A Brief Summary of Developments for the More Extensive Application of Electrocardiography

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Thesis for Doctorate of Medicine

by

William Thornton

This is a somewhat chronological description of the development and construction of instruments by the author during the past four years with some examples of their application.

The electrocardiogram is one of the more valuable procedures in the study of heart disease. It is, like most other present-day laboratory procedures, limited by technical processes involved to studies made under restricted physical conditions. Formerly the electrocardiogram could only be recorded from quiet, supine patients for a relatively short period of time. This type of study gave unique information about permanent or slowly changing states of the heart. It was early recognized, however, that many abnormal states of the heart, primarily arrhythmias and ischemias, appear only transiently or under other than basal conditions. Also, only a tiny fraction of the total number of the heart's beats could be sampled. This did not allow an adequate time profile and the effects of a normal environment could not be studied.

These limitations have long been recognized. Since 1941 Masters and others [1, 2, 3] have used "exercise tolerance tests" to evaluate the effects of one stress, exercise, on the heart. It was possible to record the electrocardiogram (ECG) only after cessation of this stress. Until about 1950, this procedure was one of the few attempts to apply the ECG under other than the usual artificial conditions and for very brief periods.

In 1959 we designed one of the first practical radio transmitters for the recording of an ECG from a subject without wires. Prior to this time units had been demonstrated by Holter[4, 5, 6], Beenken and Dunn[7], Hanish, and others but they had a variety of severe technical limitations.

This system consists of a small (1½" x 3" x 3½"), transistorized, VHG, FM transmitter powered by rechargeable batteries with an operating time of 72 hours or more per charge. The input is normally bipolar without the

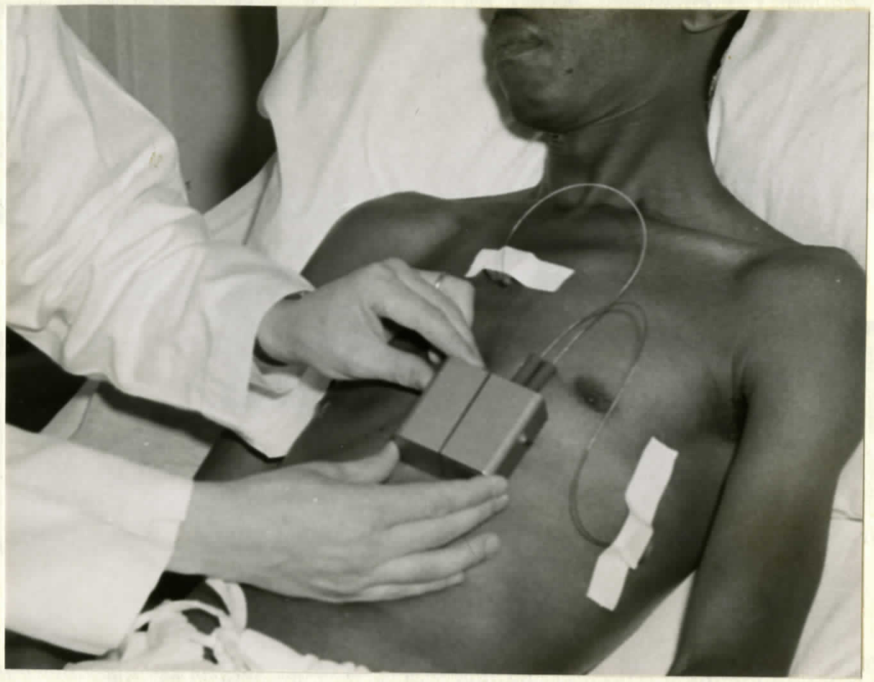


Figure 1. The transmitter and electrodes are being placed on a patient. The transmitter is usually carried in a shirt or gown pocket.

necessity for an indifferent electrode but can be connected into any desired lead/electrode configuration. The signal is received by commercial FM tuners at distances up to 150 feet indoors and 900 feet outdoors. Fidelity of transmission is equal or greater than achieved by the standard electrocardiographs. The signal that is received may be recorded directly or observed on an oscilloscope.

The goal of the initial design of this unit was to improve the ease and quality, particularly as regards to interference, of electrocardiographic monitoring in operating rooms.[8] For various technical reasons such a radio transmission system is practically immune to AC interference, has no shock or explosive hazard, greatly reduces other artefacts, and eliminates the connecting wires. After several years' usage, this method of monitoring has become the method of choice and is now used in all operating suites here. This initial experience proved several points: (1) routine transmission of the ECG by radio was possible, (2) it had definite advantages in spite of being a theoretically more complex system, and (3) it was simple and reliable enough for use by medical personnel.

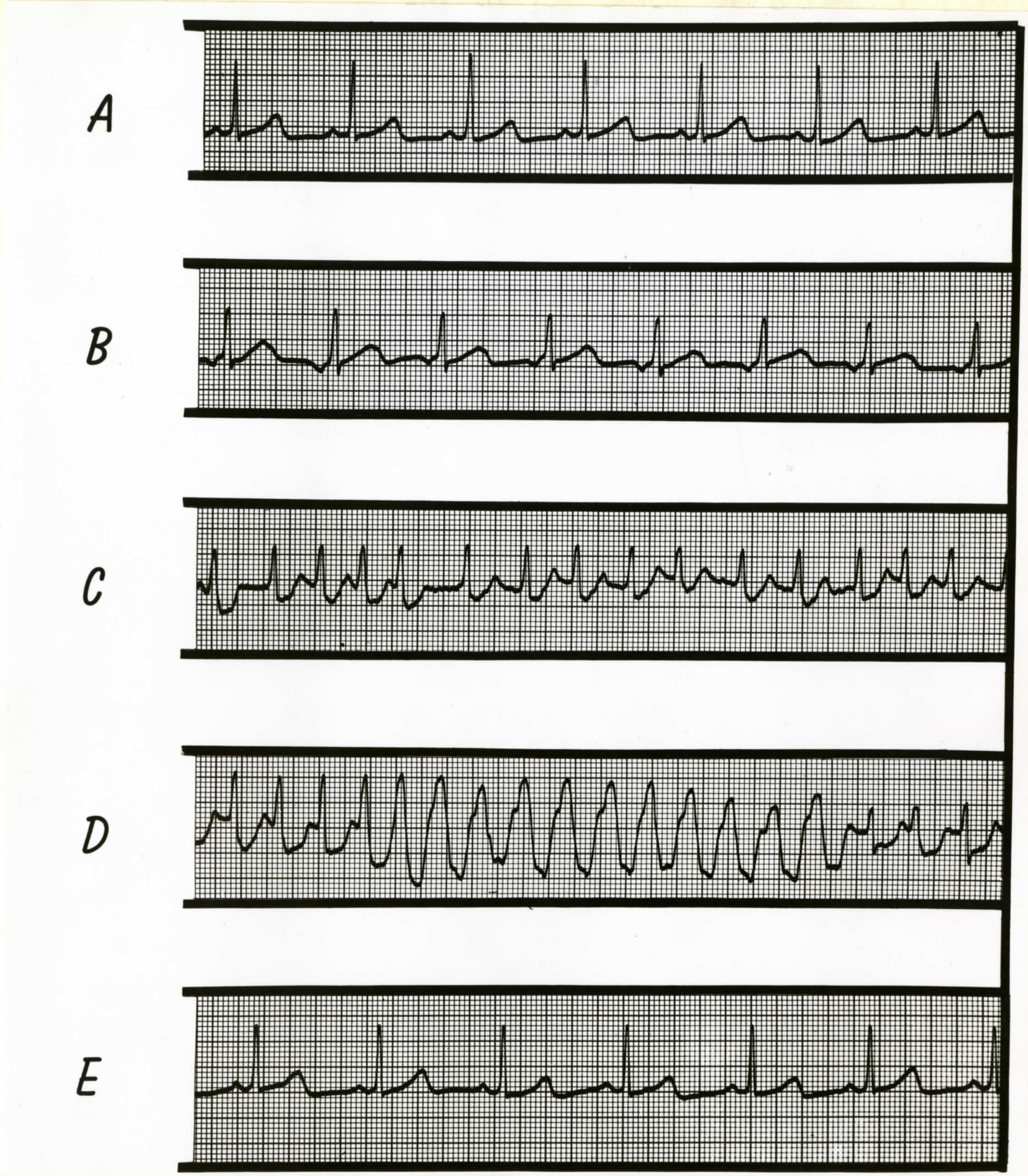


Figure 2. Serial telecardiographis from a patient undergoing craniotomy. The abnormalities in B, C, and D occurred during hypotension secondary to blood loss and was corrected as seen in E by replacement of this loss.

A number of advantages of a safe, simple, reliable monitoring system for the routine use in surgery and anesthesia were demonstrated. A wide variety of arrhythmias have been observed during anesthesia and surgery as well as more serious conditions such as a rare infarct. The advantage of early detection, usually prior to changes in other signs, does not require comment.

A somewhat similar situation where benefits have accrued from monitoring by radio telecardiography is cardiac arrest with closed chest resuscitation. The conventional electrocardiograph tolerates the touching and movement of the patient very poorly and may be damaged by the defibrillator voltage.

Other applications include the monitoring of patients in critical situations. The elimination of wires connected to patients and rapidly ensnarled by patients, personnel, and equipment makes such monitoring practical.

After demonstration of telecardiography in anesthesia, Dr. Bogdonoff at Duke and Drs. Craige and Gibson here, became interested in the clinical and research applications in cardiology. Additional refinement was required. Although the radio system is inherently free of electrical artefact, it was still limited by the information picked up and distorted by the existing electrode system; i. e. the connection to the patient had to be improved before the advantages of telecardiography in allowing complete freedom of movement and activity could be realized. Needles (#25), except for the obvious disadvantage, seemed ideal. They were a marked improvement over former electrodes and allowed reasonable amounts of movement such as walking with relative comfort but became 'noisy' in a few hours and were prone to become infected. Bentonite and a variety of pastes were next tried with electrodes separated from the skin by the paste and the whole electrode-skin area firmly immobilized by tape and bandages. These meth ds gave some improvement and allowed rather vigorous exercise but they lasted only a few hours. Bentonite, the best of the pastes, was allergenic and produced striking wheals after prolonged contact. The basic problems of electrodes devolved into: separation of the metal electrode from the skin to prevent transient contact potentials by movement; establishment of a low impedance contact to the skin by a non-irritant paste or liquid; and affixing the electrode to the skin. We finally evolved a liquid junction electrode affixed to the skin by commercial cement.* These electrodes may be left in place for over a week without deterioration of performance or the subject's skin. A great deal of effort by a number of investigators[9, 10, 11] has been spent on electrode configuration for it is one of the key problems in successful telecardiography from active patients. The liquid junction electrode meets most of the requirements for an ideal electrode and now seems to be accepted as the best of the lot.

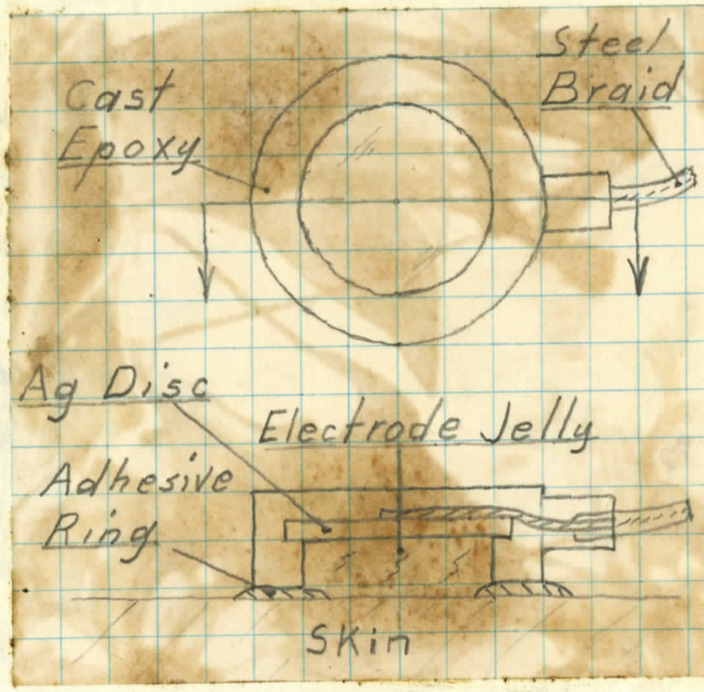


Figure 3. Electrode construction and application.

A second and related problem is reduction of interference by electromyographic potentials from somatic musculature. Much of the energy in the EMG spectrum lies above the electrocardiographic spectrum in frequency.

*Weldwood Contact Cement

By sharply limiting the frequency response[12] of the system to no more than that required for the transmission of the ECG, approximately .1 to 100 CPS, one can discriminate against much of the noise. Another reduction can be made by locating the electrodes on the body such that the ratio of ECG signal to that of EMG is a maximum. The location must be such that the essential features of the ECG are maintained; i. e. the P, QRS, and T complexes must be of reasonable amplitude and a reasonable percentage of S-T depressions must appear at the site chosen. The lead which we felt most nearly satisfied this requirement placed one electrode over the base of the heart (sternal angle) and the other over a rib at a point nearest the apex as estimated by the point of maximum impulse (see Figure 1). With this arrangement, the only somatic muscle mass which contributes an appreciable EMG voltage is the pectoralis. This lead is not standard and contains components of II and V-5. See Figure 4.

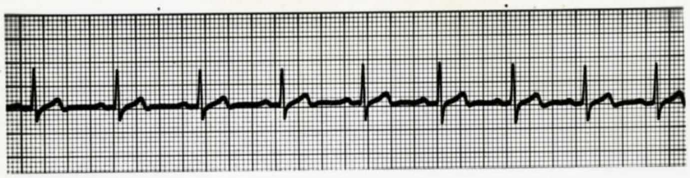
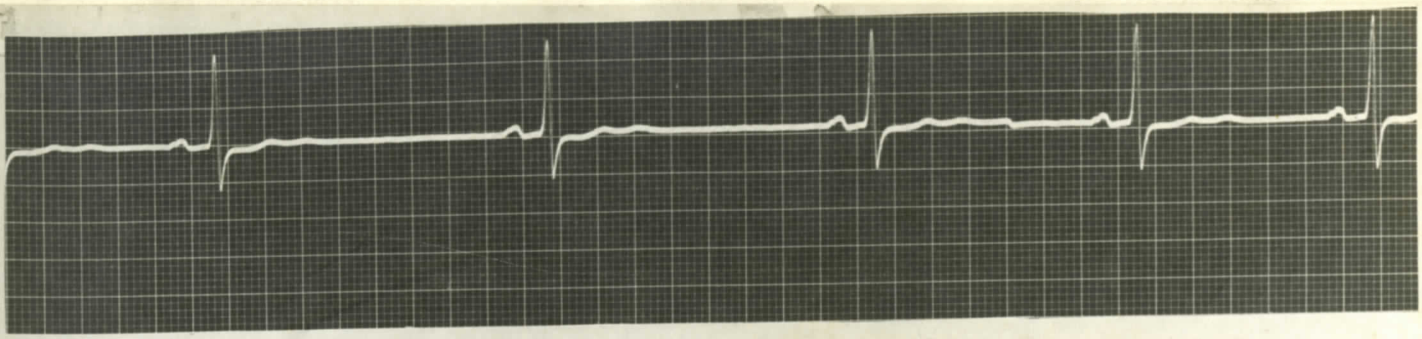


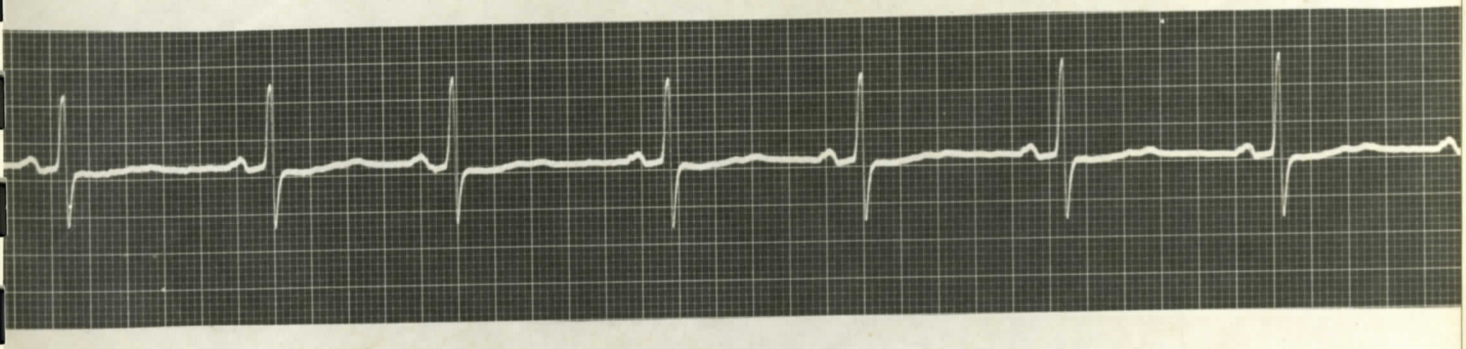
Figure 4. Normal control tracing from Base-Apex "T"elecardiographic lead.

With the electrode arrangement described above, electrocardiograms have been recorded from subjects engaged in a wide variety of activity including Marines on combat maneuvers and competitive swimmers in practice.

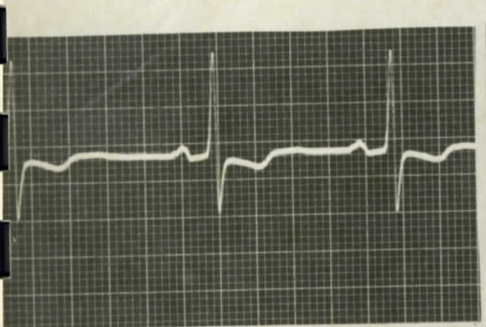
The early clinical observations using the transmitter-receiver described and an oscilloscope for observation indicated that further design and development of apparatus for this work would indeed be warranted. See Figures 5, 6, and 7.) Some of the early phenomena observed included: the docu-



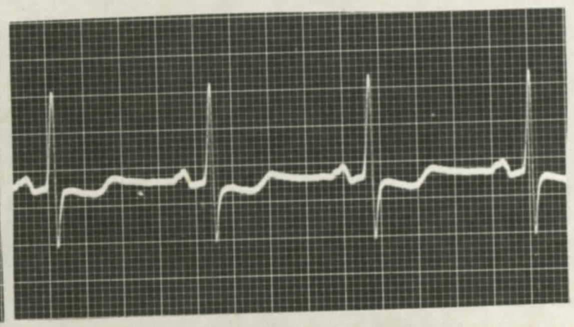
A. Control, lying quietly 4:30



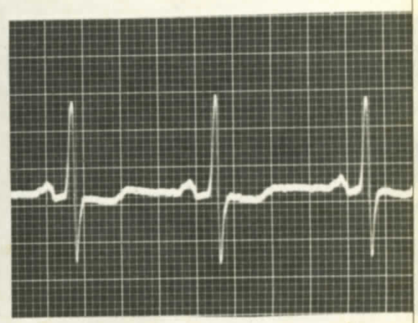
B. Exercise 4:31



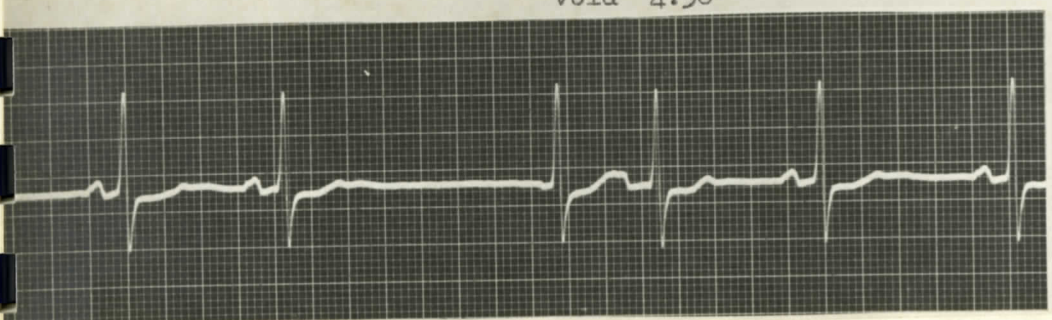
C. Onset of angina 4:35



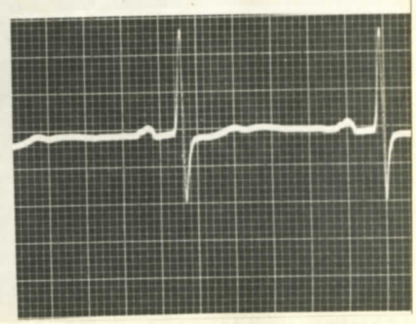
D. Continued angina with urge to void 4:36



E. Voiding 4:37

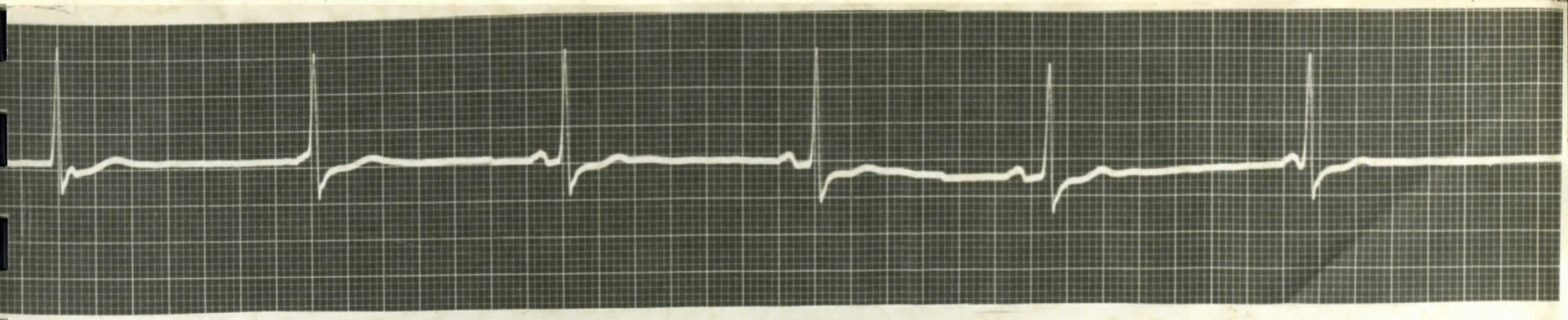


F. Sitting on bed 4:39

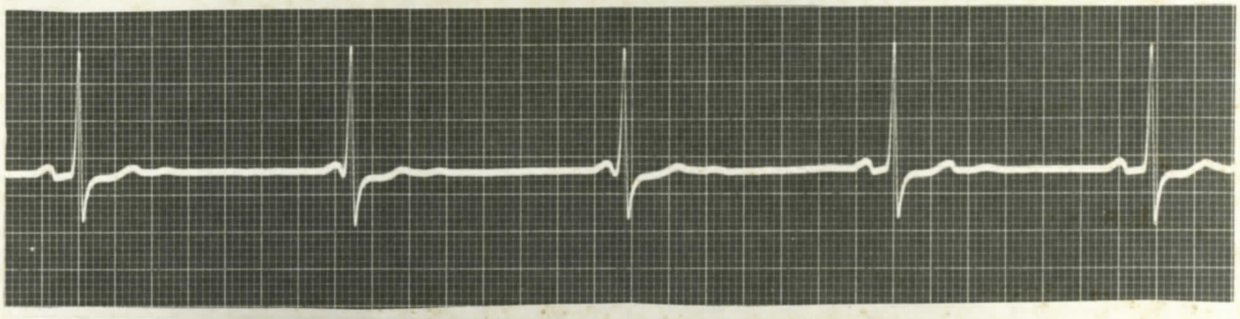


G. Lying quietly 4:44

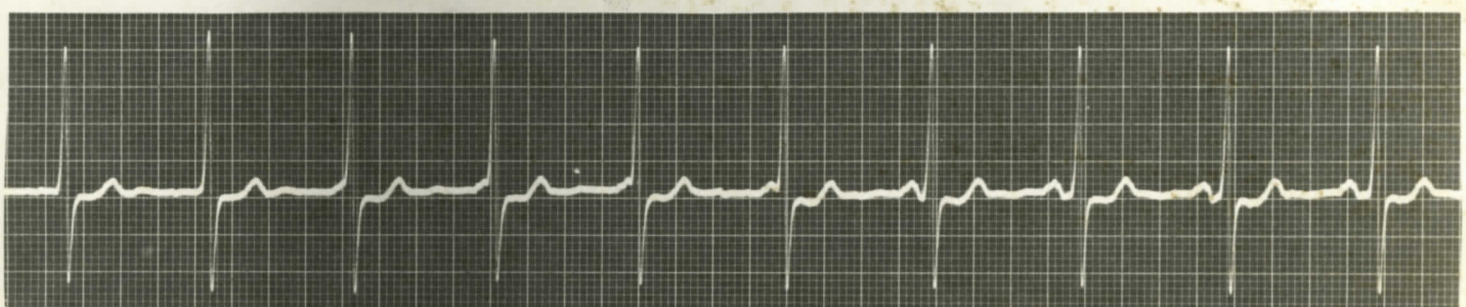
Figure 5. Telecardiographic records from J.T.D. 69 year old retired civil engineer with history of angina. Ischemia is documented by S-T depression in C, D, and E associated with exercise. T lead with standard calibration was used.



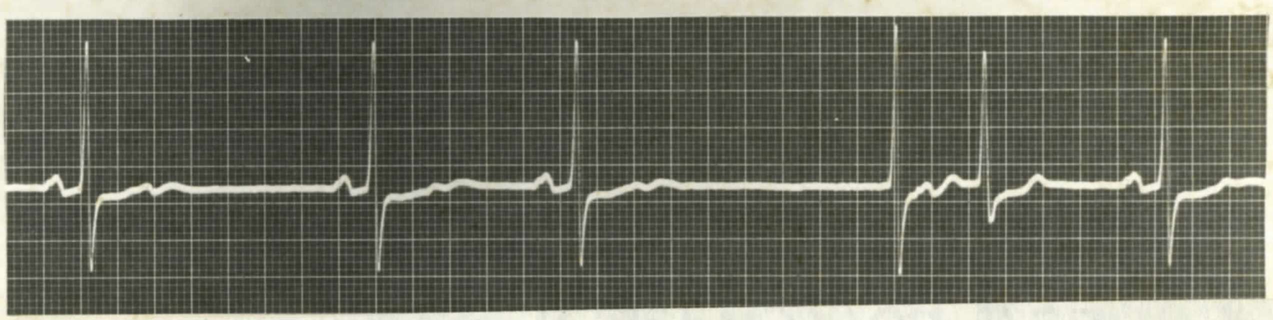
A. Patient sitting quietly 7:30



B. Urge to void after smoking for 4 minutes 7:34

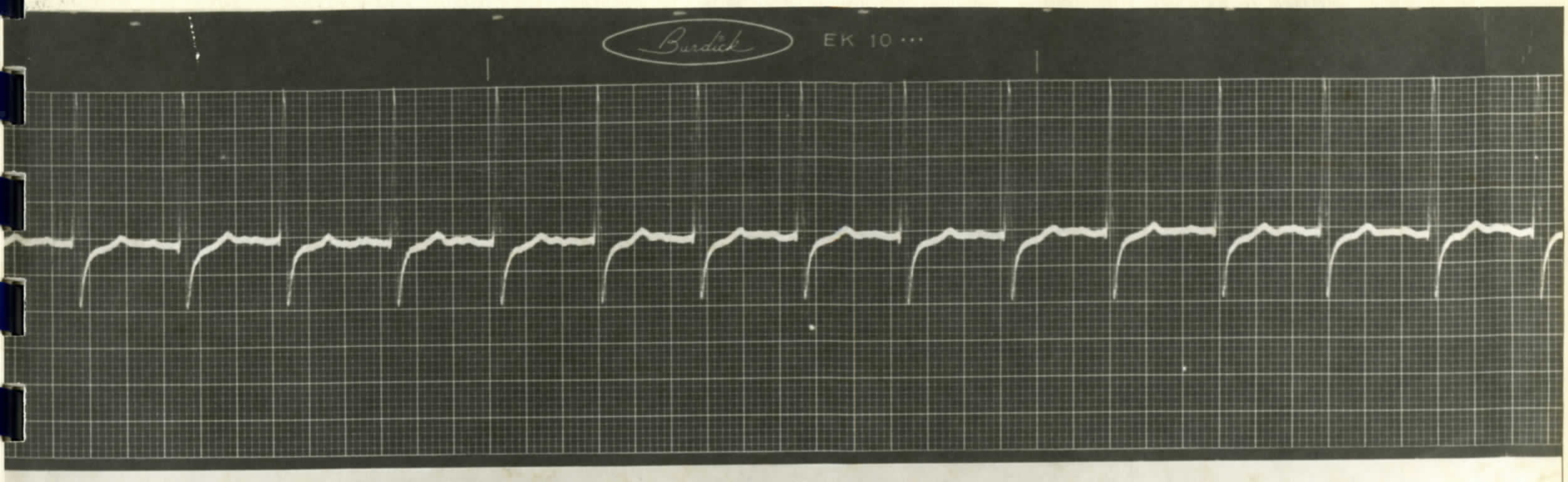


C. Voiding 7:35

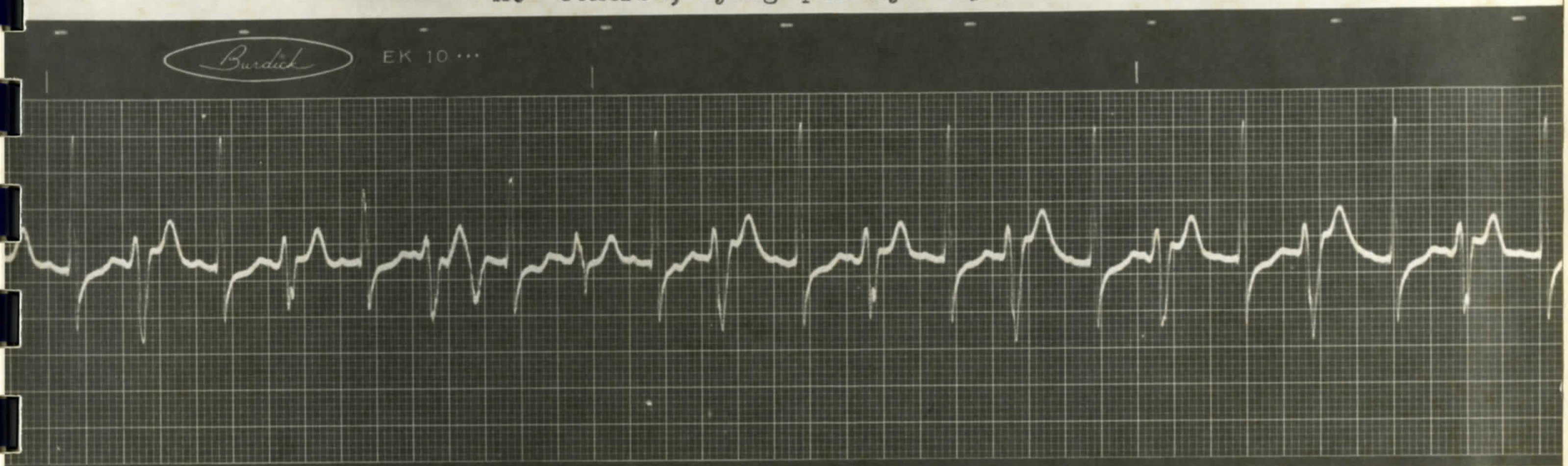


D. Sitting quietly 7:37

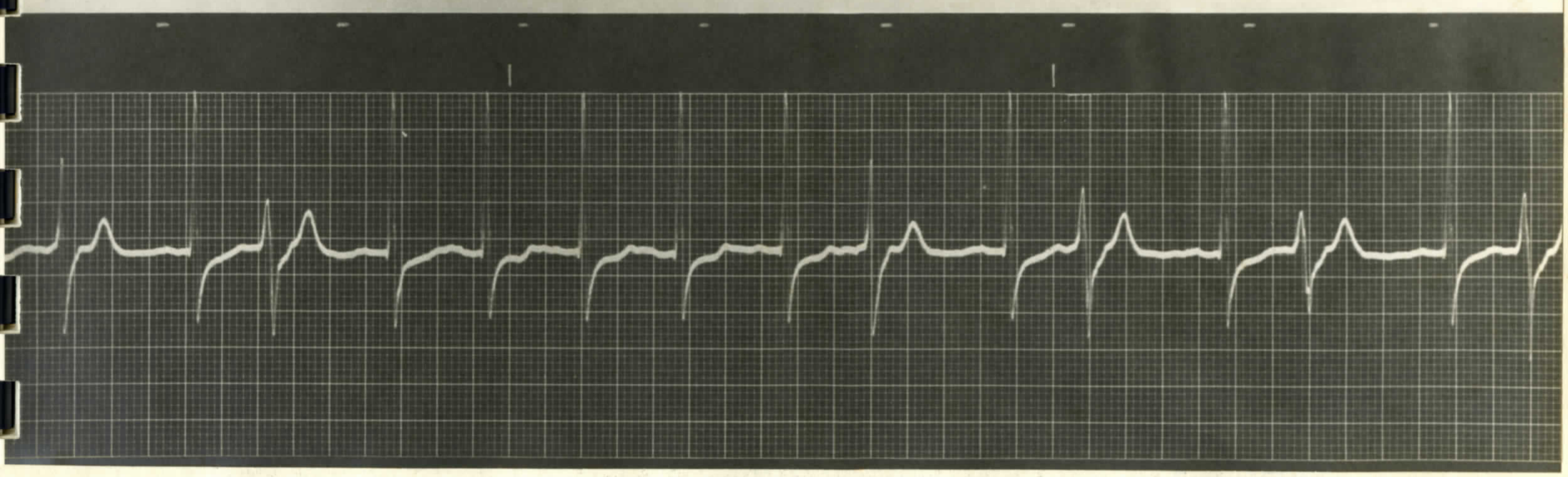
Figure 6. Additional telecardiographic records from J.F.D. Note A.V. dissociation coincident with smoking and slight S-T depression while voiding. QX-QT ratio also prolonged in A and B.



A. Control, lying quietly 2:30



B. Vigorous exercise for 3 minutes 2:33



C. Lying quietly 2:34

Figure 7. Telecardiographic records from patient with infrequent atypical angina during exercise. Note bigeminy in B during exercise and immediately after cessation in C.

mentation of cardiac abnormalities in previously undiagnosed patients that had been studied for years by conventional methods; a surprising variety of arrhythmias and evidences of ischemia in patients during stress or even during normal activities; striking changes produced by drugs or the course of disease often unseen with conventional methods; and many interesting variations in "normals" under every day conditions.

One requirement for clinical studies was some method of continuous, unattended recording and storage of the ECG. To be practical, some way to indicate the significant points for further study in such a record was also required. The only currently available method to meet the requirement for storage of large amounts of such data is by magnetic tape. Commercial instrumentation recorders capable of this are large, complex, and very expensive.

Ordinary audio frequency tape recorders have a nominal frequency range of 50 to 10^4 CPS while frequencies down to .1 CPS are required for adequate reproduction of the ECG signal. An audio frequency signal at, say 2.5×10^3 CPS may be varied in frequency as a function of amplitude of the ECG signal (frequency modulation). This varying audio frequency may then be recorded by ordinary tape recorders. By choosing suitable modulation characteristics, small, relatively inexpensive recorders may be used. The original signal may be recovered by a reciprocal process of converting frequency into amplitude (demodulation). A simple FM sub-carrier oscillator and demodulator was constructed. This allows the recording of up to eight hours ECG on a single seven-inch reel of tape. Exact reproduction of the ECG is achieved in this fashion. The reproduced signal may be recorded directly on an ordinary ECG, viewed on a scope or processed by a computer. Most of the ECG's in this paper are reproduced after such storage on magnetic tape.

The study of hours of ECG records is physically impossible by manual means. Some form of continuous automatic analysis was required to make a practical system.

The first step in the development of such a system was the design and testing of a reliable cardio-tachometer which would give a continuous record of the heart rate. This tachometer consists of a selective amplifier which passes only the QRS complexes and rejects other components of the signal. Each QRS complex is then converted to a standard current pulse. These standard pulses are averaged over a sliding fifteen-second epoch and the resulting current drives a recorder or meter. The output is a direct and linear function of rate.

It was assumed that transient abnormalities in the heart would produce a change in rate. By synchronizing the magnetic tape counter and this rate record, points that warranted investigation because of rate changes could be recorded from the tape as an ordinary ECG record and studied in detail. The record of rate alone was of importance in a variety of conditions. For example, Drs. Bogdonoff and Ira, using this equipment, did studies on the heart rate in thyrotoxicosis and in individuals undergoing a variety of normal stresses.[13] The sleeping rate record is quite valuable in the diagnosis of thyrotoxicosis and particularly in the differentiation of this from hysteria (see Figure 8). It is interesting to note that prolonged rates of 185/min were observed in presumably healthy young house officers presenting cases. This rate is the cut-off point of environmental tolerance testing in the Marine Corps. Professors presenting cases also developed similar tachycardias.

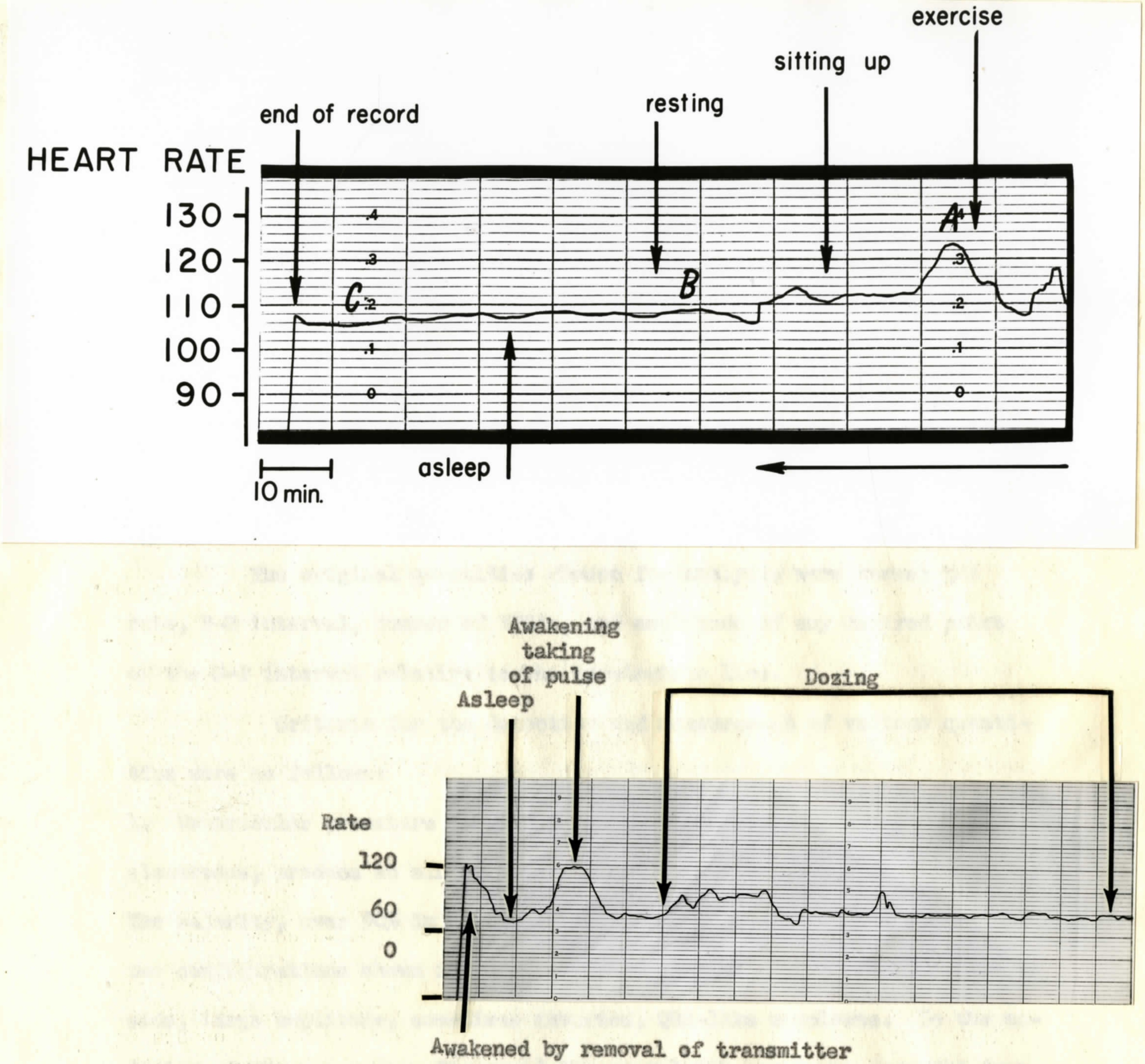


Figure 8. Comparison of heart rates obtained by telecardiography and a cardiotachometer from typical patients with hysteria and thyrotoxicosis.

The ~~upper~~ lower record is from a 21 year old white female with a history of hyperactivity, palpitation, sleeplessness, and slight weight loss. Pulse rate was always recorded as 110 or greater. Note the normal sleeping rate and the tachycardia produced by being awakened to having her pulse taken.

The ~~lower~~ upper record is from a 60 year old patient found to be thyrotoxic whose symptoms were primarily cardiovascular. Note the elevated relatively flat record that is sustained during sleep.

It was decided in the summer of 1961 to attempt to develop a computer for the analysis of the extended electrocardiographic record for other features in addition to rate.[14] This had been attempted by other investigators with indifferent success.[15] Without exception, they used very large, complex, and expensive general purpose digital computers programmed in various fashions. It was felt that a simple, small-scale, specialized hybrid computer with a capacity for unattended detection and measurement of various quantities of the ECG would be of value to the clinician and researcher.[16]

The original quantities chosen for analysis were normal QRS rate, R-R interval, number of VPB's, and amplitude of any desired point of the S-T interval relative to the isoelectric line.

Criteria for the detection and measurement of various quantities were as follows:

1. Ventricular premature beats, depending on the focus relative to the electrodes, produce an almost infinite variation of the basic configuration. The majority, over 90% in a sample population of patients, approximated the two configurations shown in Figure 9. The characteristic features were wide, large amplitude, sometimes inverted, QRS-like complexes. In the majority of the cases (see Figure 4) the normal QRS complexes recorded from the base-apex lead in our telecardiographic system are predominantly upright and contain little or no negative component. In this lead system, any large negative QRS complex is detected and counted as a ventricular ectopic beat. See Figure 9. In addition, the width of all upright complexes is measured at 1/3 amplitude. Those wider than .05 sec. are classified as VPB's and also counted. Any complex more narrow than this is considered normal and actuates the cardio-tachometer to give heart rate.

2. R-R interval is simply the period of time between two successive QRS complexes and is measured by allowing a voltage to rise from 0 at the end of each QRS complex and measuring this voltage at the beginning of the next complex. The result is a series of lines whose level above the base line is a measure of the length of time of the interval. See Figure 10.

3. Measurement of the S-T level is shown in Figure 11. The level of the segment between the end of the P and the beginning of the Q is considered isoelectric and its amplitude above base line is measured and stored. The amplitude of the S-T at any desired time (ΔT) following the J point is measured and compared to the isoelectric point. The difference is a measure of depression or elevation. Measurements are made on a beat to beat basis to eliminate error from base line shift. The differences are then averaged over a sliding thirty-second epoch and the resulting voltage is a direct measure of the amplitude of the chosen portion of the S-T segment or T wave.

The three quantities most often used are rate, number of ventricular ectopic beats, and S-T depression or elevation. These quantities are recorded on a multi-pen recorder as shown in Figure 12.

A block diagram showing the arrangement used for the recording, storage, and analysis of the ECG is shown in Figure 13. As commonly employed, the transmitter is placed on a patient who is then free to indulge in normal activities or programmed studies in his room or ward. The receiver, recorder, and an oscilloscope for monitoring--all mounted on a small dolly--may be left unattended and placed outside the room or ward. See Figure 14.

After the study is completed, the magnetic tapes containing a continuous record of the ECG are played back and automatically analyzed, as described, by the computers. Any desired portion of the ECG record may also be written out on a conventional paper tape for detailed study or record. Some typical records are shown in Figures 15 and 16.

In spite of the obvious limitations of the computer, this unit coupled with radio telecardiography and magnetic tape recorder has provided a unique tool for the study of many conditions including the following:

1. Prolonged study of the effects of environments on individuals.
2. Study of the effects of medication or other treatment.
3. Diagnosis of intermittant conditions which are often difficult to document by previous methods.
4. Study of individuals suspected of disease by their reaction to exercise tolerance tests or other controlled stresses.
5. Monitoring of patients in critical situations or during surgery, dialysis and other procedures.
6. Monitoring of patients in situations where ordinary methods are precluded such as during hypothermia or in respirators.
7. Any situation in which prolonged recording and analyses of the ECG is required.

Various versions of the devices described have been supplied to several institutions and are being used for a variety of studies including diagnosis, exercise tolerance studies, effects of psychic stress, effects of heavy labor including farm labor, and monitoring in a variety of situations.

It is hoped that the real significance of this device is that it and similar devices by others herald the development of a new breed of medical instrumentation--instrumentation which will allow the study of man in all situations and for lengths of time sufficient to observe the development and treatment of disease in man. This will be in contrast to being limited, as at present, to a few sparse restricted samples of data or to the study of artificially induced disease in species other than man for lack of adequate methods of study over prolonged periods.

Many individuals have given aid and encouragement in this work including W. Algary, Dr. E. Corday, Dr. E. Craige, W. Creech, Mrs. Judy Cryer, Dr. D. Davis, Dr. T. Gibson, Dr. A. Masters, and Dr. J. Rosenfeld.

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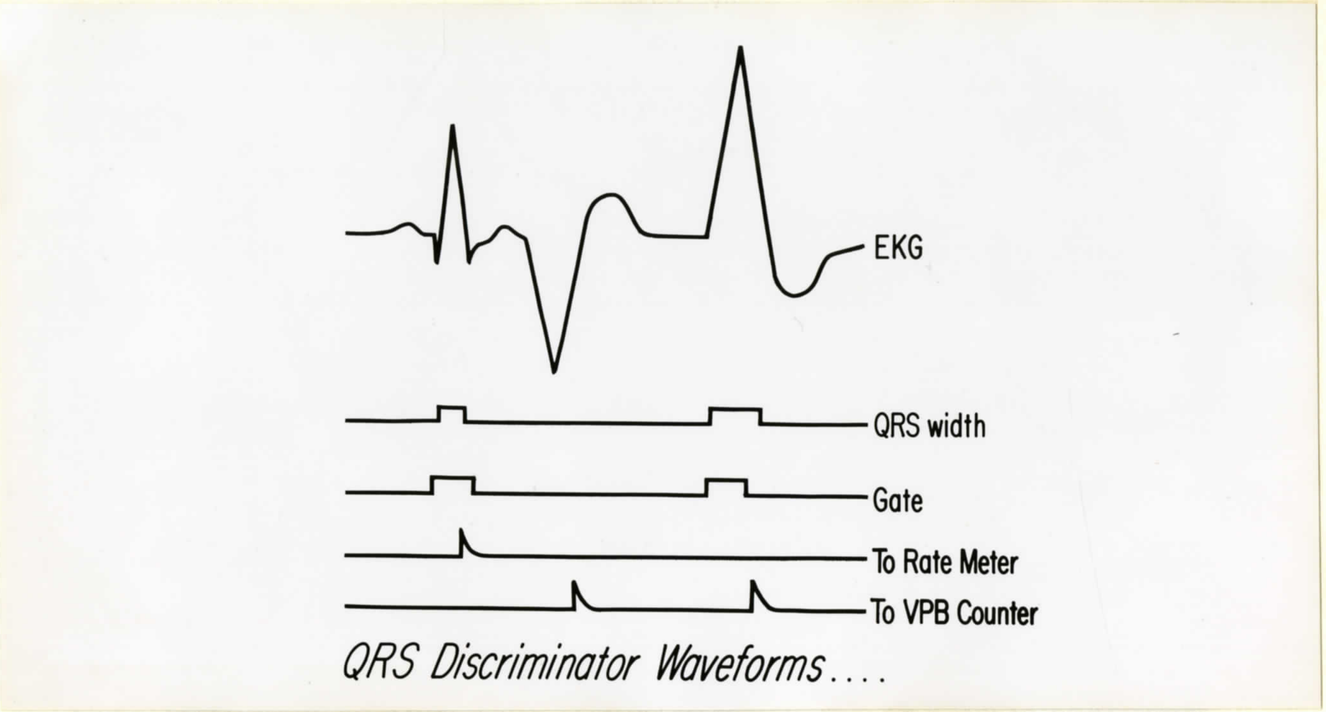
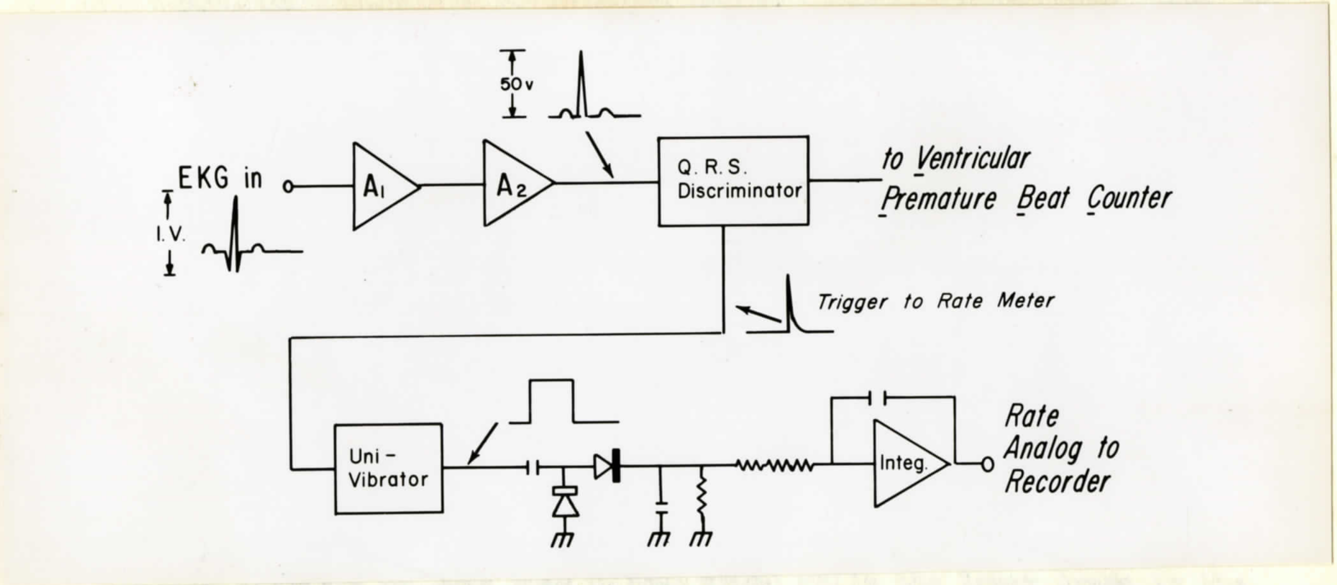


A. Idealized ECG Record showing a normal QRS followed by two VPB's from different foci with the waveforms they produce in the computer.



B. Block diagram of normal QRS counting circuit and discriminator with associated waveforms.

Figure 9.

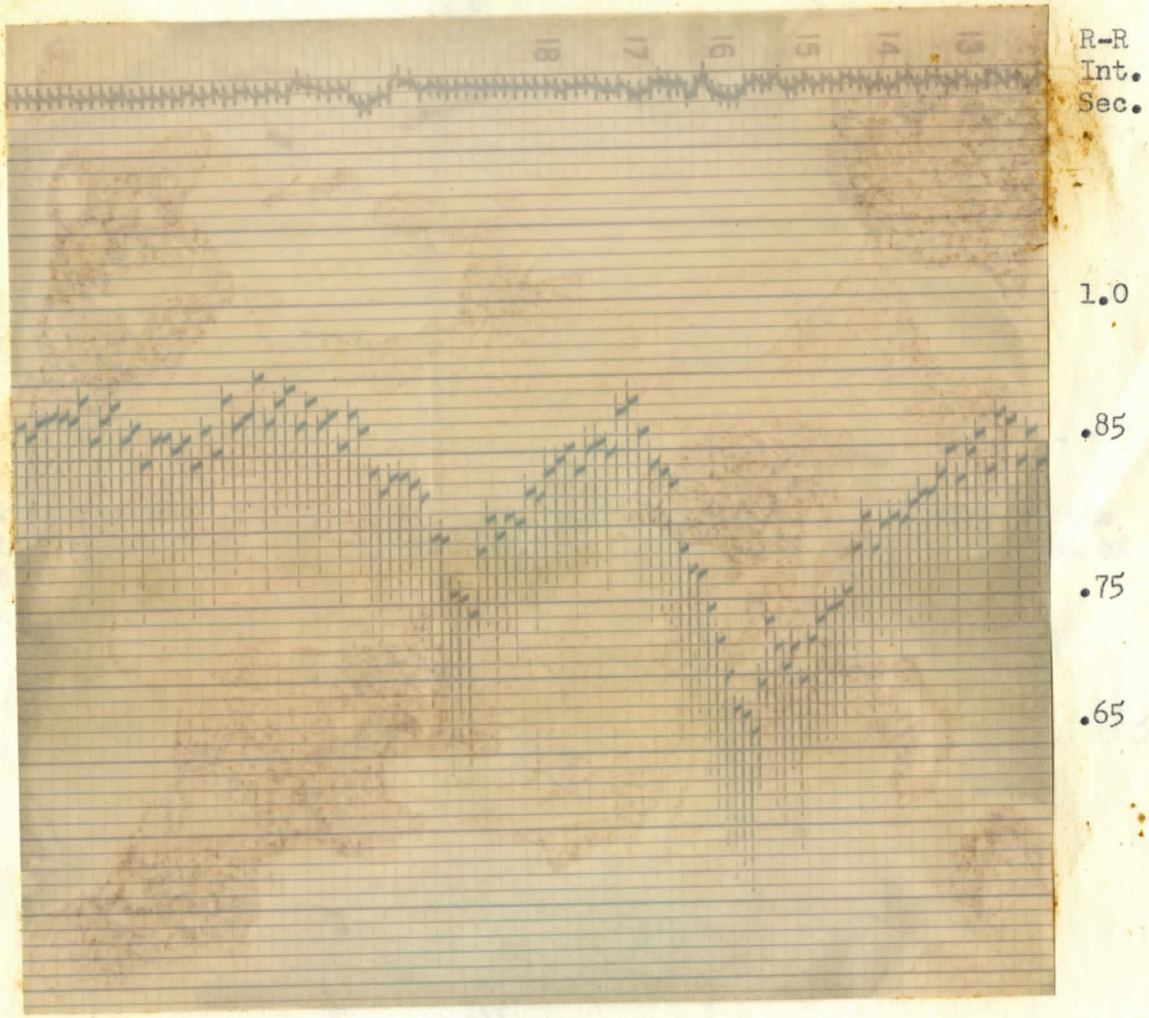


Figure 10. Record from R-R meter. The upper trace is an ECG by telecardiography recorded at less than normal speed while the lower trace is the computed R-R interval of each preceding beat. Small variations in rate are easily and immediately appreciated. This method is especially useful in study of rapid changes induced by environmental phenomena.

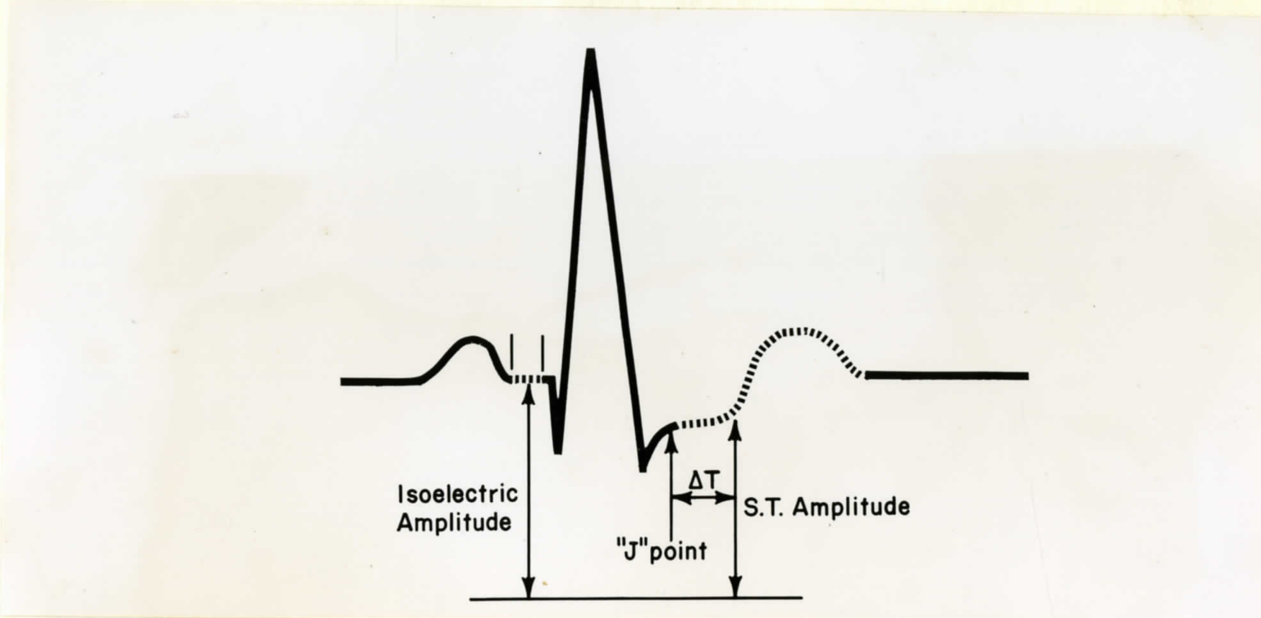
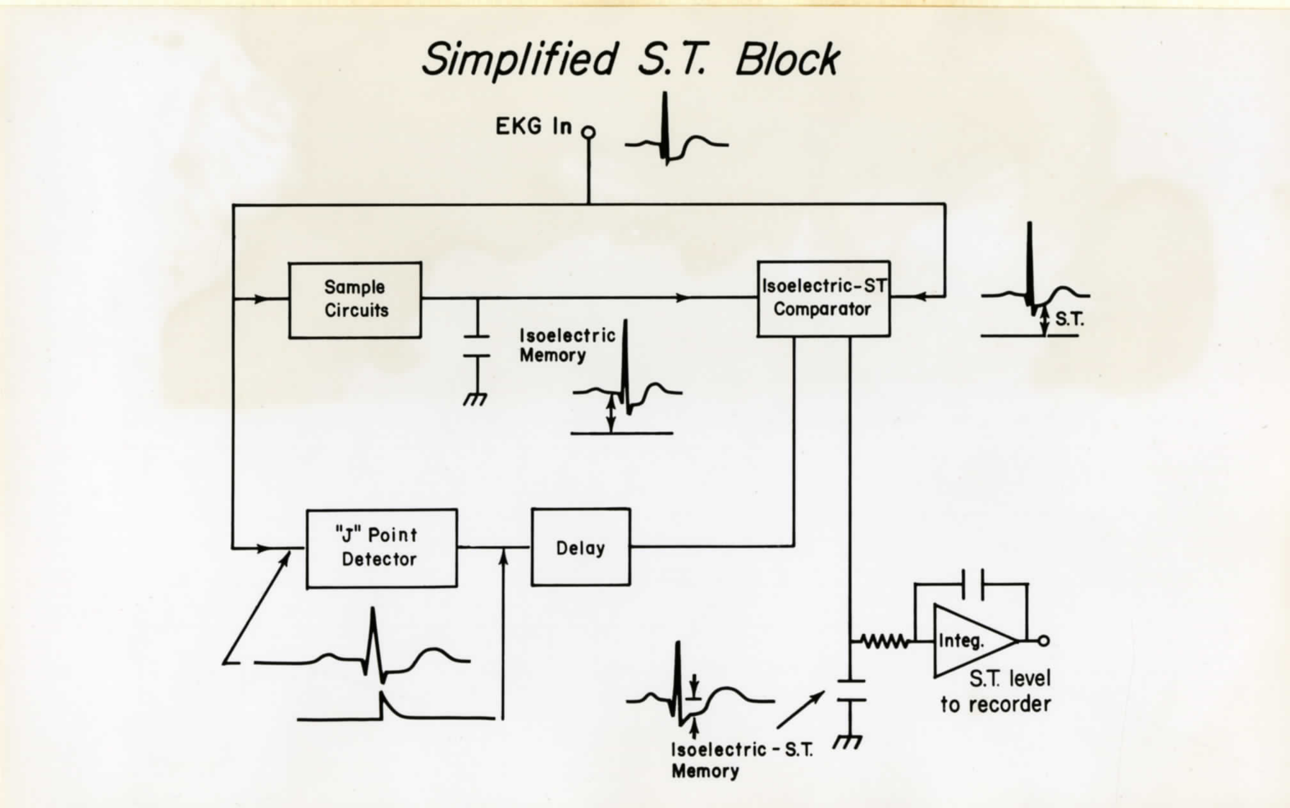
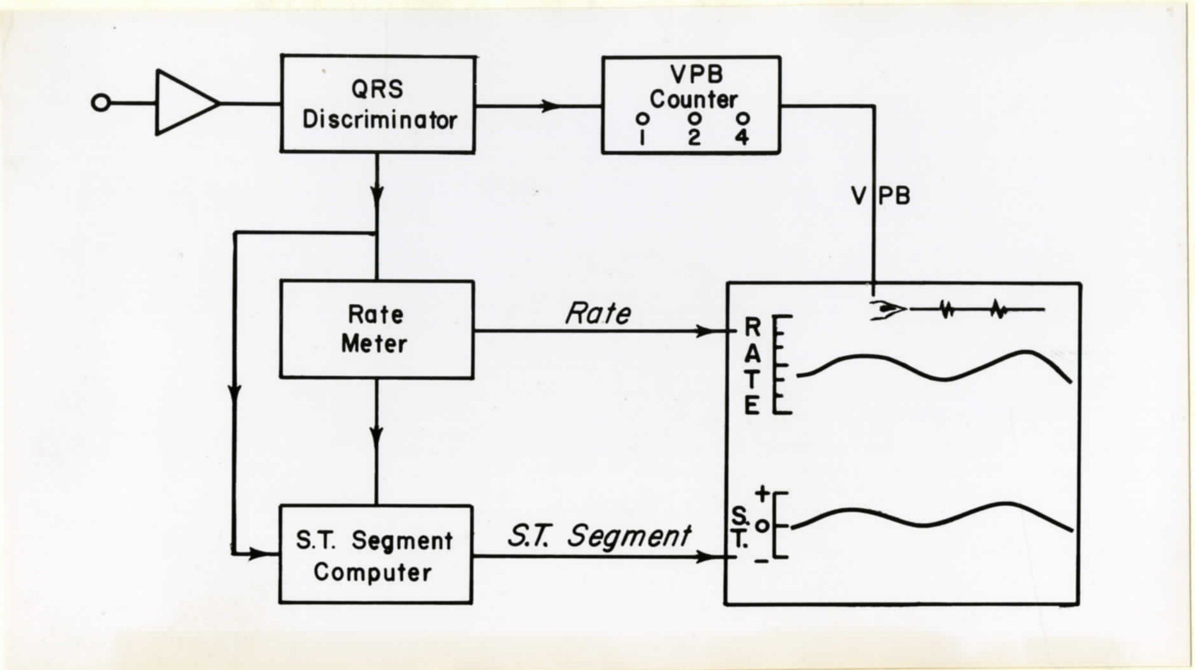


Illustration of quantities involved in the measurement of amplitude of the S-T interval. T may be set to measure at any point from "J" to the end of the T.

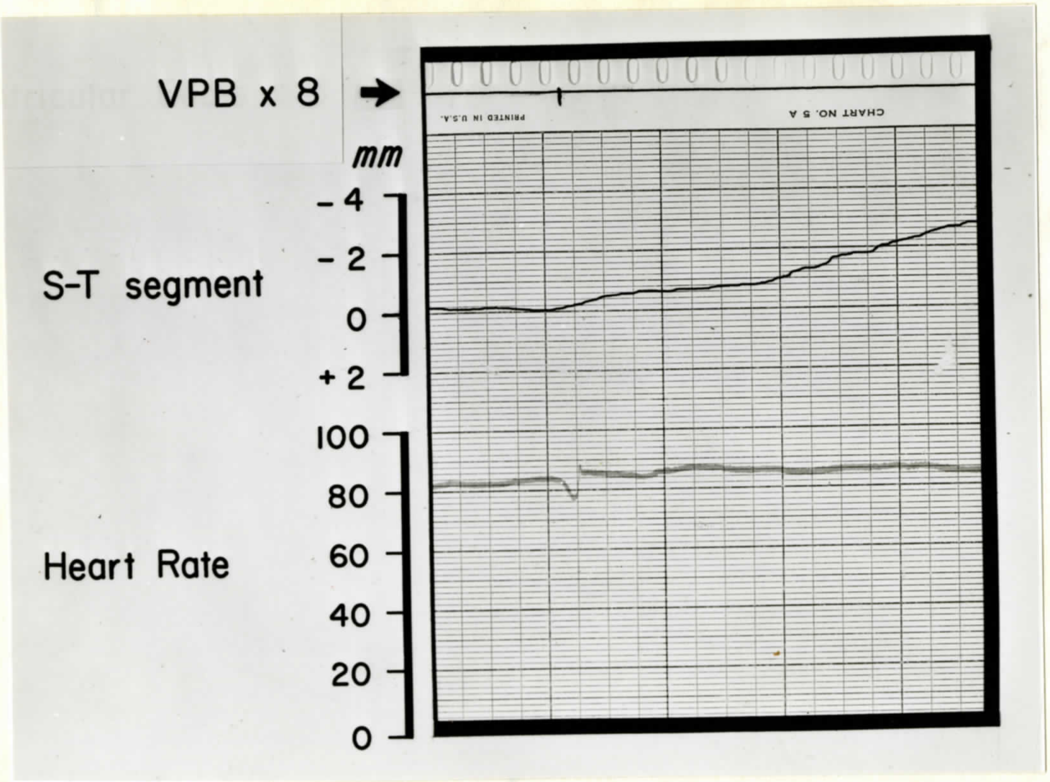


Block diagram of circuits used in detection and computation of S-T amplitudes.

Figure 11.



Arrangement for recording the output of the computer.



A portion of a record from the computer is shown. Speed of this record may be varied. Each deflection of the marginal trace represents eight VPB's.

Figure 12.

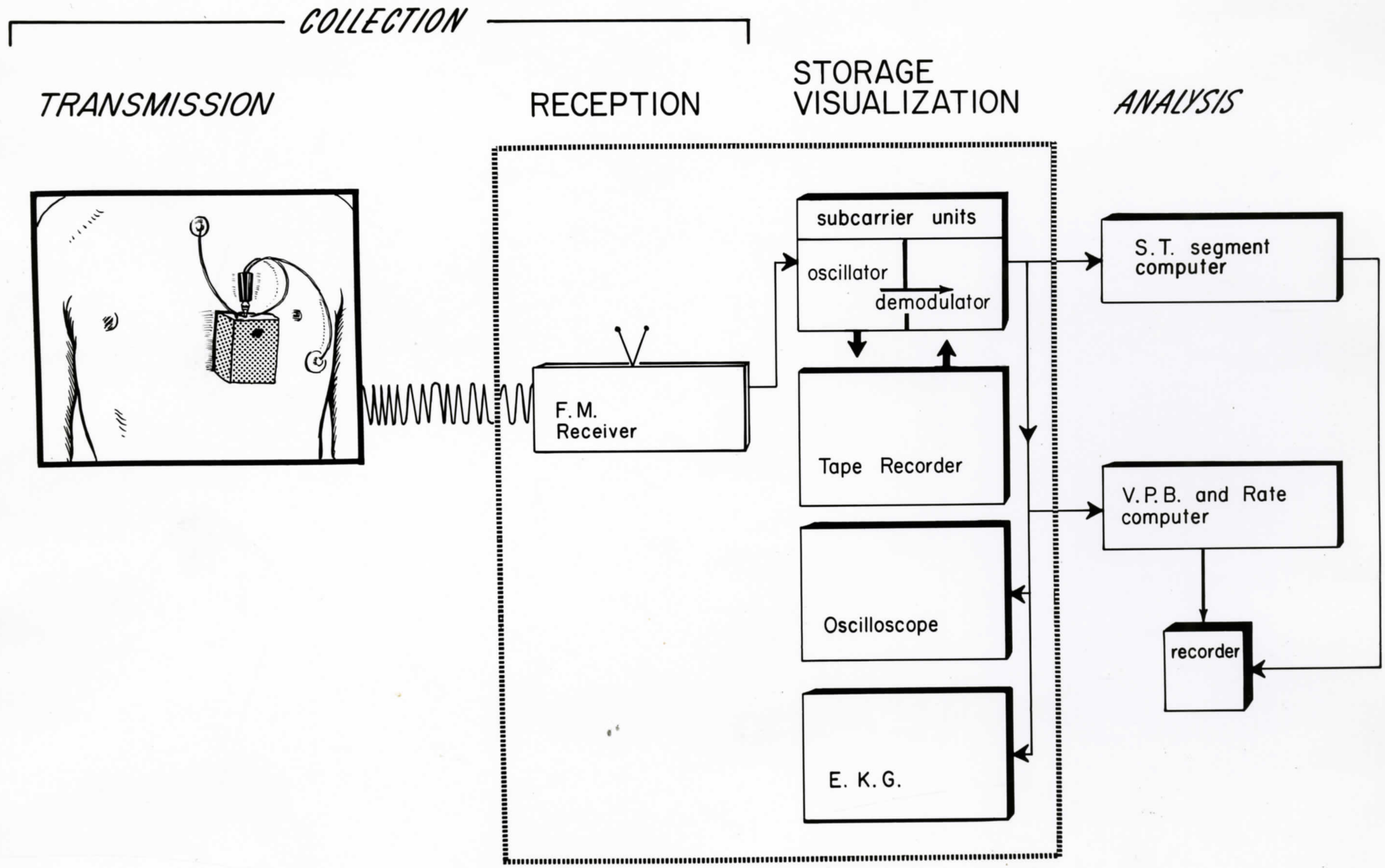


Figure 13. Block diagram of system.

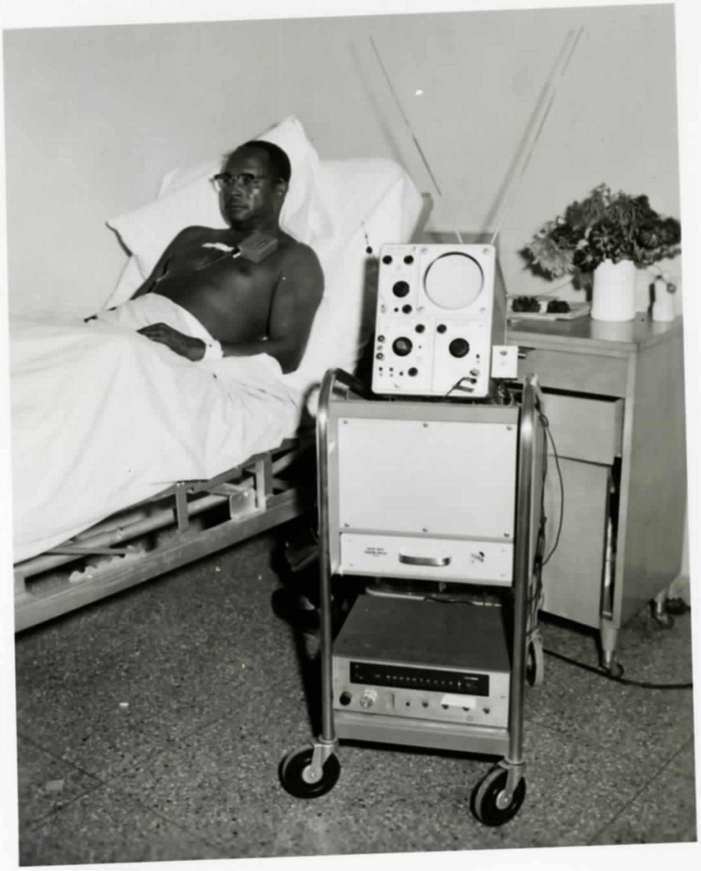


Figure 14. Photograph of a patient with the transmitter attached and the dolly containing the receiver/recorder. The rabbit ear antenna feeds the radio signal to the FM tuner on the lowest shelf. This modified tuner contains the sub-carrier oscillator and demodulator for recording and reproducing the ECG signal from a magnetic tape recorder behind the tuner. The oscilloscope is used to observe the ECG as desired. An ordinary electrocardiograph may be connected to this equipment.

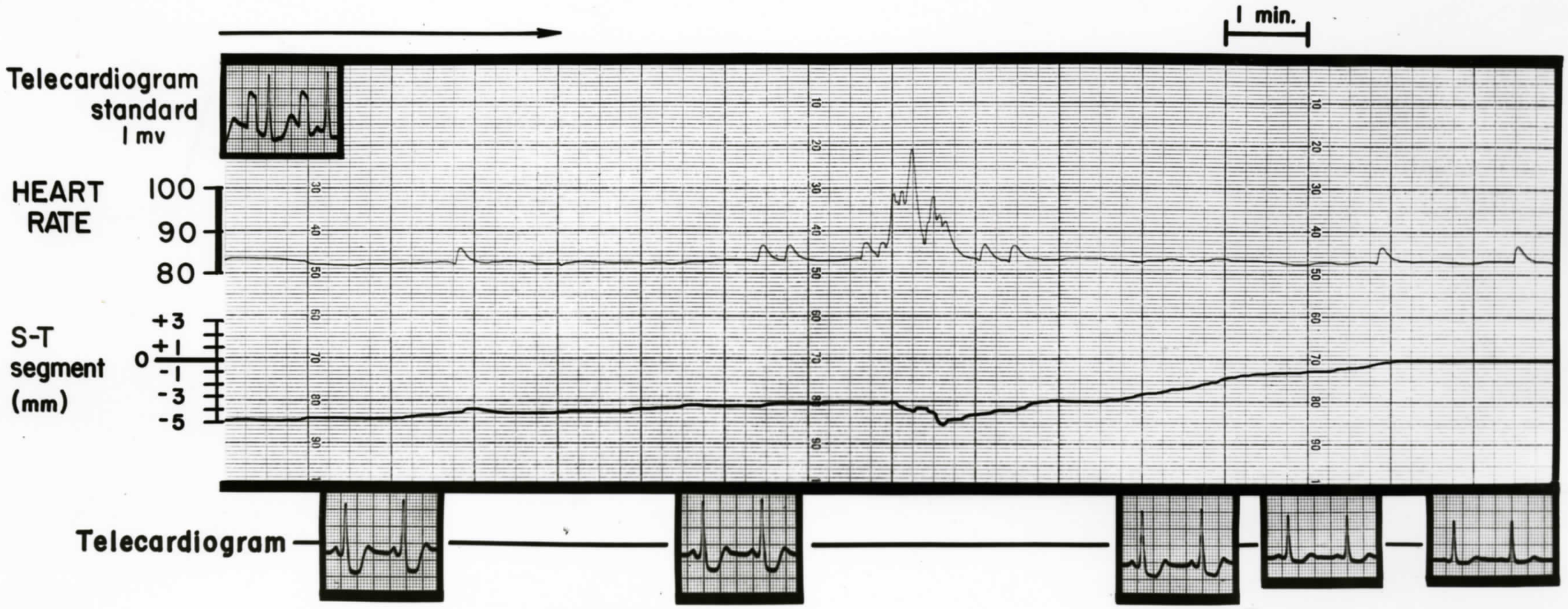


Figure 15. Computer record showing rate and S-T segment depression recovery in a patient with angina decubitus. The segments of the ECG record correspond in time to the computer record above.

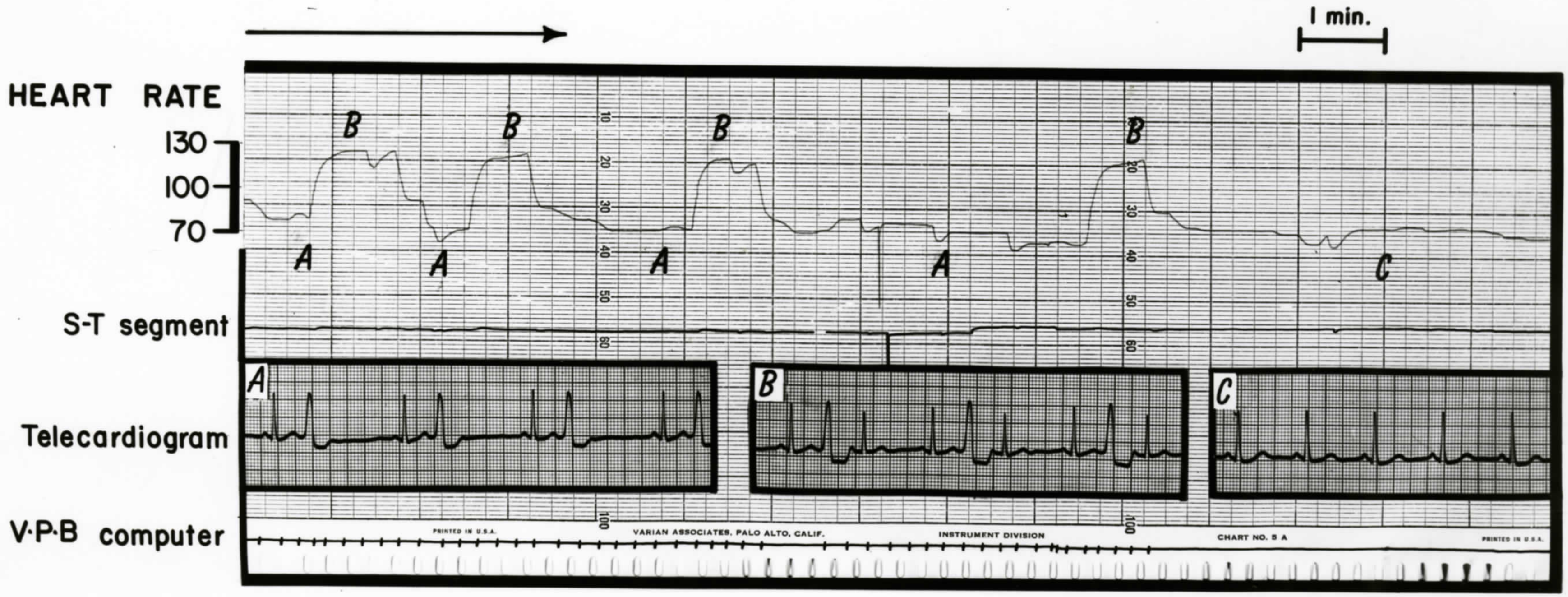


Figure 16. Computer record showing the effects of Quinidine on an arrhythmia. The drug was administered just prior to the beginning of this record when the patient's rhythm was a bigeminy as in A. The lettered portions of the record correspond to the lettered ECG records. No segment depression was present. (Segment depression is computed only from normal QRS complexes, not VPB's.)

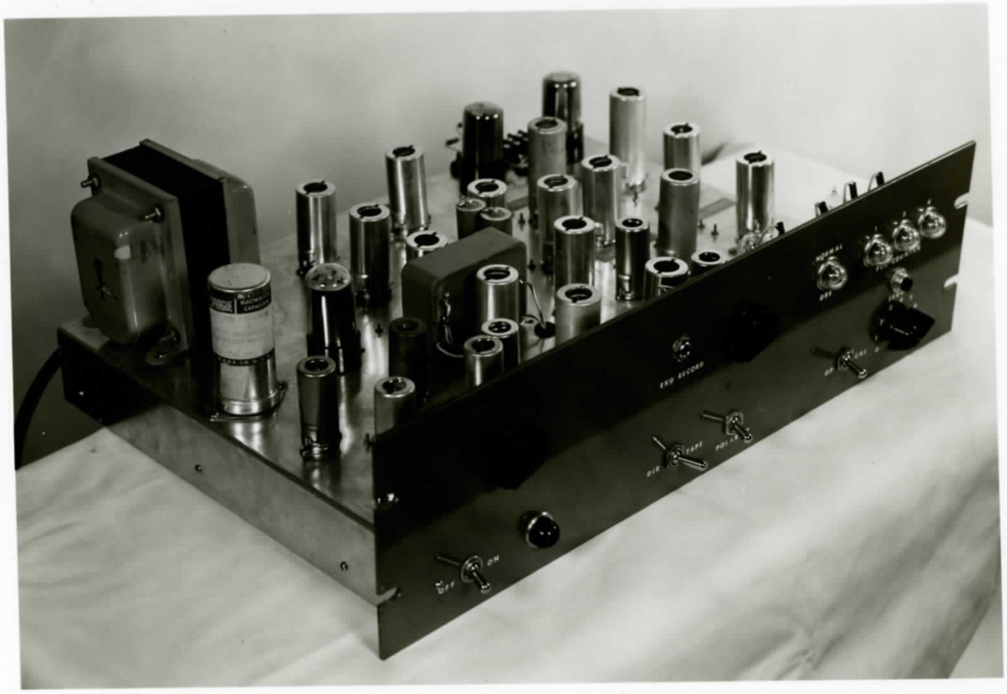


Figure 17. Photograph of the original computer. Not shown here are the tape recorder which provides the input signal for computation and the recorder for registering the output. Front panel lamps indicate the number of VPB's from 1 to 7.

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