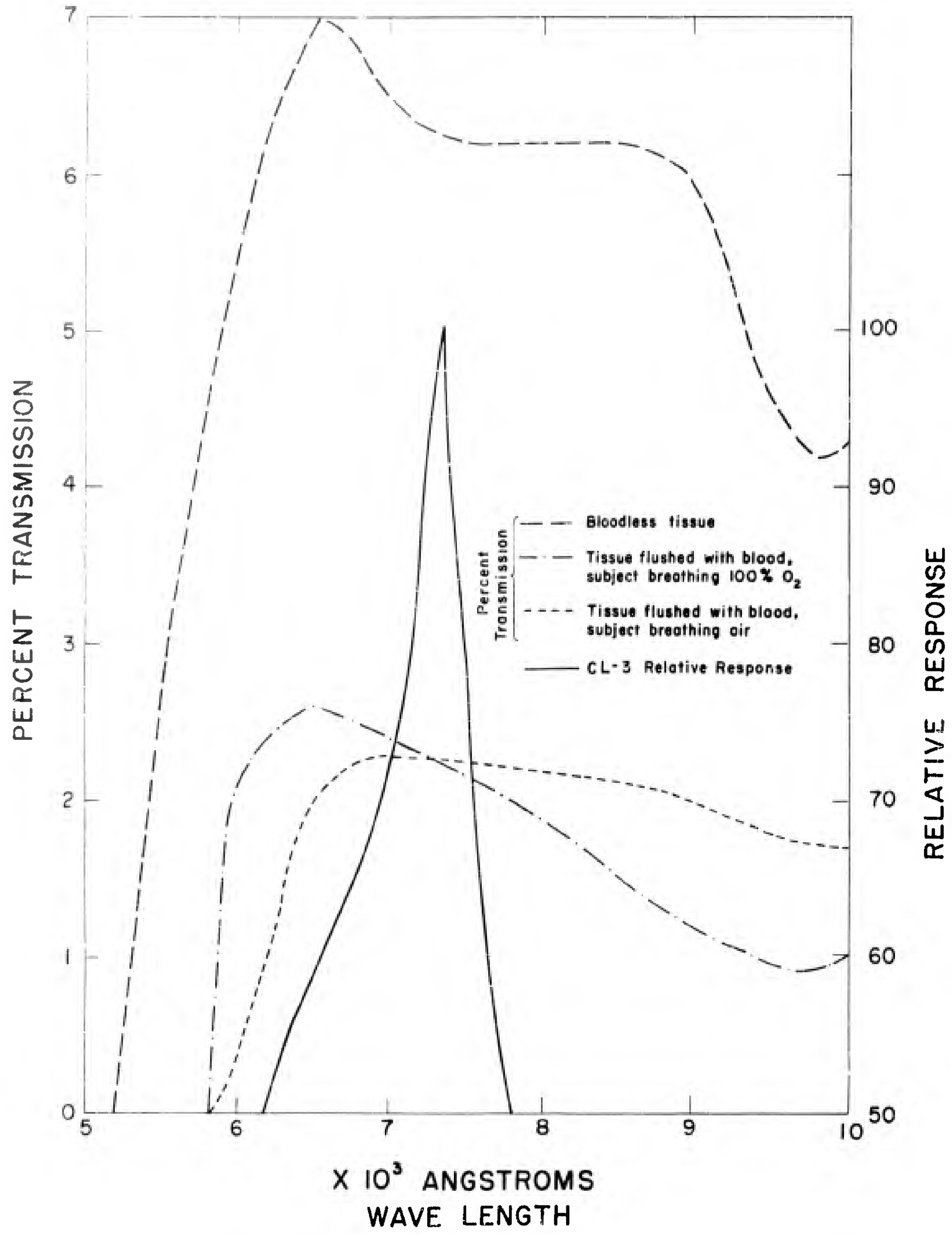

Figure 2. Transmission spectra of cartilaginous helix and relative sensitivity of CL-3 photocell.

of blood. The sensitive area of the photocell is rectangular in shape (1/16 x 3/16 inch) and is situated 1/8 inch from one end of an epoxy resin cylinder 1/4 inch in diameter and 1/2 inch long. Since the cell is extremely sensitive in the red and near infra-red regions of the spectrum, it works well with an incandescent lamp light source.

Two basic configurations of the photoelectric transducer have been constructed and tested, the earlobe transducer and hand-held type. The earlobe transducer, modeled after the earclip oximeter (3), functions by sensing changes in the intensity of light transmitted through the earlobe (1, 2). This device, shown in Figure 3, is machined from a nylon rod and coated with black Insl-x compound in order to exclude outside light and to insulate and stiffen wires connected to the light bulb and photocell. The unit is designed to encase a major portion of the earlobe and is held rigidly in place by a wire hook which is shaped to fit over the ear. Wires running from the transducer to the transmitter are fastened to the clothing, allowing a comfortable amount of head movement.

Figure 3. Earlobe transducer.

The earlobe transducer was developed for use in radio telemetry studies during which pulse rates were monitored at a remote location from test subjects who were allowed complete freedom of movement within the test area. A separate transducer has to be fitted to each test subject in this application, since the useable area of the lobe is small and placement of the pickup is extremely critical; however, once instrumented, the test subject is not required to participate actively in the measurement. The physical dimensions of this device are given in Figure 4(2).

Figure 5 shows a hand-held photoelectric transducer which is used mainly in climatic chamber studies to sample pulse rates from a large group of test subjects during heat stress studies. In this configuration, the photocell is mounted in the same plane as the light source and responds to light which is diffused through the tissue by scattering. This arrangement makes it possible to sense the pulse beat on flat surfaces of highly vascular areas and results in (1) greater sensitivity due to the longer path length for the light, (2) relative insensitivity to movement of the overlying tissue, and (3) elimination of the problem of individual differences in test subjects due to physical size and shape.

The transducer is fabricated from a hollow tube of aluminum with a black phenolic plug inserted in one end. A CL-3 photocell and a plexiglas

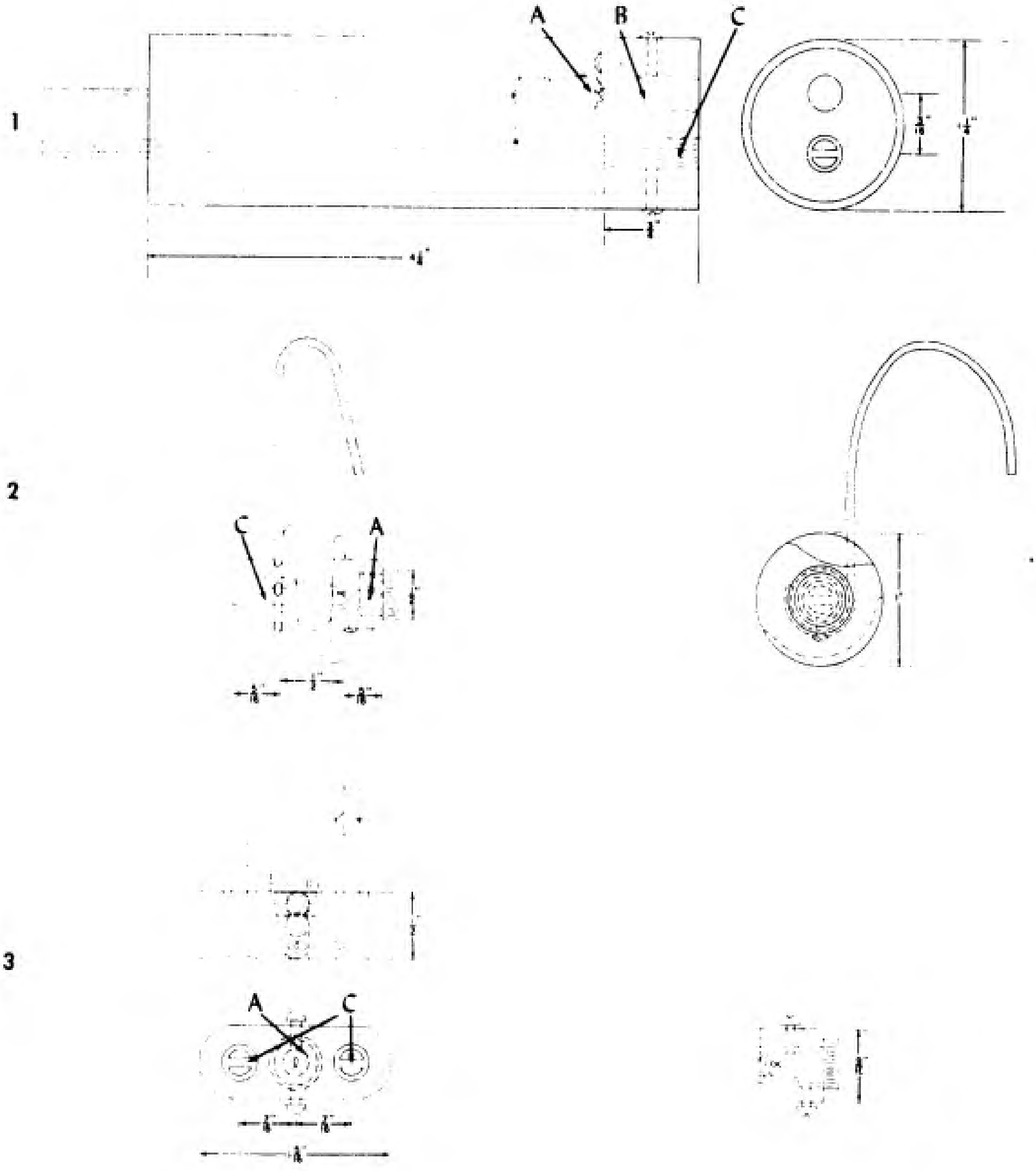

Figure 4. Dimensional drawing of (1) hand-held transducer, (2) earlobe transducer, and (3) forehead transducer. The letters, A,B and C refer to the lamp, plexiglass rod, and photocell respectively.

rod are set into the plug, flush with the exposed surface. The rod is used to bring the light from a Type 22 bulb to the surface. Physical dimensions of the hand-held transducer are given in Figure 4(1). In order to obtain a pulse-rate measurement, the investigator passes the transducer to the test subject who grasps the tube, placing his thumb pad over the light source and photocell. The signal is taken over wires which run through the open end of the tube to the amplifying and recording equipment.

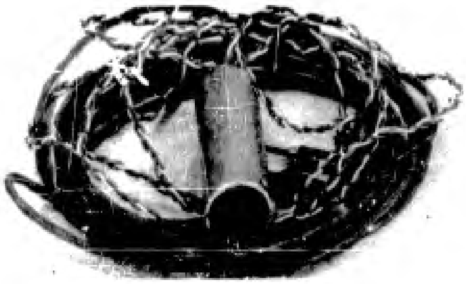

Figure 5. Hand-type transducer.

An adaptation of this transducer has been used in studies where the hands are not accessible. It consists of a disc with 2 photocells and a light source mounted in the same plane which is strapped to the forehead. A diagram of this forehead transducer is presented in Figure 4(3). Test subjects must be individually instrumented when this technique is used and considerable difficulty is experienced in placement of the transducer. However, it should be noted that the forehead is one of the last body areas to experience vasoconstriction in the cold.

3. Circuit theory

A wire telemeter which is used as a monitoring device during chamber experiments and a radio telemeter for continuous pulse beat recording have been developed which use signals from the photoelectric transducer. Both instruments are capable of producing 2 forms of pulse beat readout: (1) a graph on which pips are plotted with reference to the chart paper time base and (2) an audio frequency variation which can be recorded on magnetic tape for later analysis. Although the pulse beat signal usually exhibits a high signal-to-noise ratio, no attempt is made to determine instantaneous pulse rate by measuring the period between pulses since such measurements are not considered sufficiently significant by investigators to warrant additional circuitry.

a. Wire telemeter with analog readout

The signal at the photocell is in the form of a resistive change each time the heart beats, since the resistance of the cell is an inverse function of the intensity of light falling on its sensitive area. Figure 6 shows the CL-3 cell (C.R.1) connected in series arrangement with a 90-volt battery and the primary winding of a transformer. Each time that a light intensity fluctuation occurs, the resultant current change in the transformer primary will induce a voltage across the transformer secondary. Since the transformer will pass only the A.C. component of the signal, baseline variations due to slow changes in the average vascularity of the tissue are effectively removed. The capacitors and the audio frequency choke shown in the circuit diagram comprise a filter for signals of frequencies above 4 or 5 cycles per second. The filter eliminates 60 cycle power line pickup, noise associated with body motion and spurious ambient light fluctuations.

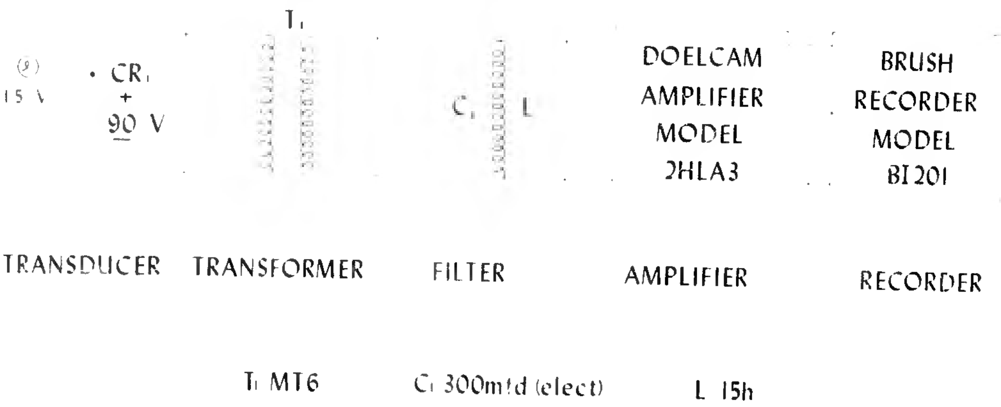

Figure 6. Circuit diagram of wire telemeter.

A noise-free signal of approximately 3 millivolts measured across a 1000-ohm load will be present at the input to the amplifier each time the heart beats. During exercise, as the pulse rate increases and the average vascularity of the tissue increases, the pulse amplitude will increase considerably. An amplifier with a gain of 10,000 at 1 to 3 cycles per second will be sufficient under all test conditions. The Doelcam D.C. Magnetic Amplifier, Model 2HLA-3 and Brush Recorder, Model B1201 were used to make the recordings shown in Figure 7.

The appearance of variations in the amplitude of the dicrotic notch during exercise can be seen in Graph A of Figure 7. The amplitude of the secondary pulse is related to the respiratory state of the test subject and will occasionally attain nearly the same height as the primary pulse. It is for this reason that the analog readout is to be preferred over other forms of display. Systems using counters in some form of automatic period measurement or counting operation require trigger level adjustment and shaping circuits which would have to discriminate between the primary and secondary pulse in order to sample over a required period of at least 20 seconds. This cannot be done by direct integration, since the pulse amplitudes are not constant.

b. Wire telemeter with audio frequency readout

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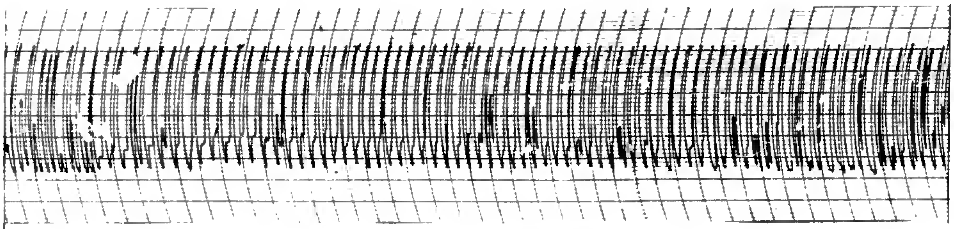
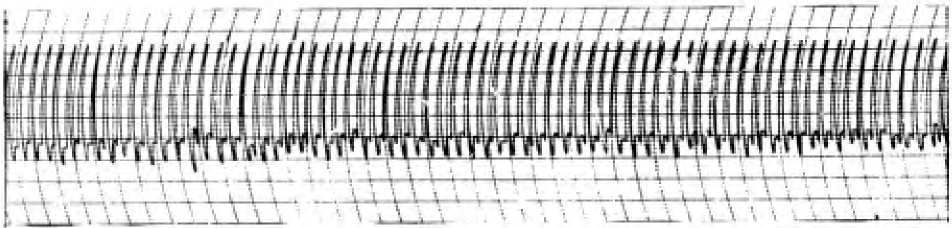
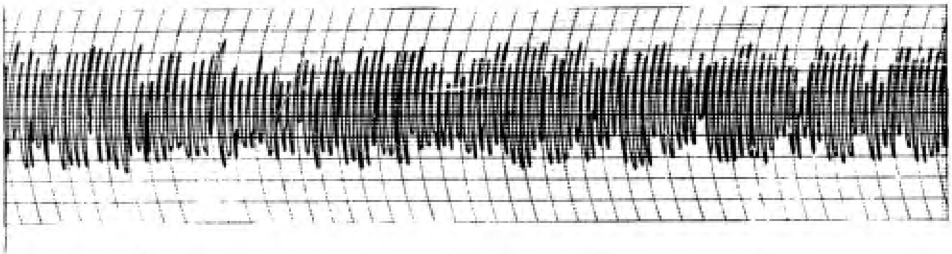


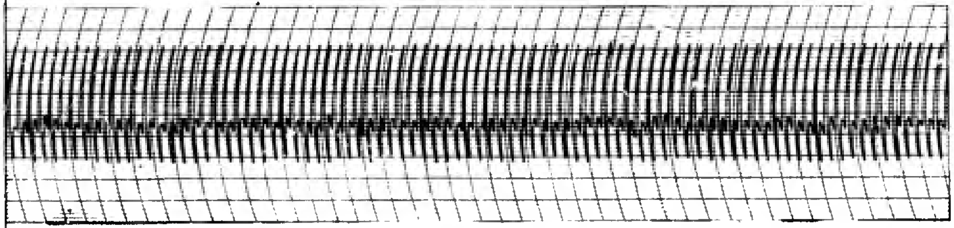
A WALKING 3.5 M.P.H. 108 B.P.M.



B STANDING 97 B.P.M.



C HARVARD STEP TEST 160 B.P.M.

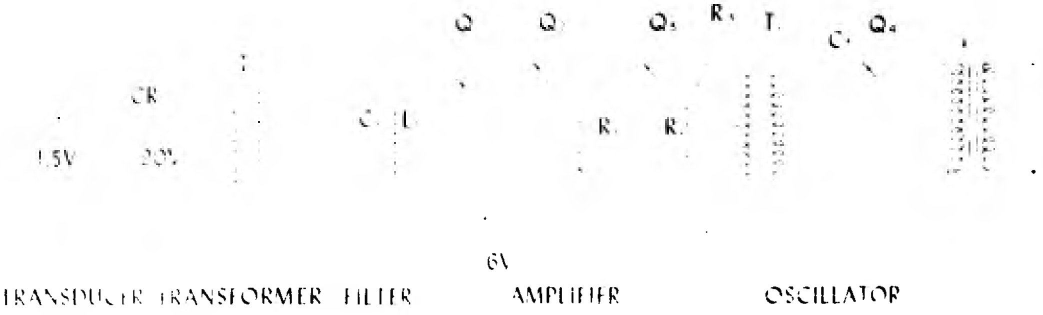


D SITTING 114 B.P.M.

Figure 7. Pulse beat recordings taken during and after different exercises.

have been evolved which are calculated from the observed rate of change of pulse rate during recovery after exercise. The measurement becomes much more exact if the entire recovery curve is available and the critical points are extracted from the fitted exponential curve, thus eliminating the errors which may arise from the characteristic oscillations in pulse rate which occur during a recovery period. It thus becomes desirable to perform automatic reduction of pulse rate over these rather long periods of observation.

The circuit shown in Figure 8 combines the photoelectric transducer described above with an amplifier and tone generator to produce audio frequency variations which can be recorded directly on magnetic tape. It can be seen from the circuit diagram that the transducer, its coupling network, and the noise filter have been retained in order to stabilize the signal baseline and remove spurious signals. Four transistors are used: Q_1 and Q_2 comprise a direct-coupled amplifier which is RC-coupled to amplifier Q_3. Q_4, Q_4 and the transformer T_2, generate the audio tone. In the absence of a pulse signal, a steady tone of about 1500 cycles per second is present at the output. Each time the heart beats, a large frequency excursion occurs in the audio signal. If it is necessary to monitor the heart beats while recording for automatic data reduction, a set of magnetic headphones may be inserted in series with the transformer T_3, and R_3 may be adjusted to set the audio tone at any desired audio frequency.



L M16
i_2 I- SO2
C 300 mfd (elect)
C_2 10mfd

C .003mfd
R 5k
L 15h
R 10k

R_2 82k
Q_1 2N34
Q_2 2N35
Q_3 CK722
Q_4 CK725

Figure 8. Circuit diagram of wire telemeter with audio readout.

In practice, the test subject holds the transducer during the recovery period after exercise and the entire record of heart beats is preserved on magnetic tape. The tape is then processed at a later time in the automatic data-reduction facility described elsewhere (2). The final result after automatic reduction appears as a column of figures showing the average period of the pulse taken over 20 beats and referred to real time. Since the complete instrument is small and inexpensive, it is possible to provide several channels of simultaneous recording supervised by a single investigator.

c. Radiocardiotachometer

The radiocardiotachometer was designed to provide short range telemetry of pulse rate in situations where it is impossible to wire the transducer directly to the recording apparatus. This situation occurs when the test subject is active over a large area and cannot be restrained by wires or when he is exercising in a clothing ensemble which has no openings. The maximal range of the transmitter is about 15 feet but will vary slightly in accordance with the background noise level and the operating frequency of the R.F. oscillator. This telemeter is used to sample pulse rates only when a test subject is within range of an antenna. The long-range (3-mile) telemeter for continuous pulse rate measurement was discussed in a previous report (2).

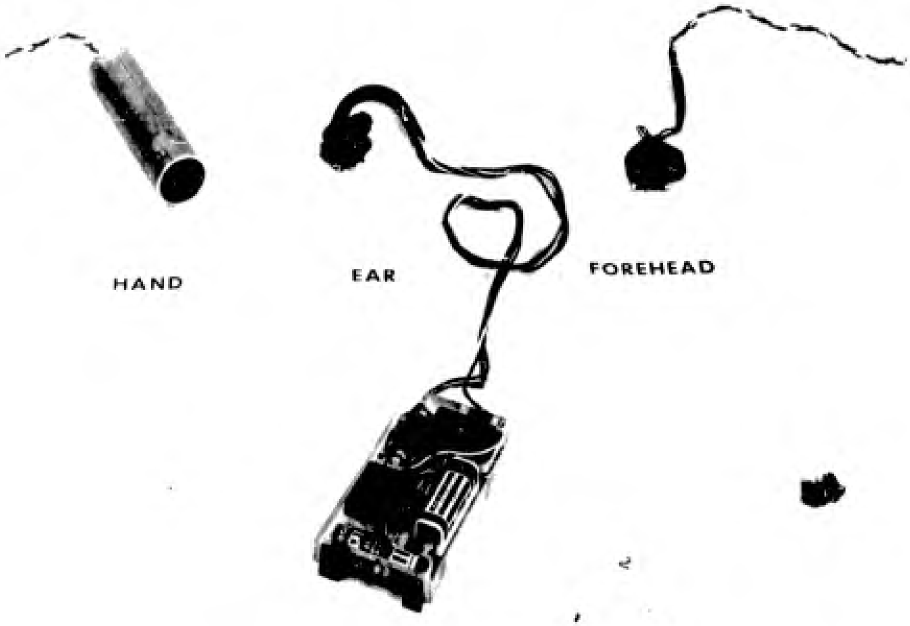


Figure 9. Radiocardiotachometer

The complete transmitter, including transducer and batteries, weighs 10 ounces. The amplifier-oscillator portion is designed to fit into the test subject's breast pocket and a small cable connects to the pickup. The transmitter is shown with both covers removed in Figure 9. The case was fabricated from plastic machined to receive batteries, crystal, and a chassis board which contains the components shown in the circuit diagram (Fig. 10).

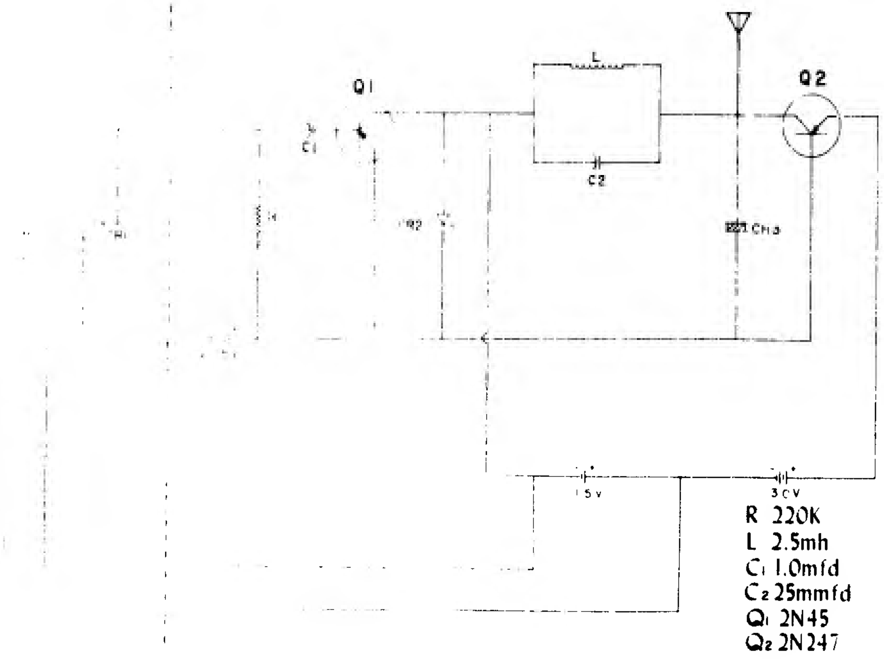


Figure 10. Circuit diagram of radiocardiotachometer.

The photoelectric transducer is A.C.-coupled to the first transistor amplifier by resistor R and capacitor C. The value of the resistor was chosen experimentally to deliver maximal signal to the base of Q_1, and is a function of the average resistance of the sensor. The coupling capacitor C was chosen to have the smallest possible impedance between 1 and 3 cycles per second without causing an inordinately long time constant to be developed in the circuit; this would nullify the pulse signals during recovery from a high amplitude noise signal. Q_1 is a simple grounded emitter amplifier directly coupled to the R.F. oscillator, Q_2, which acts as its load. CR_2 is a 1N34A crystal diode with a negative temperature coefficient of resistance which acts as a temperature compensator by stabilizing the oscillator collector current at higher temperatures. The telemeter will perform with high gain at moderate temperatures up to 90°F without temperature compensation. With compensation readable signals have been obtained at temperatures up to 120°F with slightly reduced sensitivity.

The frequency of Q_2 is controlled by resonant crystal CR_3. The values of L and C_2 are not critical and the oscillator will function properly up to a frequency of 50 megacycles per second with the values given in the circuit diagram. Frequency modulation is accomplished by variations in the oscillator collector current each time the heart beats and the amplified pulse signal appears in the collector circuit of Q_1. Although the use of a crystal-controlled oscillator seriously limits the percent deviation of the radio frequency, this circuit is used to overcome the inherent instability of high frequency transistor oscillators. Stabilization is necessary since the transmitters are normally subjected to a wide range of ambient conditions, and several identical units must operate in a very narrow frequency channel when more than 1 test subject is involved. If the R.F. frequency is stable, commutation from subject to subject can be accomplished by tuning the receiver and the possibility of interference is minimized.

The transmitter package contains a 22.5-volt battery for the transducer circuit, a 1.5-volt rechargeable nickel-cadmium cell for the light source and two 1.5-volt penlight cells in series connection which supply power to the amplifier and R.F. oscillator. The lamp requires 110 ma from the 500 ma per hour cell, limiting operation time to about 4 hours. The life of the other batteries is almost equivalent to their shelf life.

The antenna is a short length of wire which is attached to L and runs along the cable to the earpiece. The signal is received on a receiving antenna which is placed as close as possible to the test subject. With the receiver operating in the C.W. mode (beat-frequency oscillator on) the heart beats will be detected as audio excursions and may either be counted or recorded on magnetic tape. The deviation of the audio frequency is, of course, a function of the initial pulse signal amplitude. If the data are stored on magnetic tape, they may be reduced to an analog trace or punched into IBM cards as a rate referred to real time by means of the automatic data reduction system described elsewhere (2).

4. Applications

The pulse rate transducer was designed to be used primarily as a safety device to indicate when an exercising subject approaches a dangerously high pulse rate. However, the system may have far greater usefulness as a means of continuously measuring pulse rates which change due to variations in muscular activity, conditioning, or environment. Several graphs will be presented which illustrate the transient nature of variations in pulse rate caused by changes in the level of activity or environmental stress.

a. Pulse rate variations produced by changing activity and environment

Changing from a sitting position to a standing position or moving from one environment to another causes noticeable changes in pulse rate.

Any increase in muscular activity will result in a rapid rise in pulse rate at the commencement of exercise. After the initial period of adjustment, often identified with a plateau or asymptote, the pulse rate will continue to increase slowly with time if a high level of stress is maintained (14). Figure 11 shows five transient changes of pulse rate incurred by changing either the environment or the level of muscular activity. The data were obtained at Yuma Test Station using the ear pick-up and the transistorized transmitter to telemeter the information to the field laboratory where it was recorded.

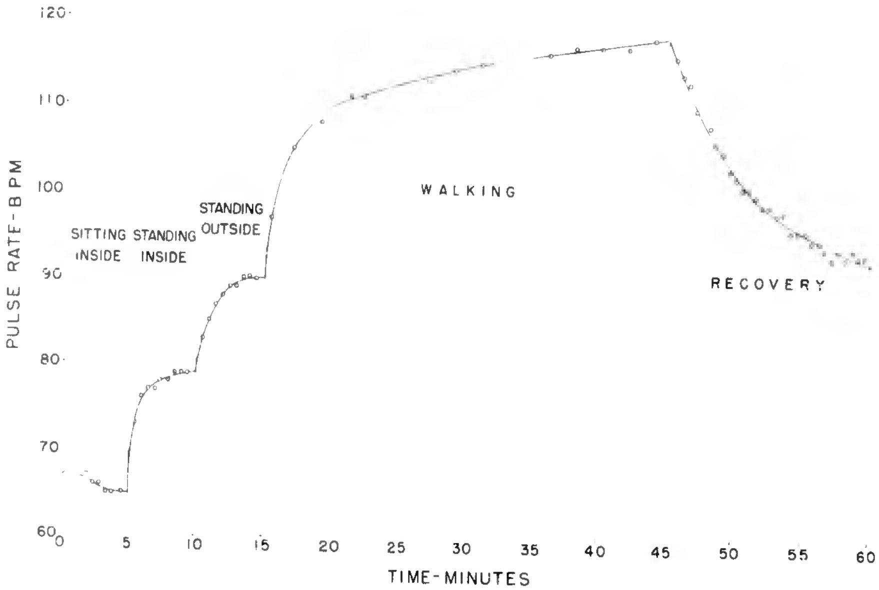


Figure 11. Effect of various stress conditions on pulse rate. Data telemetered by radiocardiotachometer during desert studies.

The first three parts of the test consisted of pre-exercise phases, each of 5 minute duration. During the first phase, the subject sat in the air conditioned laboratory (72°F); then he changed to a standing position inside the laboratory, and in the final pre-exercise phase he stood outside on the test course where the weather conditions were as follows: dry bulb temperature, 81°F; relative humidity, 27%; radiation, 1.06 gram-cal/cm^2/min; and wind, 1 mph. The subject's pulse rate was recorded continuously during these phases, and the data shown on the graph represent determinations made every 30 seconds, by doubling the number of heart beats for 15 seconds before and 15 seconds after each 30-second mark.

During the walking period, the test subject's pulse rate was measureable approximately 25% of the time when his path closely paralleled the antenna. The test course was the perimeter of a large square, approximately 135 ft. on a side. The wire antenna extended the full length of one side of the square. At a walking rate of 3 mph, it took the test subject about 2 minutes to complete each lap of the test course, and the pulse rate was measured for 30 seconds out of every 2 minutes.

After 30 minutes of walking, the test subject remained standing at the beginning of the test course for 15 minutes. His recovery rate was recorded continuously during this period.

This graph shows the usefulness of the radiocardiotachometer as a field instrument for measuring pulse rate without subject and recorder being in physical contact. Small variations in pulse rate due to changing environment or muscular activity can be sensed and recorded continuously for later analysis.

b. Nature of pulse rate response to strenuous exercise

In chamber studies involving monitoring of pulse rates, the hand transducer was generally used if the subject's hands were accessible for the measurement. Figure 12 presents the pulse rates during and after exercise for a well-conditioned test subject in a climatic chamber set for desert conditions. The temperature was 110°F; the relative humidity, 25%, and the wind 4 mph. The test subject walked at 3.5 mph and carried a 15-pound pack.

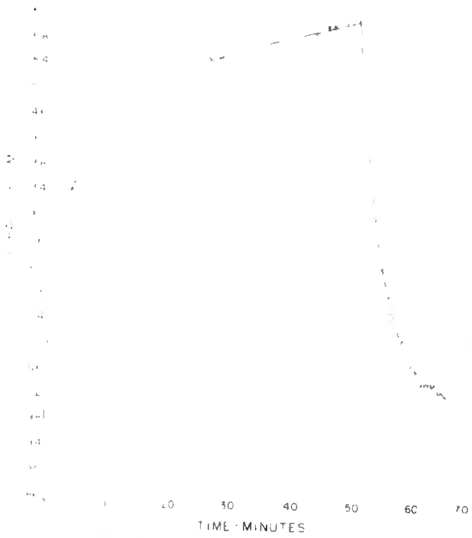


Figure 12. Typical data obtained during and after walking exercise, showing oscillatory nature of the transient pulse rate response to stress.

The graph shows the subject's standing pulse rate at time zero and then every 30 seconds for the first 5 minutes of exercise and every minute for the remainder of the exercise period. At the conclusion of exercise, the subject sat down and his pack was removed from him. His pulse rates after exercise were recorded continuously and actual values for every 30 seconds are presented.

The curve during exercise shows the transient nature of the pulse rate. The rise is very rapid at the commencement of exercise and when it reaches the higher levels it tends to oscillate in steps; thus an accurate determination of the pulse rate is impossible without continuous recording.

c. Pulse rates during Harvard Step Test

One of the most frequently used criterion for determining the physical condition of an individual is the Harvard Step Test (10). Because the pulse rate changes very rapidly due to the intensity of the exercise and because palpation or similar measuring methods are so difficult, only post-exercise measurements were previously used. Figure 13 presents data obtained with the hand transducer while the test subject was doing the exercise. The study was conducted in the climatic chamber at 63°F and 25% relative humidity. A standard 20-inch bench was used and the subject stepped up and down each second for 5 minutes. Figure 14 shows the investigator aurally monitoring heart beats of a test subject performing the Harvard Step Test while at the same time a permanent analog record is being made.

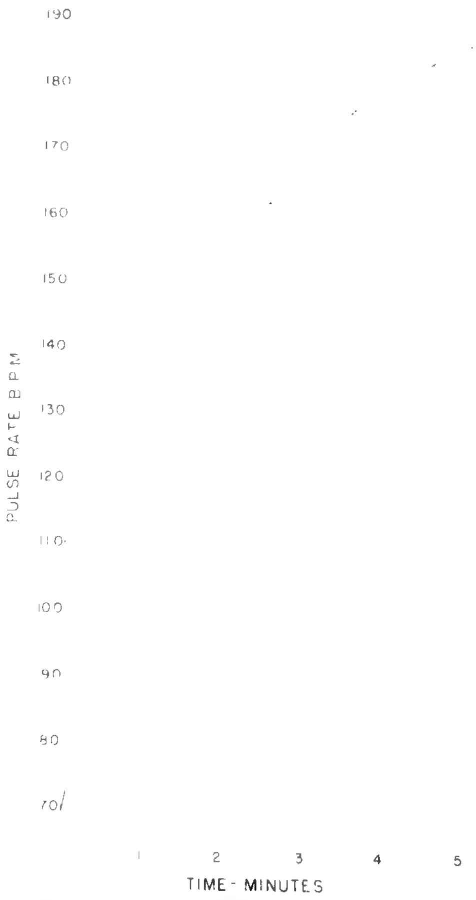


Figure 13. Pulse-rate response during Harvard Step Test.

Part of the pulse rate chart for this test is shown in section C of Figure 7 showing an average pulse rate of 160 B.P.M. taken at approximately the 2.3 minute mark. The amplitudes of the pulse rate pips are not as constant as they are for lighter exercise, but each individual beat is clearly distinct and remains so even when the pulse rate reaches as high as 186 B.P.M.

In such vigorous exercises as the Harvard Step Test, this system is very useful because it can record the pulse beats continuously where other instruments cannot maintain contact with the subject and palpation is impossible without interfering with the exercise.

d. Post-exercise recovery

Although pulse rates during exercise are important in many physiological studies, post-exercise pulse rates are the basis of many indices of physical fitness. Post exercise pulses follow the exponential form (14)

$$PR = A + Be^{-kt} \qquad (1)$$

or expressed in a more interpretive form

Figure 14. Determination of pulse rate during Harvard Step Test.

$$PR = PR_n + (PR_o - PR_n)\, e^{-\frac{t}{c}} \qquad (2)$$

where

PR = pulse rate at time t

t = time in minutes

PR_n = normal pulse or the asymptote of the curve

PR_o = pulse rate at t = o

c = time constant of recovery

e = base of the natural log

Formulation of the curve (pulse rate recovery after exercise) is very useful because it establishes the normal pulse rate, gives the time constant of recovery, and smoothes out irregularities in the data. Time constants are useful to indicate a rate of recovery and to establish the length of time required for the pulse rate to return to normal. (Pulse rate has returned to within 2% of normal at time equal to 4c.)

Figure 15 shows the recovery curve for a test subject who had been walking on a treadmill for 2 hours carrying a 15-pound pack. The temperature was 110°F; relative humidity, 25% wind speed, 4 mph; and the test subject's walking rate was 3.5 mph.

The hand pickup was used to sense his pulse rate during exercise and throughout the recovery period. His pulse rate for the final minutes of exercise was fairly constant at 185 B.P.M. At the conclusion of exercise he sat down; his pack was removed for him, and his pulse rate was recorded continuously for the thirty-minute recovery period. The circled dots are actual values of pulse rate for every thirty seconds and the solid line represents the equation

$$PR = 98 + (185 - 98)\, e^{-\frac{t}{3.4}} \qquad (3)$$

Continuous recording is again important in pulse rate recovery in order to obtain accuracy of formulation. Singular readings can be very misleading because the pulse rate tends to oscillate as it approaches normal, as seen in the last 20 minutes of Figure 15. The graph further shows that extreme caution should be taken when using pulse rates after the cessation of exercise as a criterion of the pulse during exercise, because of the fast rate of change of pulse when exercise is concluded, in this instance 23 beats per minute during the first minute.

5. Discussion

As monitoring devices, the instruments described above have proven reliable in a variety of physiological investigations. Non-ambiguous, physiologically-significant records have been obtained from all test subjects encountered without any need to compensate for individual differences. The system consisting of a hand-type transducer with analog readout is considered most reliable since, even in the presence of strong dicrotic notch variations, the characteristic shape of the pulse signal is easily identified. Although the audio readout is most convenient for fast spot checks on individuals suspected of experiencing difficulties, audio discrimination between primary and strong secondary pulses is occasionally not possible at high pulse rates.

It was shown in the sample graphs that calculations which involve the average pulse rate taken over a discrete time interval are best made from continuous registration of pulse rate because of the characteristic oscillation which occurs as the rate approaches an asymptote (during exercise or on recovery). The permanent analog record provides a high degree of resolution for such determinations; however, the time required for manual data reduction of the record is considerable. The same data can be obtained by recording the audio signals on magnetic tape and playing them back through automatic data-reduction facilities. The output from the radio telemeter for pulse rate is always processed in this way. Readout from this system can be secured as the elapsed time of 20 heart beats, stored on IBM cards, as an analog recording, or printed on tape and referred to real time.

Figure 15. Pulse rate recovery curve taken after 2 hours of walking with 15 pound pack.

The pulse shape of light intensity fluctuations occurring with each heart beat is a function of the changes in average vascularity of the flesh and the blood pressure. The technique of transillumination has been used by Hertzman et al (9,13,15), to measure blood flow. Furthermore, Franklin (5) shows a strikingly identical wave shape for aortic blood flow for each heart beat of a dog recorded by means of a sonic flowmeter. Although no attempt has been made to calibrate the devices described in this paper, it is possible to identify local changes in vascularity which occur as pulse amplitude variations. This application is similar to that reported by Guttman (8) who has developed a photoelectric ring plethysmograph useful in measurements on sedentary subjects.

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