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A LONG-RANGE AND LONG-LIFE TELEMETRY DATA-ACQUISITION SYSTEM

FOR HEART RATE AND MULTIPLE BODY TEMPERATURES

FROM FREE-RANGING ANIMALS

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SUMMARY

A long-range and long-life telemetry system for heart rate and multiple body temperatures from free-ranging animals has been designed. This system includes an implantable transmitter, external receiver-retransmitter collar, and a microprocessor-controlled demodulator. The size of the implant is suitable for animals with body weights of a few kilograms or more; further size reduction of the implant is possible. The ECG is sensed by electrodes designed for internal telemetry and to reduce movement artifacts. The R-wave characteristics are then specifically selected to trigger a short radio frequency (RF) pulse. Temperatures are sensed at desired locations by thermistors and then, based on a heartbeat counter, transmitted intermittently via pulse interval modulation. This modulation scheme includes first and last calibration intervals for a reference by ratios with the temperature intervals to achieve good accuracy even over long periods. Pulse duration and pulse sequencing are used to discriminate between heart rate and temperature pulses as well as RF interference. The implanted transmitter might be used alone for experiments on animals that frequent particular locations within a large territory; on animals in virtually any laboratory situation; or on animals in moderate-sized enclosures, such as those in a zoological garden. The implanted transmitter is otherwise interfaced with the receiver-retransmitter collar that employs commercial tracking equipment to achieve the long-range transmission. Peak energy is consumed only during the short RF pulses so that average current drain of either transmitter is in the range of tenths of milliamperes. The RF pulses from either transmitter are processed by the microprocessor controlled demodulator for the characteristics of pulse durations, intervals, and sequence. The output provides analog beat-to-beat heart rate and periodically updated temperatures as well as digital display. Heart rates to several hundred beats per minute (BPM) and body temperatures within a range of zero to 50° C with 0.1° C in resolution of change or better seem feasible. The objective of the design was to achieve a high degree of experimental flexibility and overall high quality in performance. The system was tested in prototype form on a dog.

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INTRODUCTION

This report presents the design details and rationale of an experimentally versatile, long-range, long-life, telemetry data-acquisition system for heart rate and multiple body temperatures. The design comprises an implantable transmitter for short to medium range, a receiver/retransmitter collar to be worn by the animal for long-range transmission, and a microprocessor-controlled demodulator with a signal conditioner interface circuit. The other receivers and equipment that were used, including the collar transmitter, were obtained commercially.

The parameters of heart rate and temperatures were selected for this design for two major reasons. First, they have a low data rate requirement so that signal·modulation is·compatible with the same principles of operation of the small, long-range, long-life, telemetry tracking systems. Specifically, the radio frequency (RF) pulses can be infrequent and several milliseconds long as well as frequency-stable. These pulse characteristics allow narrow-band reception and pulse width discrimination in order to achieve the effective long transmission range at low power costs. Tracking systems have long been available and widely used (refs. 1,2).

Second, these parameters are substantially influenced, either directly or indirectly, by both the autonomic and central nervous systems, by the endocrine system, and by metabolism. Heart rate and temperatures, particularly in combinations, can therefore inherently serve to index many and various interactive responses of animals to their environments. These responses would include changes in activity, emotions, health, energy allocations,·behavioral patterns, and biological rhythms. Illustrative examples have ·been presented elsewhere (e.g., refs. 3-5).

These parameters also require animal instrumentation techniques that are acceptable and not too difficult to use in a diversity of studies and environmental situations. That is, compared to the data of a tracking signal only, the gain of information from physiological data about the responses of an animal can far·outweigh the added costs in the necessary initial procedural efforts of animal instrumentation.

·Reviews and reference lists of the state of the art of physiological telemetry have been presented periodically (refs. 2,6-8). Pulse-interval modulation (PIM) in the·telemetry designs for heart rate or temperatures is not uncommon (refs. 9-14). At least one design-effort also has been able to obtain heart rates at long range with implanted and external relay transmitters (refs. 15,16). A temperature channel has recently been added to that system (Long, Department of·Engineering, University of Wyoming, personal communication). Also, statements for the justification of studies that require physiological data from free-ranging animals and for the needs of associated research and development were prepared as a report from a NASA-sponsored 1973 Santa Cruz Summer Study and a subsequent Program Plan on Wildlife·Monitoring (ref. 17). In short, the technical feasibility of a research approach and the justification for it have been demonstrated.

From the practical experimental point of view, however, the critical factor is the achievement of the quality of performance required to realize sampling procedures in experimental designs that are inherent in the idea of the use of indices. That is (except in the simpler applications), indices based on physiological parameters, such as heart rate and body temperatures, to assess animal responses will often require more or less continuous records over time in order to note relative changes. These changes can then be related to the experimental context and to the stimuli that give rise to the responses. Thus, large volumes of data are generated, and a high degree of automated data processing is virtually mandatory.

The system to be described here offers a heart rate and multiple body temperature capability but, in addition, has a number of features and advantages to improve signal quality and to increase experimental flexi- bility. The specific details of the circuits presented here represent a prototype that was designed, constructed, and tested in a Labrador dog at the Ames Research Center. A descriptive overview of the performance characteristics and design problems is presented first.

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OVERVIEW

The implantable transmitter generates a radio frequency (RF) pulse of several milliseconds duration for each heartbeat. These pulses are triggered from the specifically selected biopotential R-wave characteristics of the electrocardiogram (ECG). Tests with the prototype show that the R-wave detection is highly reliable. A crystal controlled oscillator is used to achieve the narrow-band, high-power density, and frequency-stable RF pulses.

Periodically, the transmitter's operation changes as determined by a heartbeat counter. This is set to be every 50 heartbeats in the prototype. A series of PIM temperature RF pulses are then transmitted within an approximate 1-2-sec window. This temperature pulse series is at the same RF as that for the heartbeats, but the pulse durations are approximately doubled. The modulation scheme includes a two-point interval calibration that helps to achieve continued accuracy over time with good measurement resolution over a wide temperature range.

These RF signal characteristics are then received either directly at short to medium range or after relay through the collar for long range. In either case, the received signals are appropriately conditioned by an inter- face circuitry and then processed by the microprocessor. The interface circuitry is adapted to condition a tone-burst output, in order to make it compatible with commercial tracking receivers and field tape recorders that might be used for temporary data storage. The microprocessor then sorts the

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pulses according to their widths and to the programmed data treatment for the other signal characteristics to give digital or analog outputs.

Since temperature variations occur slowly, the periodic cycle for transmission of data avoids unnecessary redundancy and conserves power both for transmission and for circuit operation. Also, the rates of change in temperature data are often correlated with heart rates so that sampling redundancy inherently increases with heart rate. The R-waves are still detected and counted by the implanted transmitter so that no information on the number of heartbeats is lost during temperature transmission. Because the temperature window is short, only a little heartbeat-to-beat information is lost.

On the other hand, the transmission of each heartbeat does not involve unnecessary redundancy. That is, animals that weigh only a few kilograms spend most of their time resting or engaged in moderate activity; their heart rates are then slow and match approximately a convenient pulse rate for location and tracking. The transmitter's duty cycle is still low so that further power reduction through reduced transmission rates is not really necessary. Operation time from several months to more than a year can be achieved, even within a small animal. Also, many experiments will require combinations between average heart rates for periods of time and beat-to-beat changes at other times. Such decisions about these formats are better made when processing the data. In this regard, the temperature cycle can be flagged optionally to obtain averages.

Figure 1 illustrates the various ways to interface the equipment for experiment flexibility.

Temperature Modulation

The modulation scheme for temperatures is illustrated in figure 2. The scheme involves ratios with the calibration values that are based on fixed resistors within the transmitter's circuitry. The fixed resistors determine the first and last intervals of the series of temperature pulses. The intermediate intervals of the series are assigned sequentially to the respective thermistors; there could be several thermistors if desired, but only two are used in the prototype design. The interval between the 50th heartbeat that triggers the series and the first temperature pulse is also determined by the same calibration resistor. After the last temperature pulse, a brief delay is insured before the next transmitted heart pulse is permitted so that pulse separation always occurs. The fixed-calibration resistors are selected to correspond to the highest and lowest resistances of the thermistors used and the range of temperatures anticipated in experiments. A measured temperature interval is therefore a percentage of the range defined by the calibration intervals and is then related to the known thermistor temperature curves.

The ability to define limits for acceptance in demodulation of the pulse durations, intervals, and sequence characteristics helps guard against

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error. In addition, however, it allows the absence of error to be recognized automatically. That is, the microprocessor will not update unless conditions are met, and this fact can be known in an automated way. This is important when a telemetry system is used near the limits of its capabilities. Under such conditions, the feature of doubling the temperature pulses also inherently yields a periodic stronger signal. This·flag, at least, helps to maintain the record of average heart rates when the noise interference for good beat-to-beat information is too great.

Because the relationship between the fixed resistors and thermistors is proportional, changes in circuit characteristics and power levels over time minimally influence accuracy. Because all the information for the PIM is transmitted in a short period of time, the variation in detection of the leading edges of the pulses ("jitter") within the pulse series ·should be slight. The degree of jitter from one·pulse series to the next is of little concern. For example, a temperature range of 50° C with 0.1° C measurement resolution seems feasible within an average time requirement of less than 0.5 sec per temperature channel. The average from sample redundancy should improve this resolution.

R-Wave Detection

The quality of performance of this and similar heart-rate telemetry systems depends first on the reliability of the R-wave detection independent of the animal's activity. Body movements and the choice of electrode locations may cause variations of amplitudes, waveforms, and polarity of the ECG signals. There may be large and rapid changes in the regularity and frequency of heatbeats, and unwanted signals from various sources may cause false triggering. The idea of a chronic implant within a healthy and free-ranging animal must be kept in mind when trying to achieve an optimum degree of success to correct for these problems. The implant must be packaged adequately, and appropriate surgical procedures must be followed in addition to giving considerations to both sensor and circuit design. Simplicity and economy are desired for any solution, but not at the expense of experimental objectives and performance requirements. The optimum also will not be identical for different species or, for that matter, for different experiments with the same species. The direction taken here allows design and procedural variations to be made easily and noninteractively.

A reasonably good first approach when the transmitter is implanted is to locate the electrodes subcutaneously on the thoracic region. The R-wave amplitudes tend to be greater when one electrode is referenced to the other located near the apex of the heart and relative to the heart's electrical axis. Amplitudes within the ranges of several tenths of a millivolt to several millivolts will often be obtained, but this depends on the species as well as on electrode location.

The frequency spectrum for the ECG is 0.1 – 100 Hz. Empirical examination with the use of filters will indicate that·dominant frequency

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components of R-waves occur at about 20 Hz. This is somewhat dependent on heart size and rates. Filtering above that frequency substantially reduces the electromyogram (EMG) in which the frequency components begin at about 30 to 50 Hz. The amplitudes of the EMG tend predominantly to be less than a few tenths of a millivolt unless a major muscle mass is involved. Skeletal muscle is anatomically unlike that which produces the behavior of an electrical syncytium in cardiac muscle. A strong electrical axis between highly coordinated polarized and depolarized regions over a long distance, as from the heart, does not occur. Location of electrodes away from muscle is therefore beneficial.

Low-frequency signals within a few hertz, such as those caused by respiratory movements, are filtered also. But amplitude changes in the signals of successive heartbeats can be substantial because of the influence of thoracic changes on the electrical axis. Changes in body position, which shift tissues and organs, also influence the electrical axis. Beat-to-beat changes in amplitudes in excess of 40% tend to be very rare and are usually much less if care is taken; however, amplitude changes over time are of course greater. It is important, therefore, to select electrode locations to reduce this variation as well as to maximize R-wave amplitude. Signal polarity changes are controlled by rectifying the signals. Automatically adjusting thresholds help to compensate for amplitude variations and to maximize noise discrimination whenever possible.

There is a variety of other signal detection problems. Excessively large potentials, which can occur, can overdrive the amplifier; discontinuous signals can cause ringing oscillation within circuits; and accentuated T-waves may occur with respect, in part, to electrode placement and cause double triggering. . T-waves can usually be controlled to be less than 50% of the R-waves. P-waves tend to be much smaller but do precede the R-wave. Fortunately, the wave forms of the ECG tend to keep a degree of amplitude proportionality so that automatically adjusting thresholds have considerable benefit. Triggering from RF feedback within the circuit or through external leads requires appropriate preventive measures, such as filtering and packaging. Spikes from stress at lead connections can occur if proper care is not taken. Lead movements can induce potential differences at the transmitter's input when the leads are separated and when there is a high impedance. This problem is reduced when the transmitter is inside the animal's body but might be heightened by a strong RF field during signal outputs. Changes of the transmembrane potentials of cells due to pressures of electrodes, and as different from activation potentials, might occur also.

In practice, many of the unwanted noise artifacts occur in the form of spike bursts rather than single spikes. A few of the spikes in a burst will have higher amplitudes than most of the others. Although these spikes are often close together, their amplitudes may exceed a triggering threshold. Rapid retriggering might occur unless limited. Nevertheless, such limits must not exceed requirements for maximum heart rates. Maximum heart rates of animals that weigh more than 1 or 2 kg rarely exceed an upper limit of as much as 8/sec. This allows 125 msec as a minimum limit for retriggering

and that limit could be extended if maximum rates are lower. This minimum limit for retriggering also helps to traverse the intervals of rectified waveform complexes and might be extended to overlap T-waves. Electrode movement artifacts can be a major problem because their signal amplitudes and frequency components range widely and overlap those of R-waves. Appropriate electrode design and implant procedures are critical here, and some suggestions will be made shortly.

In effect, the circuit design for the detection of R-waves places a window for signal characteristics among those anticipated after appropriate animal instrumentation procedures are followed. Sharp high- and low-pass filtering limits the frequency components above and below about 20 Hz. A limit on the accepted rate of change of slope of an incoming signal is also used. Amplifier gain control during RF pulses helps reduce feedback in addition to filtering. Full-wave rectification reduces polarity reversal problems and is combined with limits on retriggering rates. An absolute minimum amplitude threshold is set at about ±0.3 mV to keep above low-level signals and noise. Minimum R-wave amplitudes therefore must exceed this level. In addition, the triggering threshold automatically and pro-portionally adjusts itself above this minimum to accommodate beat-to-beat amplitude variations and anticipated durations of rectified waveform complexes, such as noise bursts. Precautions are taken to ensure rapid recovery in performance of the circuits, should unusual input signals occur

Again, the design is flexible so that adjustment in the specifications for performance requirements are largely noninteractive. The design is complex, but makes efficient use of available low-powered integrated circuits for construction. Also, the advantages that can be gained, if R-wave detection is accomplished reliably by the implanted transmitter, substantially overshadow the subsequent problems and limitations associated with complex waveform transmission of the ECG when only heart rate ultimately is required.

Electrodes

Relatively small structures, such as wires, needles, and lead-loop extensions of stainless steel are often suggested for chronically implanted ECG electrodes (refs. 18-22). Stainless steel is a convenient metal to use and is tolerated reasonably well by tissue; an alternative metal like silve is less durable and somewhat toxic (ref. 23). The small mass is advocated to reduce inertia problems and, because the skin boundary encountered by external electrodes is absent, the impedance of an internal stainless steel electrode is relatively low even for small structures that have areas of only a few square millimeters (refs. 19,20,24). Secure suturing, the promotion of tissue imbedding, and an appropriate choice of locations where body movements are minimal are often indicated procedures to reduce movemen artifact problems. Neuman (ref. 22) recently illustrated that a multi-stranded lead-loop extension is a typical design commonly used for internal telemetry.

These electrode styles are not recommended here. A large distributed area, smooth, thin, and inflexible stainless steel disc is a better yet still simple design that is suitable for chronic subcutaneous implants in active animals. An example that is compared with a lead-loop extension is illustrated in figure 3. This particular construction involves a groove and plurality of holes into which the lead is fitted with support tabs and spot welded into place. Silicone RTV coats and supports the entire region of connection and binds to itself across the holes in the disc as well as to the disc. The RTV also is tapered to the lead to reduce flexture stress. The four holes near the periphery allow the disc to be firmly sutured in place so that lead movements do not dominate electrode movement, as is the case with a small mass electrode.

Figure 4 shows the considerable difference in signal quality that can occur between the disc and lead-loop extension electrodes that were illustrated in figure 3 and when in vivo. For these records, the electrodes had been implanted 1 week earlier in a dog; they were placed side by side subcutaneously in the lead II configuration across the sternum. The leads passed transcutaneously and were connected by clips to the recorder with one pair for recording while other test pairs served for ground. Filters were set at 1.0-100 Hz; the preamplifier input impedance was 200 kohms. The dog was kept walking in a circle with side steps of the forelegs. The records were made sequentially with disc electrodes in A, and then with lead loop extensions in B. Rubbing the skin directly over the electrodes produced an even greater difference in signal quality.

Figure 5 illustrates in vitro records from these two electrode styles when one member of a pair in a 0.9% saline bath was rubbed between the fingers in an attempt to simulate the in vivo condition. The records of the potential changes of disc electrodes (A&C) and lead loop extensions (B&D) are labelled respectively. The records A&B show the direct current potential changes; filters were set at 10-100 Hz for the records in C&D. A 10 Mohm input impedance probe was used. Polarity of the disturbed electrode is defined by the potentiometer connections. In A, the negative electrode was disturbed; in B, C, and D, the positive electrode was disturbed. Note that the artifacts are directed in sign opposite to that of the disturbed electrode. This as well as the severity of the artifacts depends on metal type; a steel electrode produced an opposite result. Electrode polarity orientation when implanted can therefore help differentiate between R-waves and movement artifacts. Large pieces of copper, silver, silver-silver chloride, and aluminum exhibited polarity changes similar to stainless steel. The half cell of stainless steel was positive to all of these metals; aluminum was most negative. Magnitudes of artifacts were least from silver and silver-silver chloride, but again, their use as for chronic implant is not recommended. A few of the more exotic electrode metals or materials might be preferred. However, comparative tests of electrodes should be based on an emphasis on resistance to perturbation as well as on rate of recovery, and on tissue response and physical shape that includes lead connections in order to relate theory to practice.

The records in figures 4 and 5 show that at least an order of magnitude of difference in the susceptibility to produce major spike-like disturbance artifacts can be noted under either of the _in vivo_ or _in vitro_ conditions. Even though the disc, by virtue of a larger area, should have a somewhat lower impedance, the impedance of the lead extension with a calculated peripheral area in excess of 10 mm^2 would not be expected to be high (ref. 24). But the induced variance in half cell potential is obviously high and occurs sharply for the lead extension when under nonstationary conditions. Even the use of a 10-Mohm input impedance probe in the _in vitro_ tests was not adequate to counter this difference.

Aside from the structural suitability for an implant, some of the advantages of the disc seem to derive from the fact that the design widely and evenly distributes current flux and bridges large areas of tissue. Localized regions of either disturbance or cellular activity therefore would not dominate the entire electrode's behavior as would be the case with a small structure. On the other hand, large size would not diminish the ECG signal as expected if the biopotential were localized. Again, the ECG is generated throughout the body because the heart behaves as an electrical syncytium. Polarized and depolarized regions are created over a substantial structural distance. Even a large electrode cannot easily traverse that distance and thus tend to minimize its own net potential change relative to a distantly located reference electrode.

A plurality of electrodes or a flattened tube that is open at one end and insulated on the outside are alternative suggestions. A tube would increase the distance from surrounding tissue and tend to isolate the electrode interface from physical movements against tissue. A plurality of electrodes would further distribute current flux and may offer some advantage for minimizing amplitude fluctuations in R-waves as the heart's electrical axis changes. Maximum amplitudes, however, might be reduced because of the net potential difference across the separated parts of an individual electrode. These suggestions are secondary options, the implementation of which increases the procedural complexity; they may not be necessary. Also, flexible stainless steel mesh cloth of large area has been tried but was found unsuitable because of problems with lead connections and suture locations that seem to produce spikes. Also, the base potential difference produced by rubbing the mesh cloth when _in vitro_ was substantially greater than that for the disc, but the spikes produced this way were about the same. A small disc has been routinely used for small animals and has been illustrated elsewhere (ref. 25). For example, good quality records can be obtained from rats running on a treadmill; a larger disc is better if animal size and skin thickness for revascularization after implant permits.

RF Interference

Problems of RF noise interference and signal strength variations can, of course, cause difficulties with reception. At the implant to collar relay interface, a crystal-controlled, commercial, tracking transmitter was

used. The transmitter was modified so as to be a complete slave to the output of the collar receiver and its associated logic circuitry. The logic circuitry delays the incoming pulse characteristics and then regenerates them for retransmission. Thus, the strong retransmitted RF cannot normally interfere with reception from the implant. The pulse width and intervals are maintained through the relay but the RF is changed to that of the retransmitter. The RF of both the implant and the collar transmitter are selected to be nonharmonic to reduce possible interaction. This separation is also convenient for experimental reasons. The use of different receiver bands is helpful in any new experiment to check coupling requirements between implant and collar. During experiments, the distance between the animal and the investigator's receiver will vary. When that distance is short, interference could occur if both transmitters had a similar frequency.

Because the implant produces a relatively strong RF signal, variations in signal strength are less troublesome when an attempt is made to achieve a good coupling with the collar receiver as the animal moves and changes body positions. Also, the collar receiver sensitivity can be minimal and less susceptible to extraneous RF interference. A wider receiver bandwidth is more feasible, and the power requirements are reduced in that a passive or only a slightly active gain need be employed. Thus, the size and weight of the external collar is not greatly increased over that required for the basic tracking condition.

The similar kinds of noise problems that occur at the output of the investigator's receiver are dealt with in the demodulation interface circuit in three basic ways. First, sharp band-pass filtering selects the tone burst generated by the incoming RF. Second, the RF sensitivity gain of the receiver is coupled to threshold detection; this involves a combination of manually set and autotracking modes to accommodate signal strength variations. Third, since much of the remaining extraneous RF noise involves short random pulses, pulse width discrimination of the received signals is used to block this noise and to sort the heart rate from the temperature pulses.

The tone bursts will not always be perfectly formed, particularly when near the limits of range; that is, the individual sine waves may be amplitude-modulated. A conversion to a square wave for pulse width discrimination is used and the top of the square wave is sustained for a brief period to stretch past a temporary attenuation. This period of pulse stretching must be short, however, so that only severe random noise could produce an output that is long enough to be accepted as a heartbeat.

Packaging and Implant Procedures

Some comments and suggestions about packaging and surgical implantation procedures follow. The units should be hermetically sealed with appropriate headers, such as glass to metal, for lead passage out of the unit in order to prevent moisture penetration. The outer coat of the unit must be tissue compatible — silicone RTV can be used. Tissue, however, does not adhere to

RTV and a layer of Dacron coarse-weave cloth will facilitate tissue imbedding. This is strongly advised so that the unit can become firmly anchored within the body where it was originally sutured. When the implant is abdominal, some Dacron should be added to the leads where they will pass through the muscle wall to run subcutaneously. Appropriate sutures should be taken in that region to prevent slippage, to promote healing and reclosure of the abdominal cavity, and to prevent lead flexure at that point from pressing outward against the skin. Revascularization of the overlying skin might otherwise be inhibited.

Sensors located subcutaneously should be placed to the side of the skin incision to facilitate revascularization of the skin. All such objects should be sutured in place rather than left to float, in which case they may be more easily rejected or change location. The electrodes in particular must be well sutured for stability. An appropriate amount of lead slack is necessary so that sensors will not be stressed when the animal extends its body. Flexure stress at the lead/sensor junction is minimized also if the lead path into the sensor is not curved. Again, in no case should the leads or sensors exert an outward pressure against the overlying skin; even if healing occurs initially, a constant outward pressure to the skin may later cause rejection. A conservatively placed suture will usually alleviate problems of pressure from lead flexure and help to guide the lead path. Tight sutures around the leads or sharp angles, of course, cannot be tolerated. The job of channeling subcutaneously is not difficult, even in fairly large animals if appropriate tools are used (ref. 26).

A good flexible lead can be made with multistrand stainless steel wire, silicone tubing, and self-leveling silicone RTV. In some cases, it is adequate simply to insert the wire into a section of tubing and then inject the tube with the RTV. Greater flexibility can be achieved by coiling the wire within the tube. This can be done by coiling the wire around a piece of small-diameter metal tubing which is then inserted into the silicone tubing. The metal tube is then withdrawn. If necessary, the silicone tube can be temporarily expanded by soaking it in xylene; the xylene later evaporates and the silicone shrinks approximately to its original shape.

The common practice of using solder and solder flux to make connections to leads can cause problems. Tissue toxicity responses and the deterioration of the connection due to the battery potentials that arise from the metal discontinuities and due to the flux chemistry are likely. Spot welding, bolting, and crimping are better ways of making connections. Coating these connections, with RTV, for example, adds protection, reduces flexure stress, and offers an increased impedance boundary against electro-chemical potentials.

The use of gas sterilization techniques, for example, with ethylene oxide, is recommended. The gas penetrates the outer potting materials. Zephiran chloride can then be used as a surface cleaning agent during implantation to reduce the possibility of contamination. Because heat and pressure are often used with gas sterilization, care should be taken to avoid damage to the potting materials or to the transmitter unit.

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After the implant, closure of the skin might best be done with steel or a monofilament suture. Silk can act as a wick that might promote infection. It is best to use permanent sutures for the implant and for abdominal closure, however, rather than absorbable sutures. Antibiotics should be generously used, and their direct application to the implant and surgical area seems helpful in preventing initial infection problems. During surgery, skin separation from the underlying tissue should be kept to a minimum; the loss of vascularization promotes subsequent edema and results in cold regions that inhibit rapid healing. It is recommended that the animal's fur be shaved sparingly and that a temporary bandage be applied for support and warmth (the bandage should still allow exposure to the air). Talcum powder along with the topical antiseptic helps to keep the area dry. Of course, animal behavior after surgery and within the experimental situation influences procedures. An implant under field conditions should be done only after these things are known, particularly if the animal is to be released immediately without a day or two of confinement for purposes of observation.

IMPLANTABLE TRANSMITTER CIRCUITRY

Figure 6 is a block diagram of the implantable transmitter; figure 7 shows the entire circuit design. The major functional stages are indicated by capital letters to correspond with waveform outputs of these stages as shown in figures 8 and 9.

The RF bypassed input voltages to the R-wave detector stage are first limited by a voltage follower whose "slew rate" is set at ±1 mV/msec (fig. 6) Ⓐ. This allows normal excursions of the QRS complex while greatly reducing the magnitude of large-amplitude, sharp signals which might drive the filter and amplifier circuitry into distortion (refs. 27,28). The next stage is a six-pole, low-pass filter (ref. 29). It provides a 36 dB per octave rolloff with a 3 dB point (70% amplitude) at 31 Hz Ⓑ. Its output is connected to a two-pole, high-pass filter with a 3 dB point at 18 Hz and a rolloff of 12 dB per octave Ⓒ. This filter circuitry provides a band-pass centered near 26 Hz with a sharp rolloff at higher frequencies and a lesser rolloff at lower frequencies. These filter characteristics select the fundamental frequency component of the R-wave while greatly attenuating other components. An AC coupled amplifier with a gain of 56 is next Ⓓ. Gain was set to accommodate ECG amplitudes within a range of ±5 mV. A precision full-wave rectifier converts the amplifier's output to an absolute value so that all signals are then positive regardless of the polarity of the input signal Ⓔ. Total gain is reduced to unity during RF transmission as a further precaution against spurious responses; this circuit is indicated later.

The remaining circuitry generates a constant-amplitude, 5-msec-wide pulse each time an R-wave occurs. It does this by identifying the highest peak in the rectified and filtered QRS complex by means of a peak pulse detector (ref. 30). The detector follows the amplitude envelope of the

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rectified QRS complex and stores the maximum level on a capacitor Ⓖ. As long as the input signal is positive-going and greater than the stored charge, this stage Ⓕ functions as a voltage follower. When the input waveform reaches a point of inflection and starts negative, the stored charge back-biases the diode decoupling the negative feedback loop. With the feedback loop decoupled, the stage functions as a comparator. Thus, the output swings into negative saturation since the inverting input is more positive than the noninverting input. If subsequent peaks do not exceed the stored charge, the output remains locked in negative saturation. Thereby, the last negative output transition occurs at the highest peak of a pulse complex.

The detector's output is connected to a biased CMOS line driver whose output Ⓗ controls a retriggerable monostable device. Unless retriggered, the monostable resets in 110 msec. But in the case where the peak detector is responding to a cluster of pulses with intervals less than 110 msec, the monostable may be retriggered several times, not resetting until 110 msec from the detection of the highest pulse. The reset Ⓙ drives a second, nonretriggerable monostable with a time constant of 5 msec. Thus, a 5-msec-wide pulse is generated Ⓚ for each detected R-wave. That pulse triggers the crystal-controlled RF oscillator Ⓢ via the combination of gate control circuitry Ⓠ,Ⓡ. The fixed delay of 110 msec does not affect the beat-to-beat measurement of heart rates less than 545 BPM. But this delay effectively is increased by a period selected in the gain control circuitry that leads back to the amplifier and rectifier Ⓓ,Ⓔ. For example, the addition of 20 msec through that circuitry yields a rate limit of 461 BPM.

The 5-msec pulse Ⓚ also provides a reset control for the peak pulse detector. Reset is done by closing a normally open gate for 5 msec, discharging the capacitor on the detector Ⓖ. The level of charge left after the switch reopens is a function of RC values Ⓖ,Ⓘ and of the 5 msec. For example, a discharge voltage of half the previous peak amplitude allows the detector to track, on a beat-to-beat basis, changes in R-wave amplitude of 2 to 1. Thereby, the detector's threshold is automatically adjusted to provide a trigger level which is proportional by a desired amount to each measured R-wave amplitude. A resistive bridge in the discharge path of the detector sets the absolute minimum threshold level to ±0.3 mV and lower referred to the transmitter's ECG input. This ensures that the detector will not trigger on baseline noise when an adequate ECG is not present.

A restart circuit is provided in the event that the detector is driven into positive saturation such that the charge on the capacitor might remain higher than the subsequent incoming R-waves. In this condition, no triggering would occur to automatically adjust the threshold level. The restart circuit, which allows the capacitor to discharge until it re-acquires the R-wave, activates 1 sec after the last detected heartbeat. The 1-sec delay is related arbitrarily to the expected lower heart rates. With a 1-sec value, the search mode would be employed at all beat-to-beat intervals of rates less than 60 BPM. For many animals, this may be a resting state when artifacts from EMG and electrode movements are least

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expected, except in such special physiological conditions as diving bradycardia.

The restart circuit itself consists of a resistor and capacitor connected across the battery supply. When the charge on this timing capacitor approaches V_{dd}, a gate connected to it closes. The detector's storage capacitor Ⓖ is now discharged through the gate via resistor to ground. The resistor determines the search rate as the threshold lowers to its absolute minimum. The RC combination Ⓛ that controls the gate provides the delay between the last heartbeat and the start of the search mode. Another gate is connected to the timing capacitor so that the search mode can be canceled. When closed, it discharges the timing capacitor to V_{ss}. This gate is closed each time the detector Ⓕ indicates a new pulse has been received. The search mode, therefore, is never employed at heart rates greater than the delay time, as seen in figure 8.

Besides keying the RF oscillator and adjusting the threshold on the peak detector, the 5-msec pulse generated by each heart beat initiates a counter divider chain and signal control to allow sampling of two temperatures periodically. The circuit diagram is included in figure 7. The significant waveforms are shown in figure 9. The R-wave pulse is divided by 50 using two CD 4017 decade counter dividers. A reset pulse (M) every 50 counts initializes the second CD 4017 and starts a third CD 4017 Ⓞ. The clock for the third counter (pin 14) is a multivibrator oscillator and has its period controlled by a resistance bridge. Four independent bridge circuits are provided, two with thermistors and two with the fixed resistors that provide a 0° C and a 50° C calibration. The four bridges are sampled sequentially by four CD 4066 switches controlled by the CD 4017 that advances one step following each pulse.

The oscillator operates as follows: A D30A3 is used as a constant current source to charge a 1-µF timing capacitor with the current-level variable proportioned to the voltage level derived from the resistance (thermistor) bridges Ⓣ. An NPN D26E1 emitter follower is used to compensate the emitter-base diode voltage of the D30A3. With the constant current from the D30A3 charging the 1-µF capacitor, a linear voltage ramp is generated starting at Vss. The ramp signal is connected to the negative terminal of the L161 comparator and the positive side is connected to the L161 output by a 2-to-1 attenuator. With the ramp signal below the positive terminal voltage, the L161 output is saturated at Vdd, and the 2-to-1 divider places a 0 voltage at the positive terminal. As soon as the ramp crosses this 0-V threshold the L161 comparator switches to an output of Vss and the positive terminal is also Vss. The L161 holds the Vss level until the 1-µF capacitor is discharged and then the entire cycle starts over again with the charge current from the D30A3. The ramp signal is operated between Vss and 0 since the L161 allows operation of the inputs all the way to the negative rail; but with a Vss to Vdd supply of 2.7 to 3.0 V, it will not work with a common mode voltage closer than 1 V to the Vdd rail. This ramp generator voltage range also provides the necessary collector voltage for the D30A3. The reset after each ramp period (proportional to the bridge voltage) is accomplished with a CD 4066 switch which is connected to the L161 output via

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a CD 4001 inverter. The return reset cycle is very short because of the low impedance in the switch. By adding a 3.3 kohm thermistor in series with the switch the reset period can be adjusted to 10 msec for the pulse width for transmitting temperature data (N). The enable circuit (P,Q) allows a time delay to capture the duration of the last temperature pulse and, in combination with the gain shutdown control (Q,D), ensures that a heartbeat 5-msec pulse will not overlap with that temperature pulse.

A number of considerations suggested that a thermistor bridge circuit would be more satisfactory than a direct resistor charging circuit for the timing RC. Since at least one of the thermistors and possibly both would be located remote from the electronic package, it was desirable and probably essential to use a low impedance thermistor. For instance, whether a 30-kohm or a 3-kohm thermistor is needed depends on the adequacy of moisture protection, and that is difficult to evaluate; therefore, the lower the thermistor value, the better the chance of maintaining consistent results. A 3-kohm thermistor at 25° C is about 10 kohms at 0° C (lower temperature extreme). For a 0.1° C temperature accuracy, a 0.04% resistance accuracy is required so that a shunt impedance of 2 Mohms across the thermistor would cause a 0.1° C error. A 20-Mohm shunt would give the same effect on a 30-kohm thermistor. This indicates that even with low-impedance thermistors, careful protection from moisture is essential.

If low-impedance thermistors (most desirable because of moisture problems) are used directly in RC timing circuits, two other problems occur. One is the switch impedance of the CD 4066 which is of the order of a few hundred ohms and deteriorates rapidly as the power source is reduced from 5 V to 3.0 V. This could represent a substantial impedance in series with the thermistor. Any significant variation in this impedance is likely to cause data errors. Because about 1 sec is allocated to retrieve the temperature data, very large capacitors would be required to obtain a suitable time constant with low impedance devices. Both of these problems can be circumvented by using a resistance bridge.

A D30A3 is used as a switch to power the four resistance bridges only when the approximate 1-sec temperature data are taken. The D30A3 is driven by a D26E1 so that the D30A3 can be properly saturated without loading the CD 4017 output. With the base current levels used, the voltage drop across the switch is typically 10 mV. Even this low voltage drop would cause readout errors if a bridge circuit were not used. Since all the bridge circuits (four each) are turned on with a common switch (D30A3), whatever voltage drop occurs in the switch is corrected for by the 0° C and 50° C calibration readings.

Minimizing the total power consumption is important to achieve an operational life of more than 1 year with a modest-sized battery. Although the CMOS. devices are on continuously, they require very minute currents except during the short microsecond transitions between on and off states. The low-impedance thermistors would, however, represent a drain of many milliamperes if they were on all the time. Since the temperature is only sampled for 1 sec every 50 heartbeats, assuming an average heart rate of

100 BPM, this gives a duty cycle of 1 sec "on" and 30 sec "off." With typical thermistor values of 3 kohms and bridge resistors of 3 kohms, the "on" current for the four bridges is 2 mA; the average is 1/30 of 2 mA or about 60 µA. Switching each of the four bridges independently, which could further reduce the average current, did not seem advisable because extra parts would have been required and because of the possibility of error introduced by impedance variations in different switches.

Figure 10 shows a typical thermistor resistance vs temperature plot as well as various thermistor resistance bridge combinations. The tabled values were obtained with a breadboard bridge circuit and substitution of resistance to simulate thermistor impedances. Over the 0° to 50° C desired operating range, the thermistor changes about 10 to 1 in resistance and also is a nonlinear curve. Although a 3-kohm thermistor has been used for the data of figure 10, the shape of the curve would only change very slightly with a thermistor of a different impedance. The use of various bridge configurations results in a variety of possible curves. Limitations in the timing accuracy that can be transmitted within a limited RF bandwidth and using about a 1-sec interval for all temperature readings indicate that the raw thermistor 10-to-1 dynamic range is too large for proper use in this system. The approximately 3-to-1 range for the bridge curves seems about the best. A 1-kohm resistor is placed in series with the thermistor side of the bridge so that if the thermistor resistance were to short-circuit, the oscillator period would not be infinite. Such safeguards must be made in case a shorted or open thermistor lead causes the entire system to otherwise shut down. The bridge circuit plus some series resistance with the thermistors prevents such a failure and also yields identification intervals of such mishaps.

Some further manipulation of the bridge arrangement or resistance values could probably improve the dynamic range. This involves some sacrifice of the linearity but linearization can be done more easily through the demodulator. Calibration curves for the thermistor bridge in the transmitter circuit and with a 30 kohm thermistor are shown in figure 11.

As shown in figures 7 and 9, the temperature circuitry controls gating Ⓠ and Ⓡ to the RF oscillator's input Ⓢ and to the control circuitry to the amplifier gain Ⓓ. During a temperature measuring cycle, the 5-msec heart-rate pulses are replaced by the 10-msec temperature pulses, thereby doubling the oscillator's on-time. The R-wave counter nevertheless continues to advance so that the start of each temperature cycle represents the 50th heart beat exactly; only the dynamic beat-to-beat variation is interrupted temporarily.

The single stage RF oscillator is base-emitter tuned with a third-overtone crystal employed as the frequency determining device. The base-emitter circuit operates at the crystal's third harmonic of 54 MHz. The collector circuit is also tuned to 54 MHz. This configuration provides good frequency stability in a single-stage oscillator because the output load is effectively isolated from the base-emitter tuning loop. The oscillator's output is connected to the thermistor leads. These leads serve as the

antenna, thereby optionally eliminating the need for a separate antenna. Bypassing RF is provided at the resistance bridge as well as at the ECG input and battery supply. The oscillator is keyed "on" and "off" by the ECG and temperature pulses so that it is active only during each pulse period. Turn-on time to full RF amplitude is within a few cycles of the 54-MHz operating frequency. Thus, the resulting wavefront slope is less than 20-μsec wide compared to the data pulse intervals of over 100 msec. Peak RF output power is about 8 MW.

The system uses two center-tapped mercury cells to provide ±1.4 V. Power consumption is the sum of the continuous current drain of the circuit plus the average peak current, which is heart-rate dependent. At a heart rate of 100 BPM, the average current drain is about 350 μA, of which approximately 250 μA is continuous.

Figure 12 shows the transmitter at various stages of prototype packaging for implantation and testing. The prototype unit was fabricated with discrete parts and integrated circuits. A further reduction in size would be possible using hybrid construction techniques, since the active components used are available in chip form. The battery shown has a 2400-mAhr capacity, thereby providing a maximum operating life of about 9 months at an average heart rate of 100 BPM.

The AM receiver used with this transmitter operates at 54 MHz, with an output frequency response from 0 to 10 KHz. The low-frequency capability is important since the received pulses can have durations as long as 10 msec. The amplitude is adjusted to provide the 0 to +5 V pulse heights necessary for driving the demodulator.

RETRANSMITTER COLLAR CIRCUITRY

The retransmitter consists of an RF receiver, logic circuitry, and a commercially available animal tracking transmitter, all packaged within a collar. Figure 13 shows a prototype collar and field receiver equipment for a dog. Dimensions of the electronics package are 5 by 5 by 7 cm; weight is 320 g. Most of the size and weight is due to the tracking transmitter, which is 3 by 5 by 7 cm and weighs 277 g. The transmitting and receiving antennas are incorporated within the collar.

Figure 14 is a circuit diagram of the retransmitter; a circuit timing diagram is provided in figure 15 (the labeling with capital letters start over). At the input Ⓐ of the circuitry there is a passive RF receiver consisting of two tuning stages and a hot carrier diode detector. The stages are tuned for a bandwidth of about 8 MHz with a center frequency at 54 MHz. The receiving antenna is a flexible lead configured within the collar strap. Figure 16 shows the arrangement of the antenna lead. As can be seen, the lead begins and ends at the electronics package, with maximum extension to the collar's tip. The outgoing and return paths are separated for the width of the collar. Following the tuning stages, the hot carrier

diode circuit detects the negative envelope of the incoming RF pulse Ⓑ.
This detection provides an audio frequency pulse which is amplified Ⓒ and
then reshaped by a comparator Ⓓ. Receiver sensitivity is adjusted by
raising or lowering the comparator's threshold level. When practical, this
adjustment is made with the collar on the animal. Otherwise, it is done
prior to use by estimating the expected field strength and background noise
for the particular application. Figure 17 shows an alternate receiver with
a single stage of RF gain. This active receiver is used in the event that
signal transmission from within the animal is exceedingly weak. This
occurred during testing because of an antenna break. Variations in gain
requirements can be expected for procedural reasons and size limitations
among animals. The active receiver requires a greater current drain to
operate, about 700 µA compared to less than 5 µA for the passive receiver.
The antenna in either case is the same. The stage of RF gain in the active
receiver causes a polarity reversal at the input to the comparator. This is
easily remedied by interchanging the comparator's inputs.

The comparator drives the CMOS logic circuits which in turn generate a
control pulse for actuating the RF tracking transmitter. The control
pulses are delayed from the incoming receiver pulses, yet keep the same
width and interval as received. The delay prevents interference of the
strong retransmitted RF pulse with the reception of the weaker RF signal
from the implanted transmitter.

To generate the delayed pulse train, the output of the comparator Ⓓ is
connected in parallel to the inputs of a pair of monostable devices. One
monostable triggers on the leading edge of the incoming pulse, the other on
the trailing edge. Each provides a 20-msec-duration pulse which is
complementary to the other. These outputs (E,F) operate a pair of gates Ⓖ
that activates the transmitter Ⓗ when both are closed. As seen in
figure 15, the delay and pulse width of the RF retransmission are the
result of subtracting the outputs of the two monostables by means of the
control gates. Receiver squelch during the RF retransmission is done by a
blanking gate Ⓘ at the inputs to both monostable devices. This gate
closes Ⓕ to Ⓘ before the retransmitted RF pulse and remains closed for
about 100 msec. This insures that the retransmitter will not be self-
triggered during that time and allows the receiver circuit a recovery time
after each transmitted pulse. The blanking gate is controlled by a circuit
which stretches the pulse output from the trailing-edge-triggered
monostable. Because the collar was relatively insensitive to RF noise, it
did not seem necessary to include circuitry to prevent the occurrence of a
noise spike from triggering the monostable device. If that did occur
however, the receiver would not accept another pulse for a period of about
120 msec; the occurrence of a heartbeat or temperature pulse could then
actually be missed within that period. Initial pulse width discrimination
in the logic circuitry could, however, be done with little added cost in
terms of size or power requirements.

The tracking transmitter is a Telonic's Model MK-3A-TA-4 (fig. 13)
with a factory-modified input. That is, the standard internal control of
the RF pulse rate is omitted with control brought instead to a pair of

external inputs. The companion receiver provided by Telonics is a hand-held model designed for field use. The receiver is crystal-controlled, as is the transmitter, and operates within the RF spectrum normally utilized in animal-tracking work. In this case, a frequency of 148 MHz is used. The output of the receiver is a tone burst applied to either a self-contained speaker or a headset. The duration of the nominal 2 kHz tone is determined by the width of the incoming RF pulse, in this instance either 5 or 10 msec. The tone burst is retained, rather than modifying the receiver to obtain a standard pulse, because it is readily recorded without distortion on a hand-held cassette tape recorder. Also, since the operator must adjust the receiver's output in the field without benefit of an oscilloscope, the tone is easily recognized using only the headset or speaker.

RECEIVER DEMODULATOR INTERFACE CIRCUITRY

Once a field recording has been made, the magnetic tape is brought to the laboratory where it is replayed through a circuit that converts the tone bursts back to rectangular pulses compatible with the demodulator's input. Figure 18 is a diagram of the interface circuit. At the circuit's input is a band-pass filter (ref. 29). It is centered at 2 kHz, which is the receiver's output tone. A peak detector and a comparator then convert the sinusoidal waves within each tone burst into a group of rectangular pulses. The peak detector provides an adaptive threshold level for the comparator. Controls mounted on the front panel of the unit allow selection of automatic tracking rates and triggering amplitudes for the adaptive threshold. In addition, a fixed threshold level can be selected.

After the sinusoidal pulses have been changed into rectangular shapes, they are further filtered by means of a digital band-pass filter centered . at 1.8 kHz. The filtered rectangular pulses are applied to a digital envelope detector which converts each group into a single pulse with a width of either 5 or 10 msec, as determined by the original transmission (ref. 31). The envelope detector can be adjusted to bridge across a single, missing pulse within a group. This allows the envelope to remain unchanged in the event that the comparator misses a single, sinusoidal pulse within a tone burst. This could result from an instantaneous amplitude fluctuation to which the adaptive threshold could not respond. These single pulse-to-pulse amplitude variations result from superimposed noise or quick changes in RF signal strength. Adjustment of the bridge duration is done by altering the time constant of R_3C_3.

Additional noise rejection is provided by a circuit which sorts out envelopes with less than 3-msec periods while passing those of greater periods, such as the 5 and 10-msec data pulses. Thus, single, spurious pulses within the 2 kHz band-pass are eliminated. Pulse rejection is determined by the time constant of R_4C_4.

The output of the interface circuit uses two voltage followers ⓔ. One drives a lamp mounted on the front panel which indicates acquisition of

data pulses. The other provides pulse height of the proper amplitude for driving the demodulator.

Front panel controls, besides allowing for selection of threshold functions, also allow the selection of frequency band passes in the event that the receiver has an output tone other than the nominal 2 kHz. This flexibility allows the recorded data to be retrieved according to the experimental conditions in the field or laboratory. As an example, data recorded in the field from a fast moving animal, with resulting RF signal strength fluctuations, would be handled differently from data recorded from a resting animal with nearly steady-state signal reception.

The interface circuit is low powered and can be operated either with batteries or a direct current power supply.

DEMODULATOR CIRCUITRY

The microprocessor-based demodulator is used to accurately determine the time interval between pulses from the telemetry receiver output. It discriminates against unwanted noise and performs heart rate and temperature calculations based on the time-interval information.

To accomplish the accurate timing, a 2 MHz clock signal ($\phi2$) used to generate basic timing operations inherent to the microprocessor is divided down to a 1 kHz signal (1-msec interval).

Figure 19 is a top view of the demodulator showing the internal component layout consisting of a central processing unit card (CPU), D/A output ports and converters; IK RAM/2K ROM card and a front panel/interval timer/interrupt generator, card. All microprocessor signals use the S100 bus system as a common element for communicating between the peripherals and the CPU card. The S100 bus provides, at a low cost, a variety of peripheral interfaces popular among the home computer hobbyists that are easily available at any local computer store (ref. 32).

A detailed description of the circuit operation of the demodulator follows.

The output of the telemetry receiver and interface circuit (fig. 20 pin J64) is buffered by IC 21 and fed to a positive and a negative edge triggered "D" type flip-flop (IC 5, pins 3 and 11). Their negative true outputs are connected to an eight-bit priority decoder (IC 6, pins 1 and 2).

The highest level of priority is pin 3 of IC 6. This input is reserved for a 1-msec timing interval generated by decade counters IC 2, 3, 4 and a divide by two flip-flop IC 1. The negative-going edge detector signal (IC 6, pin 1) has the next highest priority. The positive-going telemetered signal (IC 6, pin 2) is the lowest priority request.

When an input signal level change or a 1-msec interval occurs, the priority decoder generates an interrupt signal to the microprocessor (IC 6, pin 15). The interrupt signal causes the microprocessor to stop processing and to execute a vectored interrupt-service routine. A detailed description of the software routines is included in the appendix. Using the continuator to the service routine, the CPU (microprocessor central processing unit) reads either the time interval, R wave to R wave timing, or temperature cycle data. It then processes it and returns to the interrupted task.

The CPU acknowledges the interrupt request by sending an interrupt acknowledge signal, IRACK (ref. 33). The IRACK signal is used to clear the "D" type latch holding the interrupt request. It also allows the lower priority requests (if any) to be serviced in the same manner.

Figure 21 shows the view of the demodulator front panel for entering the command modes in the operation or calibration of the demodulator and displaying the real-time data. The switches are sensed by input port No. 7 to the 8080 card (fig. 22, IC 14, pin 8 and IC 15, pins 3 and 5).

The microprocessor reads the input instruction immediately after the power is "ON" or at any time the RESET key is depressed in the front panel. The RESET switch is connected to the CPU RST line and causes the displays to be initialized to zero, clears all memory, resets the time interval, clears all the interrupt latches and initializes the microprocessor program counter (internal to the CPU) to location zero. The calibration level (HI or LO) is read as an input when the software branches to the internal calibration routines.

Data to the front panel LED display is gated by the action of a de-multiplexer (IC 13) and the output instruction status line IC 13, pin 6. The data, in BCD form, is latched to the LED displays by the six enable lines from the demultiplexer and held until a new reading is made.

The analog outputs are generated by three 12-bit D/A converters that require one's complement BCD data. The software complements the data and transfers the first 8 bits to two quad D type flip flops. All 12 bits are presented to the digital to analog converters when the software outputs the last 4 inverted bits to a quad D type flip flop and an 8212 is enabled, latching the 8 bits stored in the two 74LS175 latches.

The output of the converters are buffered and connected to the three analog output lines on the back of the demodulator.

RESULTS AND DISCUSSION

The prototype of this system was tested on a dog. Preliminary tests were made with a transmitter breadboard mounted in a backpack worn by the animal. A standard ECG transmitter was also placed in the backpack. Two ECG electrodes were implanted subcutaneously with the leads brought out to the

backpack where they were connected to both transmitters via an RF isolation junction. Chart paper recordings were then made while the dog was exercised within the range of the transmitters or on a treadmill. The recordings allowed the heartbeat pulses, derived from the new system, to be compared directly with the clearly identifiable ECG waveform. Results were positive with only an occasional heartbeat pulse being lost by the new system during periods of heavy exercise. ECG recorded during the same sequence of exercise showed R-wave amplitude fluctuations of ±35% on a beat-to-beat basis. The triggering threshold of the R-wave detector had been set for a tracking rate that would accommodate amplitude changes of less than this and seemed to account for the occasionally missing beat. A nominal tracking rate of 40 to 50% of R-wave peak should alleviate the problem. Signal artifacts occasionally occur also, but appeared to be due to movements of the external leads and connections rather than to the electrodes.

Next, the packaged transmitter was implanted in an 18-kg dog. Two ECG electrodes and one thermistor were attached subcutaneously. Another thermistor was located near the liver for measurement of deep body temperature. After 1 week, tests with the dog in a kennel were begun. The RF signal from the implanted transmitter was received, without retransmission, using a standard AM receiver. The output pulses were applied directly to the demodulator. The three analog outputs of the demodulator and the pulse train from the receiver's output were recorded on chart paper. This allowed the heart rate, on a beat-to-beat basis, and the two body temperatures to be correlated with the transmitted pulse train. Several recordings were made, the longest being 24 hr. The demodulator and receiver maintained lock during all recording sessions, as indicated by the analog outputs which followed the pulse train without dropout.

Tests of the retransmitter collar were made next with the dog still in the kennel. In this instance, the retransmitted pulses were compared to the directly transmitted pulses. This was done by recording the outputs from each system on a chart recorder. But this time the demodulator was driven by the RF transmission link. Again, the three analog outputs were recorded for correlation with the two pulse trains, representing the direct and indirect transmissions. The retransmitted RF signal proved to be intermittent. Also, one temperature channel was in a continuous state of saturation. (Later investigation showed that a thermistor lead had broken.) Since the thermistor leads also serve as the transmitting antenna for the implanted unit, RF field-strength measurements were made to determine the effect of the broken lead. The RF pulses from within the animal were very weak at the normal operating frequency of 54 MHz. The first harmonic at 108 MHz was nearly 20 dB stronger, but still weak. Therefore, the receiver in the collar was returned to the stronger 108 MHz signal and a single stage of RF amplification added. The previous tests were repeated. This time the retransmitter collar locked onto the pulses from the implanted transmitter with no loss in data.

Next, both the retransmitter and the implanted transmitter were tested for maximum range. As can be seen in figure 21, the test site was located in a heavily industrialized area with numerous power lines and metal

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buildings nearby. In A, the view is over a salt marsh toward the receiving station which was a metal building indicated by the arrow; the distance is 1 km. In B, the view is in the opposite direction which shows the instrumented dog and the investigator within a fenced ranging area. The implanted unit had a range of about 12 m. The AM receiver had an output bandwidth of 10 kHz and a sensitivity of 1 μV. The antenna, which was mounted on a 3-m mast, provided a gain of 6.5 dB. Because the transmitter, with its broken antenna lead, was operating in a greatly impeded mode, an estimate of maximum range was made. This estimate for the improved range was based on a previous comparison of the measured field strength at the normal operating frequency of 54 MHz, with that of the 108 MHz harmonic. This measurement, made with the transmitter placed within saline filled bags, showed the 54 MHz fundamental to be 42 dB greater than the 108 MHz harmonic. Additionally, simulated heart rate was transmitted successfully under these conditions over a distance of 175 m using the 54 MHz operating frequency and with receiver and antenna characteristics similar to those used in the later tests in which the lead was broken. These indications suggest that the range of a properly operating transmitter should be about 150 m. Improvement to a useful range greater than 200 m should be possible in an ideal, rural environment, particularly if a higher gain receiving antenna were used.

Range tests of the retransmitting system were conducted within the same industralized location. The retransmission system included the collar-mounted retransmitter, tracking receiver, cassette recorder, and interface unit. The receiver was located in a large one-story metal building with the antenna mounted on a 4-m mast placed on the roof. Total height above ground was 9 m. This antenna provided a gain of 14.5 dB. As before, a chart recorder was used to provide real-time measurement of heart rate and body temperatures using the demodulator's analog outputs. However, the tracking receiver, with its tone-burst output, drove the demodulator via the interface circuit. Again, the transmitted pulse train was recorded on one of the chart recorder channels. In addition to these real-time recordings, the receiver's output, along with voice commentary, was recorded on magnetic tape for subsequent analysis in the laboratory. Included were data taken while the dog was field-exercised on a leash. Two-way voice communications between the investigator in the field and the operator in the station were maintained during these tests. Next, the dog was placed within a chain-link fenced enclosure 1 km from the receiving station (fig. 21(b)). While in the 2-acre enclosure, the dog was allowed to roam about freely. Visual observation was maintained using a telescope. Finally, with the dog still in the enclosure, the receiver and a hand-held antenna (fig. 13) were taken to various remote locations to simulate tracking conditions.

These tests indicated that it was possible to retrieve data with a signal-to-noise ratio of unity at the receiver's output as viewed on an oscilloscope. This corresponds to the conditions present at about 80% or greater of the maximum tracking range. At this distance, the operator begins to experience problems hearing a tone distinct enough from background noise to allow effective tracking. The tracking system used was indicated by the manufacturer to have ground-to-ground tracking capability up to 18 km under ideal geographical conditions. Thus, the modified system

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should provide some physiological data at a distance perhaps as much as 14 km, but many things would limit that capability substantially.

Analysis of the accuracy of the temperature data gave a result closer to ±0.3° C rather than the desired ±0.1° C. This was not accounted for in the transmission link, since the intervals of the temperature pulses could be resolved repeatively within 200 μsec. The minimum pulse interval, representing 0° C, was 176 msec. Additionally, the temperature data are scanned within a second or so at each reading, including the high- and low-temperature calibrations. Thus, the resolution of the RF-transmission link, plus the continuous updating for drift during the temperature scan, should provide the desired ±0.1° C accuracy during the life of the unit (an unknown being the effects of moisture on the thermistors). However, at the time of these tests, the demodulator was set up to resolve increments of 1 msec, which does not provide the required resolution. More resolution can be had by extending the intervals at the transmitting end, or by increasing the resolution within the demodulator itself. Increasing the transmitted intervals would of course enhance the RF link, but at the expense of interrupting more of the beat-to-beat heart rate. On the other hand, the demodulator could be changed to provide the added resolution without changing the data format. The temperature cycle could be less frequent also. As indicated before, the system has sufficient flexibility within its basic design to allow a variety of easily implemented options for operation.

CONCLUSION

The system described here provides heart rate and two body temperature measurements. The implantable transmitter is pulsed at each heartbeat with an interruption of 1-2 sec every 50 beats for transmission of temperature data. Low-powered, integrated circuits allow the system to be operated for a year or longer in animals that weigh a few kilograms or more. Direct transmission to an AM receiver operating at 54 MHz is possible at maximum ranges estimated to be 200 m. A retransmitter collar allows long-range transmission at 148 MHz. Radio-frequency links, originally designed for animal tracking, are used for retransmission. Physiological data can be recovered at distances within 80% of the maximum tracking range.

The system is designed to provide flexible capabilities, both at the transmitting and receiving ends. The transmitter's circuitry can be readily altered to sample more temperature sensors, and at different heartbeat intervals, or to transmit only the heartbeats or only the temperatures at the decade counts of heartbeats. The demodulator is microprocessor controlled so that software changes and added memory can accommodate transmitter modifications, along with linearization of data parameters.

APPENDIX

TEMPERATURE AND HEART RATE BIOTELEMETRY

DEMODULATOR PROGRAM

```
0000            0005 ;*************************************************
0000            0010 ;*                                              *
0000            0015 ;*        NASA AMES RESEARCH CENTER             *
0000            0020 ;*          MOUNTAIN VIEW,CA                     *
0000            0025 ;*                                              *
0000            0030 ;*      WRITTEN BY RAFAEL MIRANDA,E.E.          *
0000            0035 ;*          JANUARY 1979                        *
0000            0040 ;*                                              *
0000    .       0045 ;*   NOTE: Z80 ASSEMBLY LANGUAGE CODE.          *
0000            0050 ;*                                              *
0000            0055 ;*************************************************
0000            0060 ;
0000            0065 ;INPUT AND OUTPUT PORT ASSIGNMENTS
0000            0070 ;
        0000    0075 PORT0:  EQU     0               ;ECG LED READOUT X10
        0001    0080 PORT1:  EQU     1               ;          X100
        0002    0085 PORT2:  EQU     2               ;T1 LED READOUT X1
        0003    0090 PORT3:  EQU     3               ;          X10
        0004    0095 PORT4:  EQU     4               ;T2 LED READOUT X1
        0005    0100 PORT5:  EQU     5               ;          X10
        0007    0105 PORT7:  EQU     7               ;FRONT PANEL IN PORT
0000            0110 ;                                AND TBG RESET FLAG.
0000            0115 ;
0000            0120 ;      **************************
0000            0125 ;      *                        *
0000            0130 ;      *    C O N S T A N T S .  *
0000            0135 ;      *                        *
0000            0140 ;      **************************
0000            0145 ;
        0000    0150 ZERO:   EQU     00H
        0001    0155 ONE:    EQU     01H
        0002    0160 TWO:    EQU     02H
        0008    0165 EIGHT:  EQU     08H
        0009    0170 NINE:   EQU     09H
        000A    0175 TEN:    EQU     10
        0011    0180 ELEVN:  EQU     11H
        0032    0185 FIFTY:  EQU     50
0000            0190 ;
0000            0195 ;SIXTY THOUSAND MILLISECONDS
        EA60    0200 SIXTY:  EQU     60000
        00FF    0205 INF:    EQU     0FFH            ;INFINITY
0000            0210 ;
0000            0215 ;TEMPERATURE PULSE WIDTH LIMITS
0000            0216 ;       IN MILLISECONDS
0000            0220 ;
        0012    0225 TMPLW:  EQU     18              ;LOW TEMP LIMIT
        0019    0230 TMPUW:  EQU     25              ;HIGH TEMP LIMIT
        0006    0235 ECGLW:  EQU     6               ;LOW LIMIT ECG
        000B    0240 ECGUW:  EQU     11              ;UPPER LIMIT ECG
0000            0245 ;
0000            0250 ;CALIBRATION TIME FOR 600 MSEC
        0058    0255 CALTL:  EQU     58H             ;CAL TIME LOW (BYTE)
        0062    0260 CALTH:  EQU     62H             ;CAL TIME HIGH (BYTE)
0000            0265 ;
0000            0270 ;NUMBER OF PULSES IN TEMPERATURE CYCLE
        000A    0275 FIVEDP: EQU     5*2
0000            0280 ;
0000            0285 ;16 BIT DIVISION SHIFT COUNT:
```

```
        0011                    0290 SHFCNT  EQU    17
0000                            0295 ;INTERRUPT RESTART ROUTINES
0000                            0300 ;
0000                            0305 ;ENABLED BY HARDWARE ONLY
0000                            0310 ;
0000                            0315 ;****************************************
0000                            0320 ;
0000                            0325 ;RSTRT: RE-START LOCATION  FORCED BY HITTING
0000                            0330 ;        THE RESET SWITCH IN THE FRONT
0000                            0335 ;        PANEL  OR  DURING  POWER-ON  START UP
0000                            0340 ;        PROCEDURE.
0000                            0345 ;
0000                            0350 ;****************************************
0000                            0355 ;
0000                            0360 ;ORG  0000H
0000                            0365 ;
0000    F3                      0370 RSTRT:  DI                  ;DISABLE HARDWARE INT.
0001    31 60 10                0375         LD     SP,ERAM      ;STACK TO END OF RAM
0004    C3 38 00                0380         JP     RESET
0007                            0385 ;
0007                            0390 ;
0007    00 00                   0395         DW     0
0009    00 00                   0400         DW     0
000B    00 00                   0405         DW     0
000D    00 00                   0410         DW     0
000F    00 00                   0415         DW     0
0011    00 00                   0420         DW     0
0013    00 00                   0425         DW     0
0015    00 00                   0430         DW     0
0017    00 00                   0435         DW     0
0019    00 00                   0440         DW     0
001B    00 00                   0445         DW     0
001D    00 00                   0450         DW     0
001F    00                      0455         DB     0
0020                            0460 ;
0020                            0465 ;****************************************
0020                            0470 ;
0020                            0475 ;NEGRST
0020                            0480 ;        NEGATIVE GOING PULSE RESTART LOCATION
0020                            0485 ;        RST4 ... LOWEST PRIORITY
0020                            0490 ;        GETS FLAG AND VERIFIES IF THE LAST
0020                            0495 ;        FLAG WAS AN ECG FLAG OR A TEMPERATURE
0020                            0500 ;        FLAG
0020                            0505 ;
0020                            0510 ;        PRESERVES ALL REGISTERS
0020                            0515 ;
0020                            0520 ;****************************************
0020                            0525 ;
0020    F5                      0530 NEGRST  PUSH   AF
0021    E5                      0535         PUSH   HL
0022    21 01 2C                0540         LD     HL,DUMTM
0025    C3 63 00                0545         JP     NEGCNT       ;EXIT TO CONTINUATOR
```

```
0028                    0555  ;*************************************************
0028                    0560  ;
0028                    0565  ;POSRST.
0028                    0570  ;          POSITIVE GOING PULSE RESTART LOCATION
0028                    0575  ;          RST5 ... PRIORITY=2 (1=HIGHEST)
0028                    0580  ;          STORES TIME INTERVAL BETWEEN PULSES
0028                    0585  ;          IN "TIME", TO BE USED IN COMPUTATIONS
0028                    0590  ;
0028                    0595  ;          PRESERVES ALL REGISTERS
0028                    0600  ;*************************************************
0028                    0605  ;
0028   F5               0610  POSRST:   PUSH   AF
0029   E5               0615            PUSH   HL
002A   21 01 0C         0620            LD     HL,DUMTM
002D   C3 8C 00         0625            JP     POSCNT    ;EXIT TO CONTINUATOR
0030                    0630  ;
0030                    0635  ;
0030                    0640  ;
0030                    0645  ;
0030                    0650  ;
0030                    0655  ;*************************************************
0030                    0660  ;
0030                    0665  ;TBGRST.
0030                    0670  ;          TIME BASE GENERATOR RESTART LOCATION
0030                    0675  ;          RST6 ... HIGHEST PRIORITY
0030                    0680  ;          INCREMENTS "DUMTM" BY ONE
0030                    0685  ;
0030                    0690  ;          PRESERVES ALL REGISTERS
0030                    0695  ;
0030                    0700  ;*************************************************
0030                    0705  ;
0030   F5               0710  TBGRST:   PUSH   AF
0031   E5               0715            PUSH   HL
0032   21 01 0C         0720            LD     HL,DUMTM
0035   C3 BA 00         0725            JP     TBCNT     ;EXIT TO CONTINUATOR
```

```
0038                0735  ;*********************************************
0038                0740  ;
0038                0745  ;RESET:
0038                0750  ;         RSTRT CONTINUATOR
0038                0755  ;         INITIALIZES FRONT PANEL LED DISPLAYS
0038                0760  ;         TO
0038                0765  ;              000    00.0    00.0
0038                0770  ;         READS FRONT PANEL SWITCHES
0038                0775  ;  .
0038                0780  ;*********************************************
0038                0785  ;
0038   DB 07         0790  RESET:   IN    A,PORT7     ;READ SWITCHES
003A   4F            0795           LD    B,A
003B   E6 01         0800           AND   ONE
003D   CA 9C 02      0805           JP    Z,CAL       ;IF PORT7=1..CALIBRATE
0040                0810  ;
0040   AF            0815  OPRTE:   XOR   A           ;CLEAR ACC. AND CY
0041   21 00 0C      0820           LD    HL,RAM      ;RAM ORG. TO HL
0044   06 13         0825           LD    B,RAMEND
0046                0830  ;
0046   77            0835  CLRLP:   LD    (HL),A      ;CLEAR RAM
0047   05            0840           DEC   B
0048   23            0845           INC   HL
0049   B8            0850           CP    B           ;WAIT UNTIL B=0H
004A   C2 46 00      0855           JP    NZ,CLRLP
004D                0860  ;
004D                0865  ;CLEAR ALL LED DISPLAYS
004D                0870  ;
004D   D3 00         0875           OUT   PORT0,A
004F   D3 01         0880           OUT   PORT1,A
0051   D3 02         0885           OUT   PORT2,A
0053   D3 03         0890           OUT   PORT3,A
0055   D3 04         0895           OUT   PORT4,A
0057   D3 05         0900           OUT   PORT5,A
0059                0905  ;
0059                0910  ;RESET REAL TIME CLOCK
0059                0915  ;
0059   D3 07         0920           OUT   PORT7,A
005B   3E 01         0925           LD    A,ONE       ;SET UP START OF CLOCK
005D   D3 07         0930           OUT   PORT7,A     ;START 1 MSEC TIMER
005F                0935  ;
005F   FB            0940           EI                ;ALLOW HARDWARE INT.
0060                0945  ;
0060   C3 60 00      0950  WAIT:    JP    WAIT        ;WAIT FOR AN INTERRUPT
```

```
0063                    0960  ;******************************************
0063                    0965  ;
0063                    0970  ;NEGCNT:
0063                    0975  ;       CONTINUATOR ROUTINE TO NEGRST
0063                    0980  ;       CHECKS TIME INTERVAL BETWEEN PULSES
0063                    0985  ;       IF IT CHECKS WITHIN THE PRE-SET LIMITS
0063                    0990  ;       UPDATES THE ECG OR TEMP. FLAG
0063                    0995  ;
0063                    1000  ;******************************************
0063                    1005  ;
0063   3E 12            1010  NEGCNT: LD      A,TMPLW   ;GET TEMP LOWER LIMIT
0065   BE               1015          CP      (HL)
0066   D2 6F 00         1020          JP      NC,NXTST  ;IF G.T. CONTINUE
0069   7E               1025          LD      A,(HL)    ;TEST UPPER LIMIT
006A   FE 19            1030          CP      TMPUW     ;IF L.T GO TO TEMPF
006C   DA 7F 00         1035          JP      C,TEMPF   ;IF NOT CONTINUE
006F                    1040  ;
006F   3E 06            1045  NXTST:  LD      A,ECGLW   ;GET ECG LOWER LIMIT
0071   BE               1050          CP      (HL)
0072   D2 7B 00         1055          JP      NC,NFLG   ;EXIT IF SMALLER
0075   7E               1060          LD      A,(HL)
0076   FE 0B            1065          CP      ECGUW     ;IF L.T. GO TO ECGF
0078   DA 84 00         1070          JP      C,ECGF    ;IF NOT CONTINUE
007B                    1075  ;
007B   AF               1080  NFLG    XOR     A         ;CURRENT FLAG=0
007C   C3 86 00         1085          JP      ENDNEG
007F                    1090  ;
007F   3E 02            1095  TEMPF:  LD      A,TWO     ;PULSE W/IN TEMP LIMIT
0081   C3 86 00         1100          JP      ENDNEG
0084                    1105  ;
0084   3E 01            1110  ECGF:   LD      A,ONE     ;PULSE W/IN TEMP LIMIT
0086                    1115  ;
0086   2B               1120  ENDNEG: DEC     HL
0087   77               1125          LD      (HL),A    ;STORE RESULT IN "FLAG"
0088                    1130  ;
0088   E1               1135          POP     HL
0089   F1               1140          POP     AF
008A   FB               1145          EI                ;ALLOW HIGHER
008B                    1150  ;                         PRIORITY INTERRUPTS
008B                    1155  ;
008B   C9               1160          RET
```

```
008C                    1170  ;*************************************************
008C                    1175  ;
008C                    1180  ;POSCNT:
008C                    1185  ;        CONTINUATOR ROUTINE TO POSRST
008C                    1190  ;        STORES TEMPORARY VALUE OF "DUMTM"
008C                    1195  ;        INTO "TIME". CLEARS TEMPORARY VALUE
008C                    1200  ;        OF "DUMTM"; COMPUTES H.R. OR TEMP
008C                    1205  ;
008C                    1210  ;        CHECKS "BUSY" FLAG (IF "BUSY", RETURNS
008C                    1215  ;        WAITS FOR INTERRUPTS
008C                    1220  ;
008C                    1225  ;*************************************************
008C                    1230  ;
008C    D3 07           1235  POSCNT: OUT    PORT7,A    ;RESET INSEL TIMER
008E    7E             1240           LD     A,(HL)     ;GET LOW BYTE OF TIME
008F    32 02 0C        1245           LD     (TIME),A   ;STORE IT IN "TIME"
0092    AF             1250           XOR    A
0093    77             1255           LD     (HL),A     ;CLEAR TEMPO. STORAGE
0094    23             1260           INC    HL
0095    7E             1265           LD     A,(HL)     ;DO THE SAME FOR
0096    32 03 0C        1270           LD     (TIME+1),A ;HIGH ORDER BYTE
0099    AF             1275           XOR    A
009A    77             1280           LD     (HL),A     ;CLEAR TEMPO. STORAGE
009B                    1285  ;
009B    3A 12 0C        1290           LD     A,(BUSY)   ;CHECK IF BUSY
009E    FE 01          1295           CP     ONE        ;IF NOT DONE RETURN
00A0    C2 A7 00        1300           JP     NZ,SKIPIT  ;IF DONE GO TO SKIPIT
00A3                    1305  ;
00A3    E1             1310           POP    HL
00A4    F1             1315           POP    AF
00A5                    1320  ;
00A5    FB             1325           EI                ;ALLOW HARDWARE INT.
00A6    C9             1330           RET
00A7                    1335  ;
00A7    E1             1340  SKIPIT: POP    HL
00A8    F1             1345           POP    AF         ;FLAG WAS DONE
00A9    FB             1350           EI                ;ALLOW 18G TO INT
00AA                    1355  ;
00AA    3A 00 0C        1360  CHLOUT: LD     A,(FLAG)
00AD    47             1365           LD     B,A        ;PREVENT CHANGING THE
00AE    E6 01          1370           AND    ONE        ;TIME VALUES
00B0    C2 C7 00        1375           JP     NZ,ECGSUB  ;IF FLAG=1 THEN ECGSUB
00B3                    1380  ;
00B3    78             1385           LD     A,B
00B4    E6 02          1390           AND    TWO        ;TEMP CALCULATION?
00B6    C2 04 01        1395           JP     NZ,TMPSUB  ;IF NOT RETURN TO WAIT
00B9                    1400  ;
00B9    C9             1405           RET
```

```
00BA                              1415  ;**********************************************
00BA                              1420  ;
00BA                              1425  ;TBCNT:
00BA                              1430  ;       CONTINUATOR ROUTINE TO TBGRST
00BA                              1435  ;       INCREMENTS TEMPORARY STORAGE FOR TIME
00BA                              1440  ;       BY ONE MILLISECOND. RETURNS
00BA                              1445  ;
00BA                              1450  ;       ALL REGISTERS PRESERVED
00BA                              1455  ;
00BA                              1460  ;**********************************************
00BA                              1465  ;
00BA                              1470  ;
00BA      3E 01                   1475  TBCNT:  LD      A,ONE     ;INCREMENT "DUMTM"
00BC      86                      1480          ADD     (HL)      ;BY ONE
00BD      77                      1485          LD      (HL),A    ;STORE IT
00BE      23                      1490          INC     HL        ;INCR. HIGH ORDER BYTE
00BF      3E 00                   1495          LD      A,ZERO
00C1      8E                      1500          ADC     (HL)      ;ADD CY TO (HIGH) BYTE
00C2      77                      1505          LD      (HL),A    ;BYTE AND STORE IT
00C3                              1510  ;
00C3      E1                      1515          POP     HL
00C4      F1                      1520          POP     AF
00C5                              1525  ;
00C5      FB                      1530          EI                ;ALLOW HARDWARE INT.
00C6      C9                      1535          RET
```

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00C7                    1545 ;********************************************
00C7                    1550 ;
00C7                    1555 ;ECGSUB:
00C7                    1560 ;          COUNTS NUMBER OF ECG PULSES:
00C7                    1565 ;          CALCULATES HEART RATE
00C7                    1570 ;          CONVERTS BINARY RESULT TO BCD
00C7                    1575 ;          OUTPUTS RESULT TO FRONT PANEL
00C7                    1580 ;          RETURNS TO WAIT FOR A NEW
00C7                    1585 ;          INSTRUCTION OR INTERRUPT
00C7                    1590 ;
00C7                    1595 ;********************************************
00C7                    1600 ;
00C7  3A 09 0C          1605 ECGSUB: LD    A,(ECGCNT);GET NUMBER OF R WAVES
00CA  FE 00             1610         CP    ZERO      ;IS IT THE FIRST BEAT?
00CC  C2 DE 00          1615         JP    NZ,COUNT1 ;IF YES, CONTINUE
00CF                    1620 ;
00CF                    1625 ;FIRST BEAT INDICATES A T CYCLE OR ECG BEAT
00CF                    1630 ;
00CF  3A 06 0C          1635         LD    A,(CTRTEM);GET # OF TEMP. PULSES
00D2  FE 0A             1640         CP    FIVEDP    ;IS # OF PULSES
00D4                    1645 ;EQUAL TO FIVEPY. IF YES GO TO TMPOUT
00D4                    1650 ;TO CALCULATE TEMPERATURES & OUTPUT RESULTS
00D4  CA C8 01          1655         JP    Z,TMPOUT
00D7                    1660 ;
00D7  AF                1665         XOR   A         ;NOT A TEMP CYCLE
00D8  32 06 0C          1670         LD    (CTRTEM),A;RESET TEMP COUNTER
00DB  C3 E4 00          1675         JP    GOBACK
00DE                    1680 ;
00DE  FE 32             1685 COUNT1: CP    FIFTY     ;50 R WAVES COUNTED?
00E0  C2 E9 00          1690         JP    NZ,SKPCLR ;IF NOT CONTINUE
00E3  AF                1695         XOR   A         ;CLEAR R WAVE COUNT
00E4                    1700 ;
00E4  3C                1705 GOBACK: INC   A
00E5  32 09 0C          1710         LD    (ECGCNT),A;STORE VALUE OF ONE
00E8  C9                1715         RET
00E9                    1720 ;
00E9  3C                1725 SKPCLR: INC   A         ;UPDATE R WAVE COUNT
00EA  32 09 0C          1730         LD    (ECGCNT),A;STORE IT
00ED                    1735 ;
00ED                    1740 ;START CALCULATING HEART RATE
00ED                    1745 ;
00ED  CD 25 01          1750         CALL  BSYDNE    ;SET BUSY FLAG
00F0  11 60 EA          1755         LD    DE,SIXTY  ;DIVIDEND=60000 MSEC.
00F3                    1760 ;
00F3                    1765 ;DIVIDE 60000 MSEC BY RR INTERVAL IN "TIME"
00F3                    1770 ;
00F3  CD 37 01          1775         CALL  DIVIDE    ;GET BINARY HEART RATE
00F6  CD 71 01          1780         CALL  BINBCD    ;BINARY TO DECIMAL
00F9                    1785 ;
00F9  79                1790         LD    A,C       ;GET H.R. X 1
00FA  D3 00             1795         OUT   PORT0,A    ;LEAST SIGNIFICANT LED
00FC  78                1800         LD    A,B       ;GET HEART RATE X 100
00FD  D3 01             1805         OUT   PORT1,A    ;MOST SIGNIFICANT HR
00FF  AF                1810         XOR   A         ;CLEAR BUSY FLAG
0100  32 12 0C          1815         LD    (BUSY),A  ;STORE IT
0103                    1820 ;
0103  C9                1825         RET
```

```
0104                    1835    ;******************************************
0104                    1840    ;*                                        *
0104                    1845    ;*  TMPSUB:                                *
0104                    1850    ;*         STORES TEMPERATURE INTERVAL IN  *
0104                    1855    ;*         SEQUENCE: T0(REF),T1,T2,T50(REF) *
0104                    1860    ;*         CLEARS R WAVE COUNT             *
0104                    1865    ;*                                        *
0104                    1870    ;******************************************
0104                    1875    ;
0104    CD 25 01        1880    TMPSUB: CALL    BSYDNE
0107                    1885    ;
0107    3A 06 0C        1890            LD      A,(CTRTEM);GET TEMP. CYCLE COUNT
010A    3C              1895            INC     A
010B    3C              1900            INC     A        ;UPDATE IT BY TWO
010C    32 06 0C        1905            LD      (CTRTEM),A,STORE IT
010F                    1910    ;
010F    21 08 0C        1915            LD      HL,SAVTIM ;MSAVE IT
0112    85              1920            ADD     L
0113    6F              1925            LD      L,A      ;UPDATE T CYCLE PTR
0114    3A 03 0C        1930            LD      A,(DIVTM)
0117    77              1935            LD      (HL),A   ;STORE TIME INTERVAL
0118                    1940    ;
0118    23              1945            INC     HL
0119    3A 04 0C        1950            LD      A,(DIVTM+1)
011C    77              1955            LD      (HL),A   ;HIGH ORDER BYTE
011D    AF              1960            XOR     A        ;CLEAR ECG COUNT
011E    32 09 0C        1965            LD      (ECGCNT),A
0121                    1970    ;
0121    32 12 0C        1975            LD      (BUSY),A
0124                    1980    ;
0124    C9              1985            RET
0125                    1990    ;
0125                    1995    ;******************************************
0125                    2000    ;*                                        *
0125                    2005    ;* BSYDNE:                                 *
0125                    2010    ;*         SETS UP BUSY FLAG               *
0125                    2015    ;*         MOVES TEMPORARY TIME INTERVAL   *
0125                    2020    ;*         TO "DIVTM"..TIME TO BE USED IN   *
0125                    2025    ;*         COMPUTATIONS                     *
0125                    2030    ;*                                        *
0125                    2035    ;******************************************
0125                    2040    ;
0125    3E 01           2045    BSYDNE  LD      A,ONE    ;SET UP BUSY FLAG
0127                    2050    ;
0127    32 12 0C        2055            LD      (BUSY),A
012A    21 02 0C        2060            LD      HL,TIME
012D    7E              2065            LD      A,(HL)   ;GET LOW ORDER TIME
012E    32 03 0C        2070            LD      (DIVTM),A ;STORE IT IN PERMNT.
0131    23              2075            INC     HL
0132    7E              2080            LD      A,(HL)   ;HIGH ORDER TIME
0133    32 04 0C        2085            LD      (DIVTM+1),A;STORE IT
0136                    2090    ;
0136    C9              2095            RET
```

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0137                    2105  ;************************************************
0137                    2110  ;*                                            *
0137                    2115  ;*   DIVIDE:                                   *
0137                    2120  ;*         DIVIDES A 16 BIT DIVISOR IN THE BC  *
0137                    2125  ;*         REGISTERS BY A 16 BIT DIVIDEND IN   *
0137                    2130  ;*         THE DE REGS.  RESULT IS RETURNED    *
0137                    2135  ;*         IN THE DE & HL REGISTERS.           *
0137                    2140  ;*                                            *
0137                    2145  ;************************************************
0137                    2150  ;
0137  21 05 0C          2155  DIVIDE:  LD    HL,BNUM    ;COUNTER ADDRESS
013A  36 11             2160           LD    (HL),SHFCNT;START SHIFT COUNT
013C  01 00 00          2165           LD    BC,ZERO
013F                    2170  ;
013F  7B                2175  DLOOP:   LD    A,E        ;ROTATE DIVISOR
0140  17                2180           RLA              ;LEFT ONE BIT
0141  5F                2185           LD    E,A
0142  7A                2190           LD    A,D
0143  17                2195           RLA
0144  56                2200           LD    D,(HL)     ;DECREMENT BIT COUNTER
0145  15                2205           DEC   D
0146  72                2210           LD    (HL),D
0147  57                2215           LD    D,A
0148  CA 6F 01          2220           JP    Z,ENDDIV   ;RETURN IF COUNT=0
014B                    2225  ;
014B  79                2230           LD    A,C        ;ROTATE RESULT
014C  17                2235           RLA              ;LEFT ONE BIT
014D  4F                2240           LD    C,A
014E  78                2245           LD    A,B
014F  17                2250           RLA
0150  47                2255           LD    B,A
0151  21 03 0C          2260           LD    HL,DIVIH   ;GET DIVIDEND ADDR.
0154                    2265  ;
0154  79                2270           LD    A,C        ;SUBTRACT LOW
0155  96                2275           SUB   (HL)       ;ORDER BYTE OF
0156  4F                2280           LD    C,A        ;DIVIDEND
0157  2C                2285           INC   L
0158  78                2290           LD    A,B        ;SUBTRACT HIGH
0159  9E                2295           SBC   (HL)       ;ORDER BYTE
015A                    2300  ;
015A  47                2305           LD    B,A        ;NO BORROW?
015B  D2 66 01          2310           JP    NC,DSKIP   ;IF YES ADDRESS LO BYTE
015E  2D                2315           DEC   L
015F  79                2320           LD    A,C        ;ADD DIVIDEND BACK
0160  86                2325           ADD   (HL)
0161  4F                2330           LD    C,A
0162  2C                2335           INC   L
0163  78                2340           LD    A,B
0164  8E                2345           ADC   (HL)
0165  47                2350           LD    B,A
0166                    2355  ;
0166  21 05 0C          2360  DSKIP    LD    HL,BNUM    ;RESTORE ADDR. OF CNTR
0169  9F                2365           SBC   H          ;COMPLEMENT CARRY
016A  DE 80             2370           SBC   080H
016C  C3 3F 01          2375           JP    DLOOP      ;REPEAT
016F                    2380  ;
016F  EB                2385  ENDDIV·  EX    DE,HL      ;STORE RESULT IN HL
0170  C9                2390           RET
```

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```
0171                    2395  ;************************************************
0171                    2400  ;                                              ;
0171                    2405  ; BINBCD:                                      ;
0171                    2410  ;          16 BIT BINARY TO BCD CONVERSION     ;
0171                    2415  ;          BINARY NUMBER IN HL:                ;
0171                    2420  ;              H=HIGH  L=LOW ORDER BYTE         ;
0171                    2425  ;          RESULT:  A=X10,000 B=X100  C=X1      ;
0171                    2430  ;                                              ;
0171                    2435  ;************************************************
0171                    2440  ;
0171    1E 11           2445  BINBCD: LD      E,ELEVN    ;SET BIT COUNTER
0173    CD 84 01        2450          CALL    BCD
0176    4F              2455          LD      C,A        ;SAVE L.SIG. BCD BYTE
0177    1E 11           2460          LD      E,ELEVN
0179    C3 7E 01        2465          JP      BNEXT
017C                    2470  ;
017C    1E 09           2475          LD      E,NINE
017E    CD 84 01        2480  BNEXT:  CALL    BCD
0181    47              2485          LD      B,A
0182    7D              2490          LD      A,L
0183    C9              2495          RET                ;DONE
0184                    2500  ;
0184    AF              2505  BCD:    XOR     A
0185    1D              2510  CVT:    DEC     E
0186    C8              2515          RET     Z
0187    29              2520          ADD     HL,HL
0188    8F              2525          ADC     A
0189                    2530  ;
0189    27              2535          DAA
018A    D2 85 01        2540          JP      NC,CVT
018D    23              2545          INC     HL
018E    C3 85 01        2550          JP      CVT
```

```
0191                    2560 ;**********************************************
0191                    2565 ;                                            ;
0191                    2570 ; MULT·               \                      ;
0191                    2575 ;      16 BIT BY 8 BIT MULTIPLICATION         ;
0191                    2580 ;      BC=MULTIPLICAND   X H(MULTIPLIER)=     ;
0191                    2585 ;      DE(PRODUCT). BC X H=DE REGISTERS        ;
0191                    2590 ;                                            ;
0191                    2595 ;**********************************************
0191                    2600 ;
0191   11 00 00         2605 MULT:   LD    DE,ZERO    ;ERASE PRODUCT
0194                    2610 ;
0194   87               2615 MLOOP:  OR    A          ;CLEAR CARRY
0195   7C               2620         LD    A,H
0196   1F               2625         RRA
0197   67               2630         LD    H,A
0198                    2635 ;
0198                    2640 ;IF MULTIPLIER BIT=1,ADD MPCND TO PRODCT
0198   DC A7 01         2645         CALL  C,MADD
019B                    2650 ;
019B   7C               2655         LD    A,H        ;EXIT IF MPIER IS 0
019C   A7               2660         AND   A
019D   C8               2665         RET   Z          ;RETURN
019E                    2670 ;
019E   79               2675         LD    A,C        ;  OTHERWISE
019F   17               2680         RLA              ;    SHIFT
01A0   4F               2685         LD    C,A        ; MULTIPLICAND
01A1   78               2690         LD    A,B        ;    LEFT
01A2   17               2695         RLA              ;    AND
01A3   47               2700         LD    B,A        ;    REPEAT
01A4   C3 94 01         2705         JP    MLOOP
01A7                    2710 ;
01A7   79               2715 MADD:   LD    A,C        ;ADD PARTIAL
01A8   83               2720         ADD   E          ;PRODUCT
01A9   5F               2725         LD    E,A
01AA   78               2730         LD    A,B
01AB   8A               2735         ADC   D
01AC   57               2740         LD    D,A
01AD   C9               2745         RET
```

```
01AE                    2755  ;*************************************************
01AE                    2760  ;                                               ;
01AE                    2765  ;  MPYX10:                                       ;
01AE                    2770  ;        MULTIPLIES DE REGISTER BY 16            ;
01AE                    2775  ;        AND PLACES RESULT IN DE                 ;
01AE                    2780  ;                                               ;
01AE                    2785  ;        REGISTERS AFFECTED: HL,AB,DE            ;
01AE                    2790  ;                                               ;
01AE                    2795  ;*************************************************
01AE                    2800  ;
01AE    6B              2805  MPYX10: LD     L,E          ;MOVE HL TO DE
01AF    62              2810          LD     H,D
01B0    06 FD           2815          LD     B,-3         ;SET UP COUNT
01B2    B7              2820          OR     A            ;CLEAR CARRY
01B3                    2825  ;
01B3    04              2830  LOOP10: INC    B
01B4    7D              2835          LD     A,L
01B5    17              2840          RLA
01B6    6F              2845          LD     L,A          ;MULTIPLY RESULT
01B7    7C              2850          LD     A,H          ;   BY
01B8    17              2855          RLA                 ;   EIGHT
01B9    67              2860          LD     H,A
01BA    78              2865          LD     A,B
01BB    C2 B3 01        2870          JP     NZ,LOOP10 ;X8 IN HL REG.
01BE                    2875  ;
01BE    B7              2880          OR     A            ;MULTIPLY
01BF    7B              2885          LD     A,E          ;   AGAIN
01C0    17              2890          RLA                 ;   BY
01C1    5F              2895          LD     E,A          ;   TWO
01C2    7A              2900          LD     A,D
01C3    17              2905          RLA
01C4    57              2910          LD     D,A          ;X2 IN DE REG.
01C5    19              2915          ADD    HL,DE        ;ADD X8 + X2
01C6    EB              2920          EX     DE,HL        ;RESULT TO DE
01C7                    2925  ;
01C7    C9              2930          RET
```

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```
01C8                    2940 ;*****************************************
01C8                    2945 ;                                        ;
01C8                    2950 ; TMPOUT:                                 ;
01C8                    2955 ;        COMPUTES T1 AND T2 (UNKNOWN):    ;
01C8                    2960 ;                                         ;
01C8                    2965 ; T(UNKNOWN)=((T(UNKNOWN)-T0)/(150-T0))*50 ;
01C8                    2970 ;                                         ;
01C8                    2975 ;        IF T50 WAS NOT UPDATED OR        ;
01C8                    2980 ;        IF T(UNKNOWN)-T0 IS NEGATIVE OR   ;
01C8                    2985 ;        IF RESULT IS G.T  50 IT ABORTS   ;
01C8                    2990 ;                                         ;
01C8                    2995 ;        OUTPUTS RESULTS TO FRONT PANEL   ;
01C8                    3000 ;                                         ;
01C8                    3005 ;        DISABLES INTERRUPTS DURING CRITICAL ;
01C8                    3010 ;        CALCULATIONS                     ;
01C8                    3015 ;                                         ;
01C8                    3020 ;*****************************************
01C8                    3025 ;
01C8      3E 01         3030 TMPOUT: LD    A,ONE      ;SET BUSY FLAG
01CA      32 12 0C      3035         LD    (BUSY),A   ;STORE IT
01CD      32 09 0C      3040         LD    (ECOUNT),A ;ECL COUNT=1
01D0      AF            3045         XOR   A          ;CLEAR CARRY
01D1      32 06 0C      3050         LD    (CTPTEM),A ;TEMP CTR=0
01D4                    3055 ;
01D4      21 10 0C      3060         LD    HL,TEMPST+6; GET T50(REF)
01D7      7E            3065         LD    A,(HL)     ;A HAS T50
01D8      FE 00         3070         CP    ZERO       ;UPDATED?
01DA      CC 1D 02      3075         CALL  Z,TEST2    ;IF NOT,RETURN
01DD                    3080 ;
01DD      21 0A 0C      3085         LD    HL,TEMPST  ;GET T0 (REF)
01E0      4E            3090         LD    C,(HL)     ;C HAS LOW ORDER BYT
01E1      96            3095         SUB   (HL)
01E2      32 03 0C      3100         LD    (DIVTM),A  ;PARTIAL RESULT
01E5      21 11 0C      3105         LD    HL,TEMPST+7;BYTE 2
01E8      7E            3110         LD    A,(HL)
01E9      21 0B 0C      3115         LD    HL,TEMPST+1;T0 (REF) HIGH
01EC      F3            3120         DI
01ED      46            3125         LD    B,(HL)
01EE      9E            3130         SBC   (HL)       ;T50-T0 HIGH ORDER
01EF      DA 0B 02      3135         JP    C,CLRFLG   ;IF NEGATIVE EXIT
01F2      32 04 0C      3140         LD    (DIVTM+1),A;STORE IT
01F5      23            3145         INC   HL         ;GET T1 POINTER
01F6      C5            3150         PUSH  BC
01F7                    3155 ;
01F7      CD 27 02      3160         CALL  TMPGO      ;CALCULATE T1
01FA      D3 02         3165         OUT   PORT2,A    ;T1 TO LED display
01FC      78            3170         LD    A,B        ;Most significant
01FD      D3 03         3175         OUT   PORT3,A    ;result to T1
01FF      C1            3180         POP   BC
0200                    3185 ;
0200      21 0E 0C      3190         LD    HL,TEMPST+4;GET T2 POINTER
0203      CD 27 02      3195         CALL  TMPGO      ;CALCULATE T2
0206                    3200 ;
0206      D3 04         3205         OUT   PORT4,A    ;L.S. BCD out
0208      78            3210         LD    A,B        ;Most significant
0209      D3 05         3215         OUT   PORT5,A    ;result to T2
```

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```
020B                3225 ;          ****************************************
020B                3230 ;          *                                      *
020B                3235 ;          *     TMPOUT (CONTINUATION)     *
020B                3240 ;          *                                      *
020B                3245 ;          ****************************************
020B                3250 ;
020B   FB           3255 CLRFLG: EI
020C   AF           3260        XOR     A            ;CLEAR BUSY FLAG
020D   32 10 0C     3265        LD      (TEMPST+6),A ;CLEAR TSO(REF)
0210   32 11 0C     3270        LD      (TEMPST+7),A
0213   32 12 0C     3275        LD      (BUSY),A
0216   C9           3280        RET                  ;RETURN TO MAIN PROG.
0217                3285 ;
0217                3290 ;
0217   21 0B 02     3295 EXEND: LD      HL,CLRFLG    ;EXCHANGE
021A   C1           3300        POP     BC           ;TOP OF STACK
021B   E3           3305        EX      (SP),HL      ;& RETURN TO CLR FLG
021C   C9           3310        RET
021D                3315 ;
021D                3320 ;
021D   4F           3325 TEST2: LD      C,A          ;STORE HIGH BYTE
021E   23           3330        INC     HL
021F   7E           3335        LD      A,(HL)
0220   C6 00        3340        ADD     ZERO         ;TEST LOW BYTE
0222   CA 0B 02     3345        JP      Z,CLRFLG
0225   79           3350        LD      H,C          ;RESTORE (HIGH) BYTE
0226   C9           3355        RET
0227                3360 ;
0227                3365 ;
0227   AF           3370 TMPGO: XOR     A            ;CALCULATE TEMP
0228   7E           3375        LD      A,(HL)
0229   91           3380        SUB     C
022A   4F           3385        LD      C,A
022B                3390 ;
022B   23           3395        INC     HL           ;SUBTRACT
022C   7E           3400        LD      A,(HL)       ;TS0(REF)-T0(REF)
022D   98           3405        SBC     B
022E   DA 17 02     3410        JP      C,EXEND      ;IF NEGATIVE RETURN
0231   47           3415        LD      B,A          ;TEMP STORE
0232                3420 ;
0232   21 03 0C     3425        LD      HL,DIVTM
0235   7E           3430        LD      A,(HL)
0236   3C           3435        INC     A
0237   91           3440        SUB     C            ;BC=T1 OR T2-T0(REF)
0238   23           3445        INC     HL
0239   7E           3450        LD      A,(HL)
023A   98           3455        SBC     B            ;(TS0-10+1)-(T1-T0)
023B   DA 17 02     3460        JP      C,EXEND      ;IF NEG.RETURN
023E   26 32        3465        LD      H,FIFTY      ;DEGREES
0240                3470 ;
0240   CD 91 01     3475        CALL    MULT         ;CALCULATE T1 OR T2
0243   CD 4B 02     3480        CALL    DIVSP
0246   CD 71 01     3485        CALL    BINBCD
0249   7D           3490        LD      A,L          ;Result X1
024A   C9           3495        RET
```

```
0248              3505  ;**********************************
024B              3510  ;                                 ;
024B              3515  ;DIVSP.                           ;
024B              3520  ;     CALLED BY TEMPGU, IT CALCULATES    ;
024B              3525  ;     ((T1 OR T2)-TU(REF)*50)/(T50-T0)   ;
024B              3530  ;     PRECISE TO ONE DECIMAL PLACE XX.X  ;
024B              3535  ;     DOES NOT ROUND OFF RESULT     ;
024B              3540  ;                                 ;
024B              3545  ;**********************************
024B              3550  ;
024B              3555  ;
024B  2A 03 0C    3560  DIVSP:  LD    HL,(DIVTM);GET DIVISOR
024E              3565  ;
024E              3570  ;DIVIDE T-T0*50/T50-T0
024E              3575  ;
024E  CD 6B 02    3580          CALL   DIV16U
0251  E5          3585          PUSH   HL          ;SAVE REMAINDER
0252              3590  ;
0252  CD AE 01    3595          CALL   MPYX10      ;DE(RESULT)=DEX10
0255  E1          3600          POP    HL          ;SAVE RESULT
0256  D5          3605          PUSH   DE
0257  EB          3610          EX     DE,HL       ;REMAINDER IN DE
0258  CD AE 01    3615          CALL   MPYX10      ;REMAINDERX10 IN DE
025B              3620  ;
025B  2A 03 0C    3625          LD    HL,(DIVTM);DIVIDE AGAIN
025E  CD 6B 02    3630          CALL   DIV16U      ;RESULT IN DE REG
0261  EB          3635          EX     DE,HL       ;RESULT TO HL
0262              3640  ;
0262  D1          3645          POP    DE          ;GET FIRST QUOTIENT
0263              3650  ;
0263              3655  ;ADD QUOTIENT TO RESULT
0263              3660  ;
0263  19          3665          ADD    HL,DE
0264  3E 01       3670          LD     H,ONE
0266  BA          3675          CP     D
0267  D0          3680          RET    NC          ;RETURN IF POSITIVE
0268  C3 17 02    3685          JP     EXEND
```

```
026B              3695  ;***************************************
026B              3700  ;                                      ;
026B              3705  ; DIVI6Q:                              ;
026B              3710  ;       CALLED BY DIVSP: IT CALCULATES  ;
026B              3715  ;       T(UNKNOWN) BY DIVIDING DE(DIVIDEND) ;
026B              3720  ;       BY HL (DIVISOR AND REMAINDER)   ;
026B              3725  ;       DE=RESULT                       ;
026B              3730  ;                                      ;
026B              3735  ;***************************************
026B              3740  ;
026B   22 07 0C   3745  DIVI6Q: LD    (TEMP),HL  ;SAVE DIVISOR
026E   21 05 0C   3750          LD    HL,BNUM    ;STORE BIT COUNT
0271   36 11      3755          LD    (HL),ELEVN
0273   01 00 00   3760          LD    BC,ZERO    ;INIT RESULT
0276   C5         3765          PUSH  BC
0277              3770  ;
0277   7B         3775  LOOPD:  LD    A,E        ;GET LWR DIVIDND BYT
0278   17         3780          RLA
0279   5F         3785          LD    E,A        ;SHIFT DIVIDEND
027A   7A         3790          LD    A,D
027B   17         3795          RLA              ;LEFT ONE BIT
027C   57         3800          LD    D,A
027D   35         3805          DEC   (HL)       ;DECR COUNT
027E   E1         3810          POP   HL         ;RESTORE TEMP RESULT
027F   C8         3815          RET   Z          ;ZERO COUNT?
0280   3E 00      3820          LD    A,ZERO
0282   CE 00      3825          ADC   ZERO       ;ADD CARRY
0284   29         3830          ADD   HL,HL      ;SHIFT LEFT ONCE
0285   44         3835          LD    B,H        ;HL TO ACC.
0286   85         3840          ADD   L
0287   2A 07 0C   3845          LD    HL,(TEMP)  ;GET DIVISOR ADDR
028A   95         3850          SUB   L          ;SUBTRACT IT
028B   4F         3855          LD    C,A
028C   78         3860          LD    A,B        ;TEMP RESULT
028D   9C         3865          SBC   H
028E   47         3870          LD    B,A
028F   C5         3875          PUSH  BC         ;SAVE TEMP RESULT
0290   D2 95 02   3880          JP    NC,SKIPD
0293   09         3885          ADD   HL,BC      ;ADD DIVISOR BACK
0294   E3         3890          EX    (SP),HL    ;REPLACE TEMP RESULT
0295   21 05 0C   3895  SKIPD:  LD    HL,BNUM    ;RESTORE HL
0298   3F         3900          CCF              ;COMPLEMENT CARRY
0299   C3 77 02   3905          JP    LOOPD      ;REPEAT
```

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```
029C              3915  ;*************************************************
029C              3920  ;                                              ;
029C              3925  ;  CHL-                                        ;
029C              3930  ;        EXERCISES ALL SUBROUTINES USED IN      ;
029C              3935  ;        CALCULATING HR. OR TEMPS.              ;
029C              3940  ;        OUTPUTS RESULTS TO FRONT PANEL         ;
029C              3945  ;                                              ;
029C              3950  ;*************************************************
029C              3955  ;
029C  3E 01       3960  CHL:    LD    A,ONE       ;SET UP FLAG
029E  32 00 0C    3965          LD    (FLAG),A    ;FOR HR MODE
02A1  32 69 0C    3970          LD    (LCCNT),H   ;SET UP HR ROUTINES
02A4  79          3975          LD    A,B
02A5  E6 02       3980          AND   TWO         ;TEST CAL FLG
02A7  CA 8F 02    3985          JP    Z,HICAL     ;IF LOW CAL,CONTINUE
02AA              3990  ;
02AA  AF          3995  LOCAL-  XOR   A
02AB  32 02 0C    4000          LD    (TIME),A
02AE  3E FF       4005          LD    A,INF       ;LARGE INT. BET P WAVES
02B0  3A 03 0C    4010          LD    A,(TIME+1)  ;STORE IT
02B3  CD D2 02    4015          CALL  GOCHL
02B6  11 F3 02    4020          LD    DE,TABLE     ;CAL TABLE
02B9  CD DE 02    4025  ENDCHL- CALL  PCHL         ;GET DATA OUT
02BC  C3 00 03    4030          JP    RSTRT        ;RE-START PROGRAM
02BF              4035  ;
02BF  3E 56       4040  HICHL-  LD    A,CALTL      ;CAL TIME LOW ORDER TO
02C1  32 02 0C    4045          LD    (TIME),A     ;GET TIME=600 MSEC
02C4  3E 62       4050          LD    A,CALTH      ;CAL TIME HIGH ORDER
02C6  32 03 0C    4055          LD    (TIME+1),A
02C9  CD D2 02    4060          CALL  GOCHL
02CC  11 FB 02    4065          LD    DE,HTABLE    ;HIGH CAL TABLE
02CF  C3 D9 02    4070          JP    ENDCHL
02D2              4075  ;
02D2  CD AA 00    4080  GOCHL-  CALL  CALOUT       ;ECG OUT
02D5  AF          4085          XOR   A            ;GET TEMP READY
02D6  32 09 0C    4090          LD    (ECOUNT),A
02D9  3E 0A       4095          LD    A,FIVEDP     ;GET BT CYCLE #
02DB  32 06 0C    4100          LD    (CTRTEM),A   ;STORE IT
02DE              4105  ;
02DE  21 0A 0C    4110  PCHL-   LD    HL,TEMPST
02E1  AF          4115          XOR   A
02E2  06 08       4120          LD    B,EIGHT      ;GET TABLE COUNT
02E4  1A          4125  PCONT-  LD    A,(DE)
02E5  77          4130          LD    (HL),A       ;TABLE TO RAM
02E6  05          4135          DEC   B
02E7  CA EF 02    4140          JP    Z,PEND       ;CONTINUE IF NOT DONE
02EA  13          4145          INC   DE
02EB  23          4150          INC   HL           ;UPDATE POINTERS
02EC  C3 E4 02    4155          JP    PCONT
02EF  CD AA 00    4160  PEND:   CALL  CALOUT       ;RET TO NORMAL
02F2  C9          4165          RET
```

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```
02F3                    4175  ;        ******************************************
02F3                    4180  ;        *                                        *
02F3                    4185  ;        *       CALIBRATION TIME TABLES:          *
02F3                    4190  ;        *                                        *
02F3                    4195  ;        *       NOTE: USED BY CAL ROUTINE         *
02F3                    4200  ;        *                                        *
02F3                    4205  ;        ******************************************
02F3                    4210  ;
02F3                    4215  ;CAL INTERVAL FOR T0,T1,T2 AND T50(REF)
02F3                    4220  ;EXPRESSED IN MILLISECONDS
02F3                    4225  ;
          02F3          4230  TABLE:   EQU      $
02F3  1E 01             4235  T0L:     DW       286
02F5  5A 01             4240  T1L:     DW       346
02F7  5A 01             4245  T2L      DW       346
02F9  96 01             4250  T50L:    DW       406
02FB  .                 4255  ;
02FB                    4260  ;
          02FB          4265  HTABLE:  EQU      $
02FB  1E 01             4270  T0H:     DW       286
02FD  96 01             4275  T1H:     DW       406
02FF  96 01             4280  T2H:     DW       406
0301  96 01             4285  T50H:    DW       406
```

```
0303                    4295            ORG     0C00H
0C00                    4300    ;*********************************************
0C00                    4305    ;*                                          *
0C00                    4310    ;*              RAM MEMORY                   *
0C00                    4315    ;*                                          *
0C00                    4320    ;*********************************************
0C00                    4325    ;
        0C00            4330    RAM:    EQU     $       ;BEGIN SYS RAM
0C00                    4335    ;
0C00    0001            4340    FLAG:   DEFS    1
0C01    0001            4345    DUMTM:  DEFS    1       ;TEMPORARY TIME
0C02    0001            4350    TIME:   DEFS    1       ;TIME INTERVAL
0C03    0002            4355    DIVTM:  DEFS    2
0C05    0001            4360    BNUM:   DEFS    1
0C06    0001            4365    CTRTEM: DEFS    1
0C07    0001            4370    TEMP:   DEFS    1
0C08    0001            4375    SAVTIM: DEFS    1
0C09    0001            4380    EDGCNT: DEFS    1       ;R WAVE COUNT
0C0A    0008            4385    TEMPST: DEFS    8       ;T CYCLE STORE
0C12                    4390    ;
0C12    0001            4395    BUSY:   DEFS    1
        0013            4400    RAMEND: EQU     $-RAM
0C13                    4405    ;
        1000            4410    ERAM:   EQU     1000H   ; END OF STACK
```

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REFERENCES

1. Werber, Morton: A Bibliography of Wildlife Movements and Tracking Systems. NASA CR-130380, 1970.

2. Ysenbrandt, H. J. B.; Selten, Th. A. L.; Verschuren, J. J. M.; Kock, T.; and Kimmich, H. P.: Biotelemetry, Literature Survey of the Past Decade. Biotelemetry, vol. 3, 1976, pp. 145-250.

3. Lund, Gordon, F.: Time and Energy Budgets by Telemetry of Heart Rate from Free Ranging Black-Tailed Prairie Dogs in Natural and in Model Environments. Ph.D. Thesis, Dept. of Zoology, University of Iowa, Iowa City, 1974.

4. Lund, Gordon F.; and Folk, G. Edgar, Jr.: Simultaneous Measurements of Heart Rate and Oxygen Consumption in Black-Tailed Prairie Dogs (Cynomys ludovicianus). Comp. Biochem. Physiol., vol. 55A, 1976; pp. 201-206.

5. Sebesta, Paul D.; and Lund, Gordon F.: Overview of NASA Wildlife Sensing Projects. Paper presented at the Pecora IV Symposium on Application of Remote Sensing Data on Wildlife Management, Oct. 10-12, 1978, Sioux Falls, South Dakota. Sponsored by the National Wildlife Federation, Washington, D. C.

6. Fryer, Thomas B.: Implantable Biotelemetry Systems. NASA SP-5094, 1970.

7. Fryer, Thomas B.; and Sandler, Harold: A Review of Implant Telemetry Systems. Biotelemetry, vol. 1, 1974, pp. 351-374.

8. MacKay, Ralph Stuart: Bio-Medical Telemetry. Second ed. John Wiley and Sons, New York, 1970.

9. Baldwin, Howard A.: Instrumentation for Remote Observation of Physiology and Behavior. Ecological Energetics of Homeotherms, Gessaman, J. A., ed, Utah State University Press, Logan. Monograph Series, vol. 20, 1973, pp. 67-76.

10. Fell, Roger B., Skutt, H. Richard; and Waterfield, Allan: A Four-Channel Ultrasonic Telemetry System for Obtaining Physiological Data from Ocean Divers. Biotelemetry, vol. 1, 1974, pp. 50-59.

11. Lin, Wen C.; and Pillay, Sasi K.: A Micropower Pulsewidth-Modulation-Pulse-Position-Modulation Two-Channel Telemetry System for Bio-medical Applications. IEEE Transac, BME vol. 21, 1974, pp. 273-280.

12. Pauley, J. Donald; Reite, Martin; and Walker, Stephen D.: An Implantable Multi-channel Biotelemetry System. Electro-encephalography and Clinical Neurophysiology, vol. 37, 1974, pp. 153-160.

13. Smith, E. Norbert: Multichannel Temperature and Heart Rate Radio-Telemetry Transmitter. J. Appl. Physiol, vol. 36, 1974, pp. 252-255.

14. Winter, David A.; and Trenholm, Brian G.: Reliable Triggering for Exercise Electrocardiograms. IEEE Transac, BME vol. 16, 1969, pp. 75-79.

15. Cupal, Jerry J.; Weeks, R. W.; and Kaltenbach, C.: A Heart-Rate-Activity Biotelemetry System for Use on Wild Big Game Animals. Biotelemetry III, Fryer, T. B., H. A. Miller, and H. Sandler, eds., New York, Academic Press, 1976, pp. 219-222.

16. Weeks, R. W.; Long, F. M.; and Cupal, J. J.: An Improved Repeater Heart Rate Telemetry System for Use on Wildlife. Proceedings of the First International Conference on Wildlife Biotelemetry, July 27-29, Laramie, Wyoming, 1977, pp. 2-8.

17. Sebesta, P. D.; and Arno, R. D.: Report on 1973 Santa Cruz Summer Study on Wildlife Resource Monitoring. NASA TM-78578, 1979.

18. Ferris, Clifford D.: Introduction to Bioelectrodes. Plenum Press, New York, 1974.

19. Geddes, Leslie A.: Electrodes and The Measurement of Bioelectric Events. John Wiley and Sons, New York, 1972.

20. Geddes, Leslie A.; and Baker, L. E.: Principles of Applied Biomedical Instrumentation. Second ed. John Wiley and Sons, New York, 1975.

21. Miller, Harry A.; and Harrison, Donald C., eds: Biomedical Electrode Technology, Theory and Practice. Academic Press, New York, 1974.

22. Neuman, Michael R.: Biopotential Electrodes. Medical Instrumentation Application and Design, J. G. Webster, ed., Houghton Mifflin Co., Boston, 1978, pp. 215-272.

23. Dymond, Anthony M.: Recording Electrodes for Chronic Intracerebral Implantation in Man. Biomedical Electrode Technology, Theory and Practice, Miller, H. A. and D. C. Harrison, Academic Press, Inc., New York, 1974, pp. 41-66.

24. Geddes, L. A.; and Baker, L. E.: The Relationship Between Input Impedance and Electrode Area in Recording the ECG. Med. Biol. Eng., vol. 4, 1966, pp. 439-450.

25. Fryer, Tom B.; Lund, Gordon F.; and Williams, Bill A.: An Inductive Powered Telemetry System for Temperature, EKG, and Activity Monitoring. Biotelemetry and Patient Monitoring, vol. 5, 1978, pp. 53-76.

26. Lund, Gordon F.; Simmonds, Richard C.; and Williams, Bill A.: A
    Subcutaneous Channeling Probe for Implanting Long Leads. Lab. Anim.
    Sci., vol. 27, 1977, pp. 1040-1041.

27. Larsen, J. L.; Dillman, R. F.; Nardizzi, A. M.; and Tverdoch, R. N.:
    An Effective ECG Telemetry System. Hewlett-Packard Journal, vol.
    23, no. 8, April 1972, pp. 2-8.

28. Wright, M. J.: Use Slew-Rate Filtering. Electronic Design, vol. 24,
    no. 19, Sept. 1976, pp. 110-12.

29. Deboo, Gordon J.: An RC Active Filter Design Handbook. NASA SP-5104,
    1977.

30. Courtin, E.; Ruchay, W.; Salfeld, P.; and Sommer, H.: A Versatile,
    Semiautomatic Fetal Monitor for Non-Technical Users. Hewlett-
    Packard Journal, vol. 28, no. 5, Jan. 1977, pp. 16-23.

31. RCA COS/MOS Integrated Circuits, Databook SSD-203C. RCA Solid State,
    Somerville, New Jersey, 1975, pp. 518-538.

32. Morrow, G.; and Fullmer, H.: Proposed standard for the S-100 Bus
    Computer, vol. 11, no. 5, May 1978, pp. 84-90.

33. Intel 8080 Microcomputer System User's Manual. Intel, Inc., Santa
    Clara, Calif., Sept. 1975, pp. 2-11.
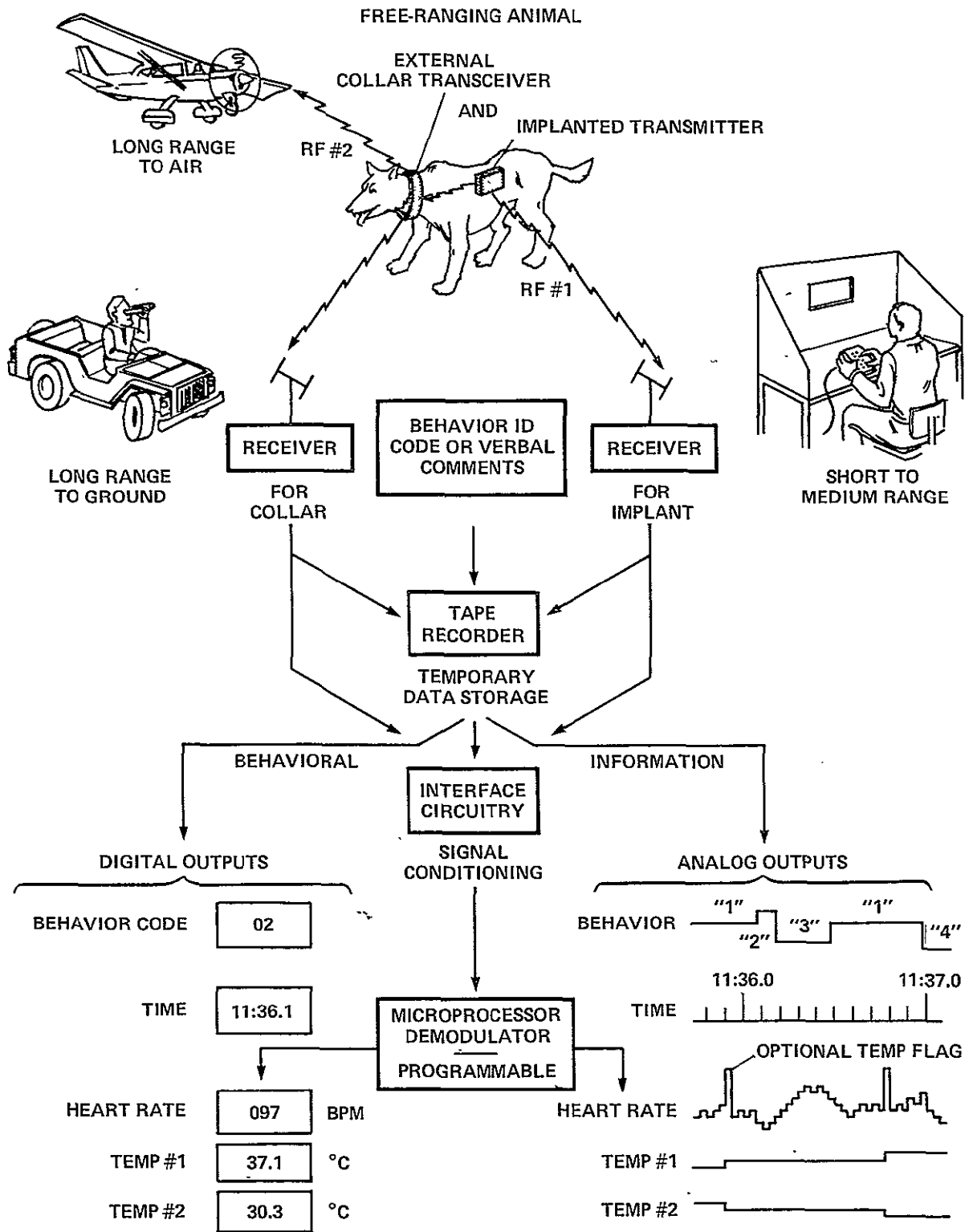
Figure 1.– Telemetry data–acquisition system for heart rate and multiple body temperatures.

ECG INPUT   50TH   1ST
               HEART-   HEART-
               BEAT   BEAT
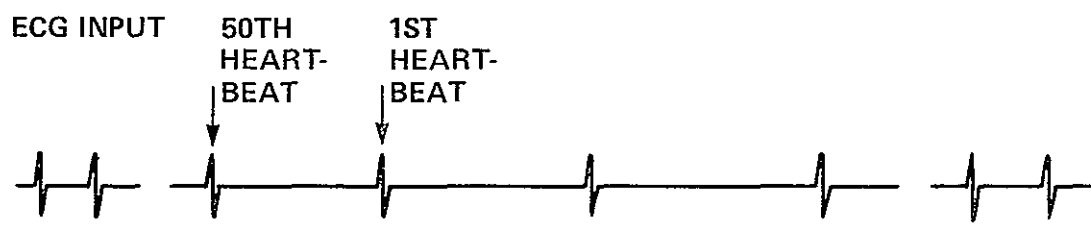
TRANSMITTER PULSE CONTROL

5 msec WIDE HEARTBEAT PULSES   10 msec WIDE TEMPERATURE PULSES

|← TOTAL PERIOD IS ONE TO TWO SECONDS →|

C_1' C_1 T_1 T_2 C_2 DELAY

0°C   TEMPERATURES   50°C
CALIBRATION   CALIBRATION
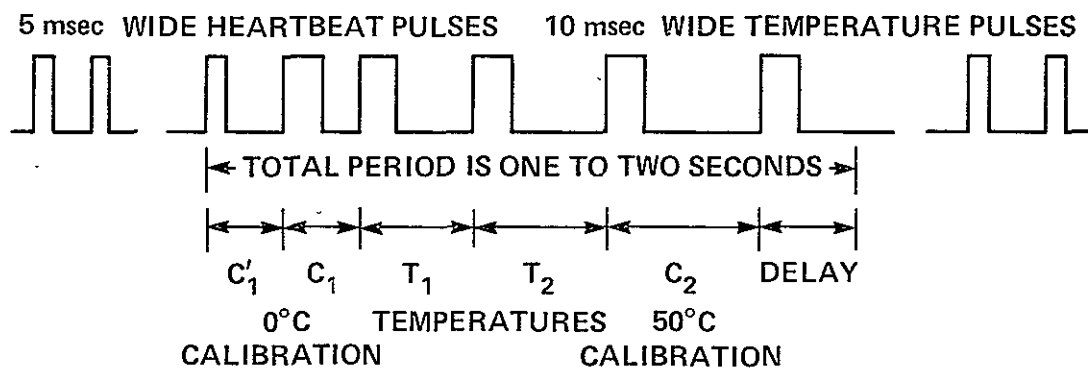
RF PULSE TRAIN OUTPUT
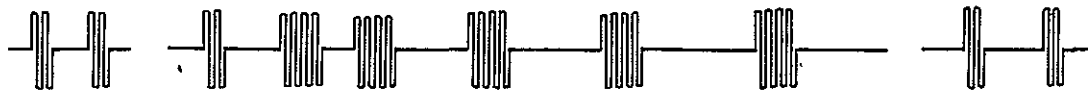
Figure 2.- Modulation scheme for heart rate and multiple body temperatures.

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SUTURE HOLES

LEAD CONNECTION
WITH SPOT WELD
AND TAB

ADDITIONAL HOLES
FOR RTV BONDS

SUPPORT TABS SPOT
WELDED TO
ELECTRODE

2 cm

RTV

MULTISTRANDED CONDUCTOR

SUTURE WHEN
IMPLANTED

2 cm DISC ELECTRODE

SUTURE WHEN
IMPLANTED

5 mm

INTERWOVEN KNOT

MULTISTRANDED
CONDUCTOR

RTV

LEAD EXTENSION ELECTRODE

RTV
SUPPORT TAB
CONDUCTOR

2 mm

DISC

DISC CROSS SECTION
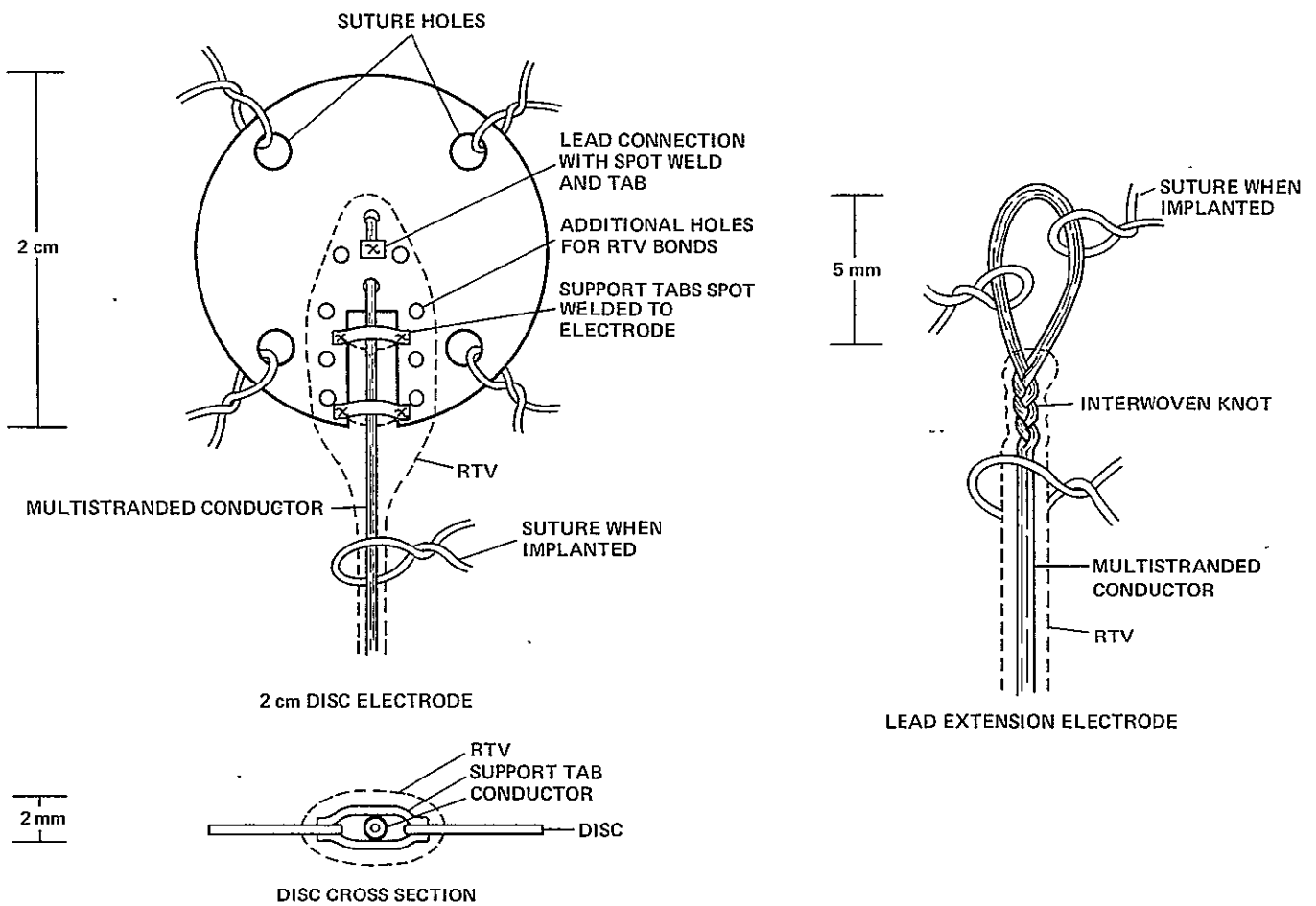
Figure 3.- Implantable ECG electrodes.

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A

3 mV

I sec

B

3 mV

I sec
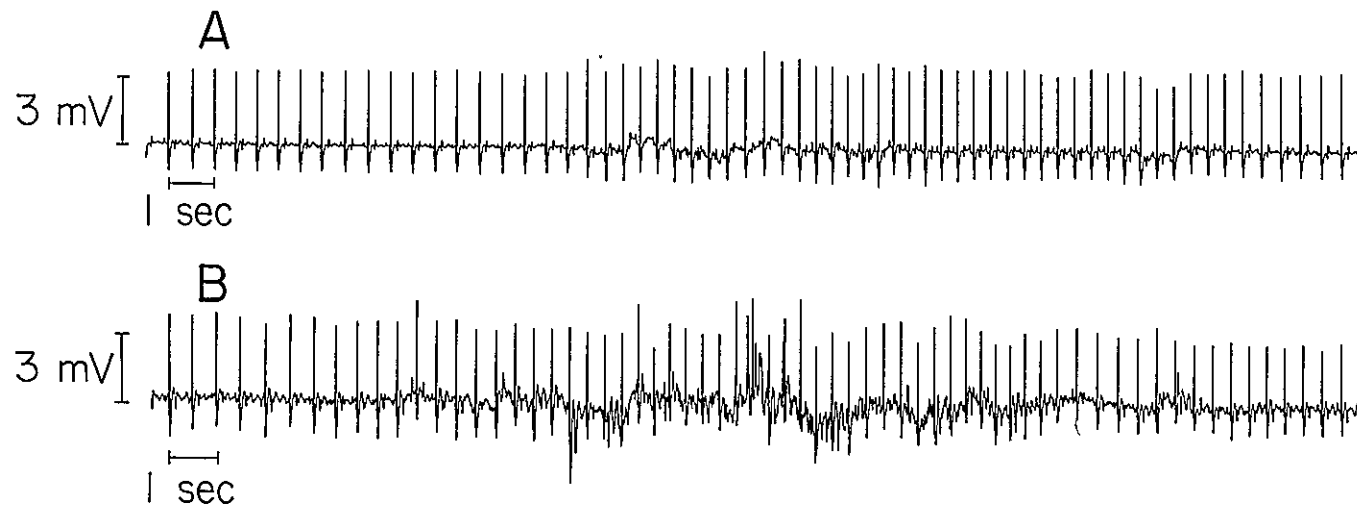
Figure 4.- Activity ECG records from different electrodes implanted
in a dog.
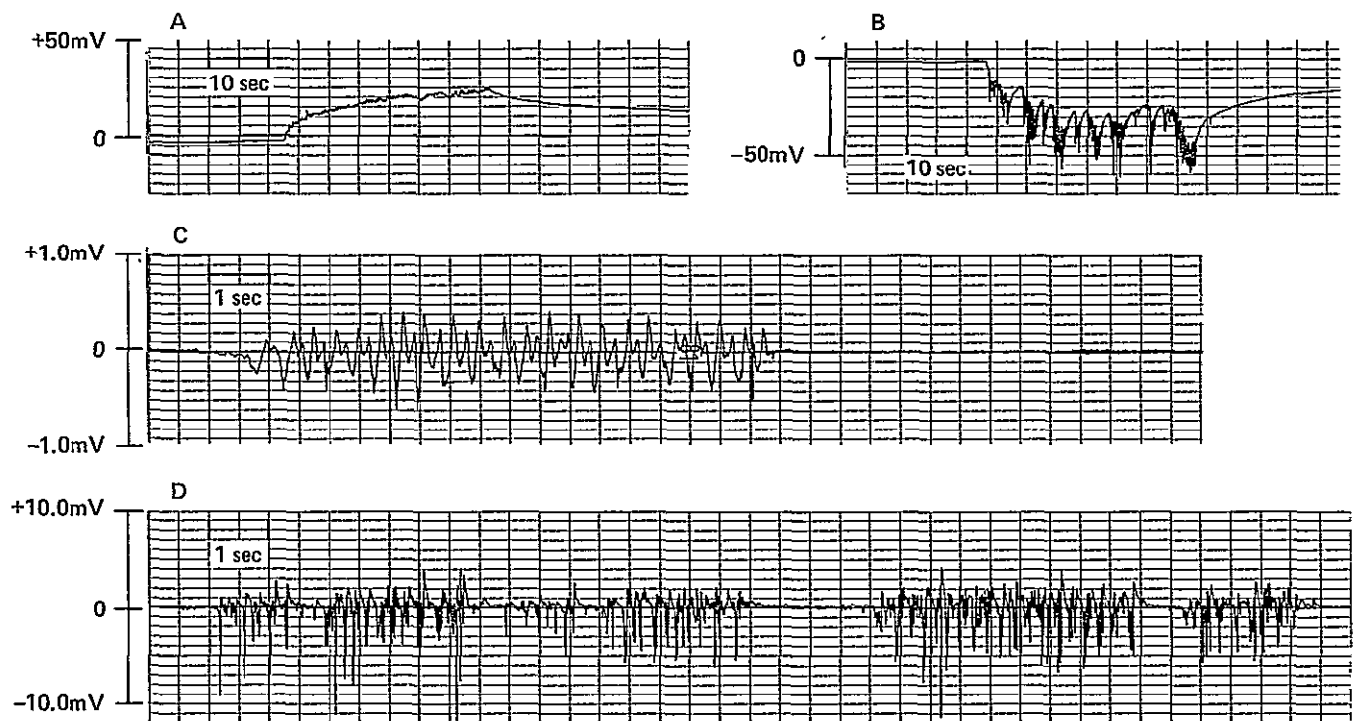
Figure 5.— Disturbance artifact susceptibility of different
electrodes in vitro.
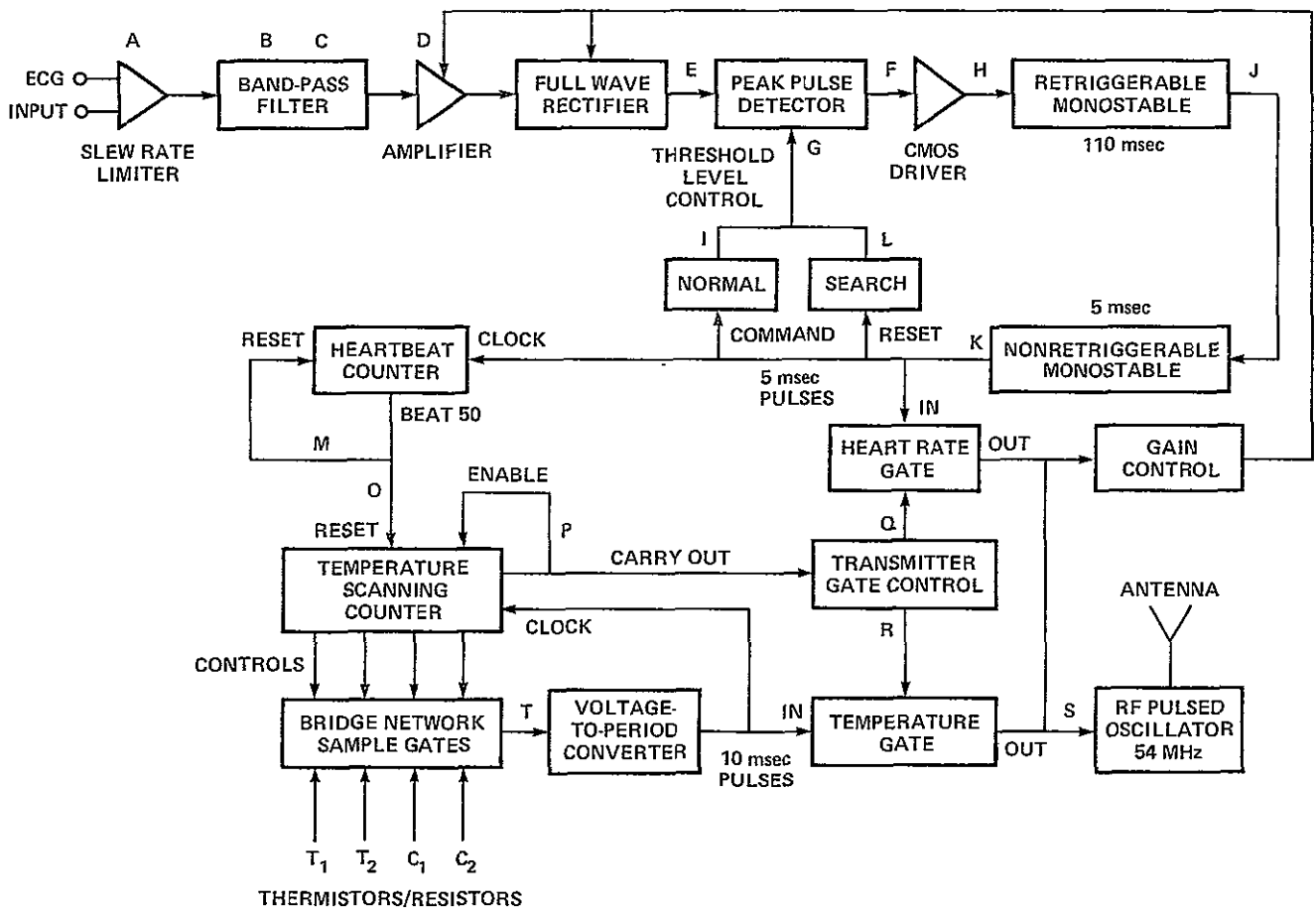
Figure 6.- Block diagram of implantable transmitter.
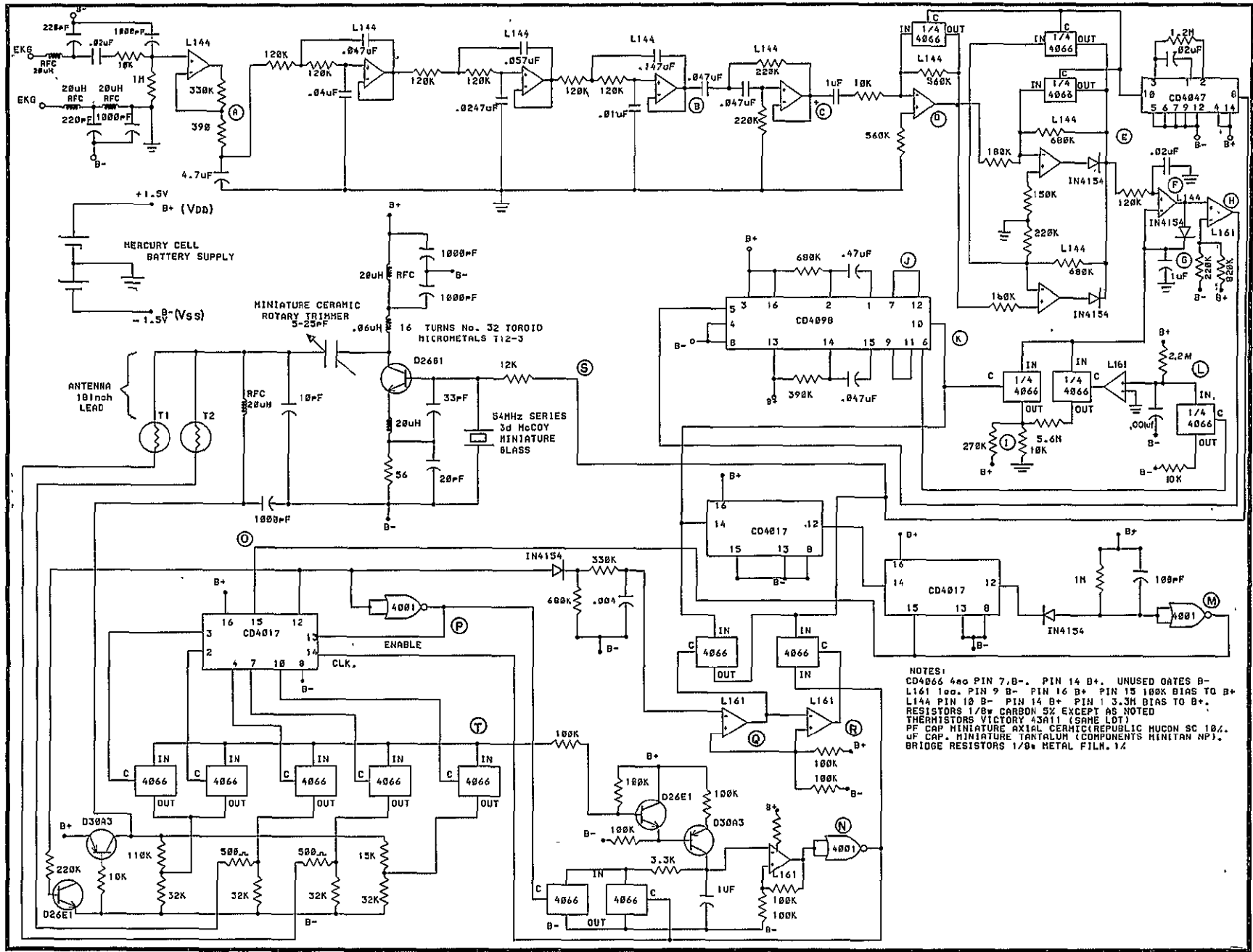
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Figure 7.– Circuit diagram of implantable transmitter.

A   ECG, B LOW-PASS FILTERED ECG,   C HIGH-PASS FILTERED ECG,   D   AMPLIFIED ECG,
I   SETS MINIMUM TRIGGER LEVEL (270K, 10K), NORMAL THRESHOLD ADJUST (10K), SEARCH
     MODE-TRACKING RATE (5.6M),   L SETS START OF SEARCH MODE (2.2M)
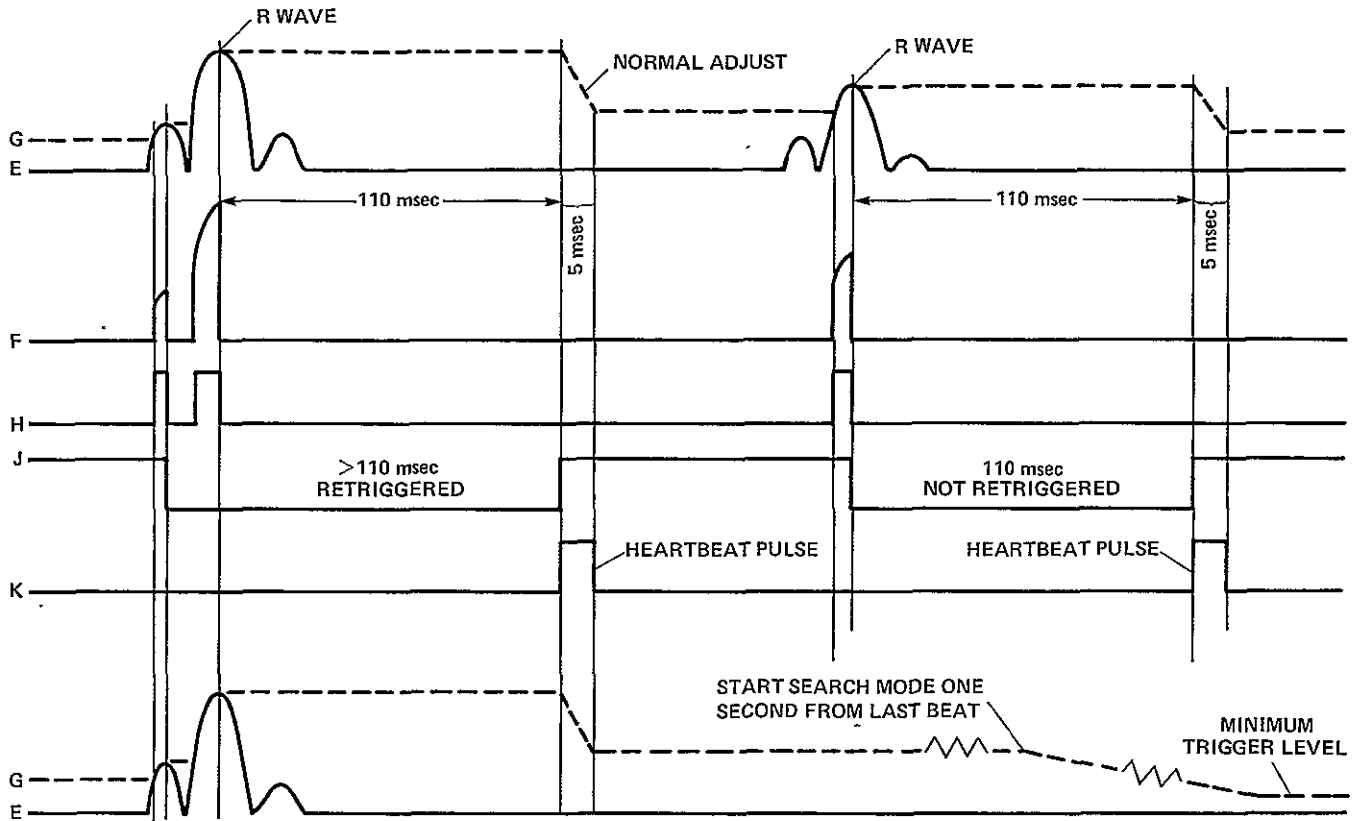
Figure 8.– R-wave detector stage functions for threshold control.

ECG   A

R-WAVE DETECTOR   K

5 msec PULSES

COUNTER RESET PULSE 1 PER 50 BEATS   M

|← 50 HEARTBEATS →|

TEMPERATURE SAMPLING 5 AT READINGS   N

5, 10 msec PULSES

A   B   C   D   E   A   B   ETC.

TEMPERATURE SAMPLE GATE   O

O INVERTED   P

TIME DELAYED TO CAPTURE 5TH 10 msec PULSE

O WITH A HOLDING DELAY   Q

Q INVERTED   R

10 msec PULSES   5 msec PULSES

S

EXPANDED SCALE OF TEMP SAMPLE

CALIBRATION & THERMISTOR BRIDGE VOLTAGES   T

V_{DD}

V_{SS}

|← PERIOD DEPENDENT UPON THERMISTOR VALUES, TOTAL PERIOD APPROX. 1 sec →|

N

O

TIME DELAY TO CAPTURE LAST 10 msec PULSE

Q

Figure 9.— Temperature waveforms for circuit modulation.

TEMP., °C	THERMISTOR, kohm	V_{SS} (A)	V_{SS} (B)	V_{SS} (C)
0	10	2.308	0.692	0.643
12	5	1.875	1.125	1.000
25	3	1.500	1.500	1.286
37	1.8	1.125	1.875	1.552
50	1.08	0.794	2.205	1.772
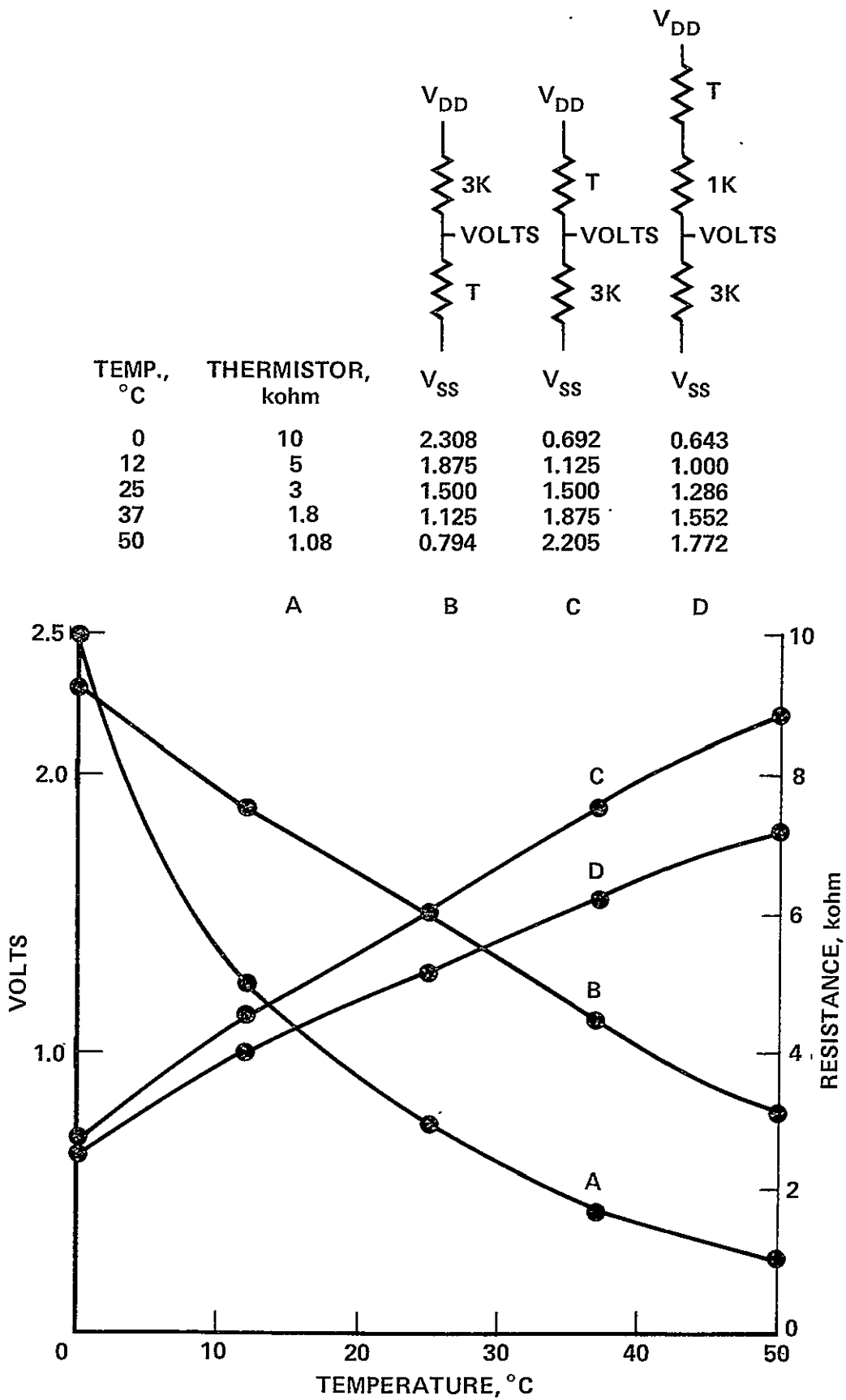
Figure 10.– Thermistor bridge outputs.

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TEMPERATURE °C	THERMISTOR R + 500Ω	OSCILLATOR PERIOD ms 0.5μF ○	1μF CAP. ●
0	100.5K	65.13	137.3
12	50.5K	76.25	159.9
25	30.5K	90.32	188.2
37	18.5K	111.9	230.8
50	11.3K	141.8	287.7

V_{DD}
T
500Ω
TO EXISTING CIRCUIT
30KΩ
V_{SS}

±0.2 msec ACCURACY FOR ±0.1°C OUTPUT AT LOWER TEMPERATURE RANGE
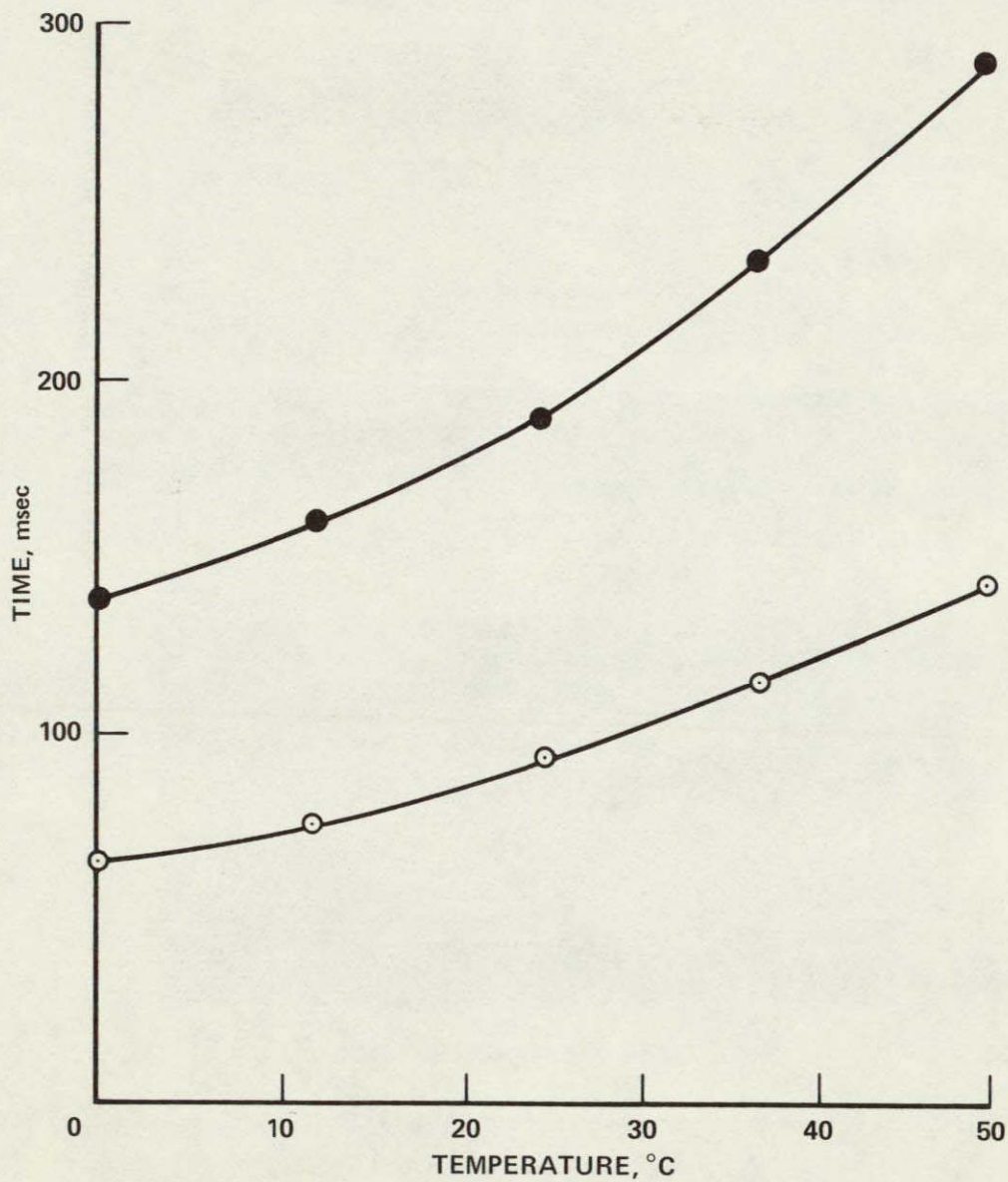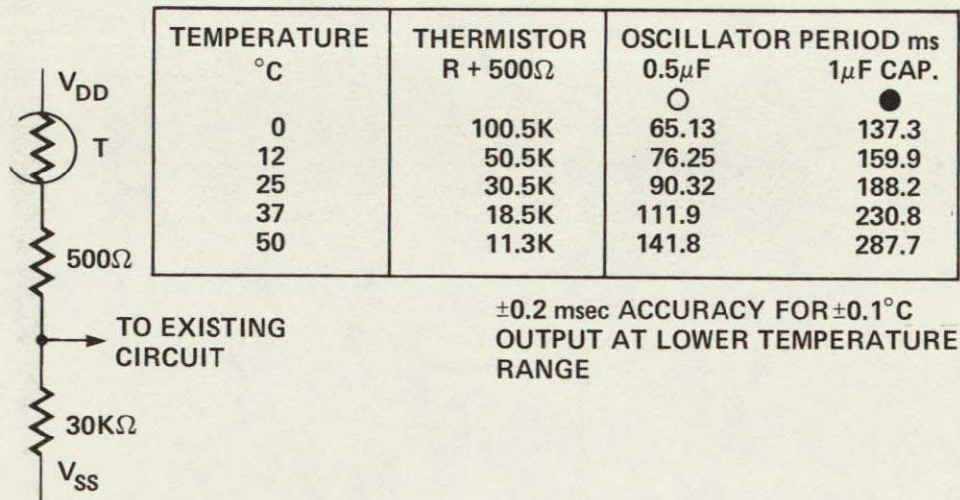
Figure 11.- Thermistor bridge calibrations.
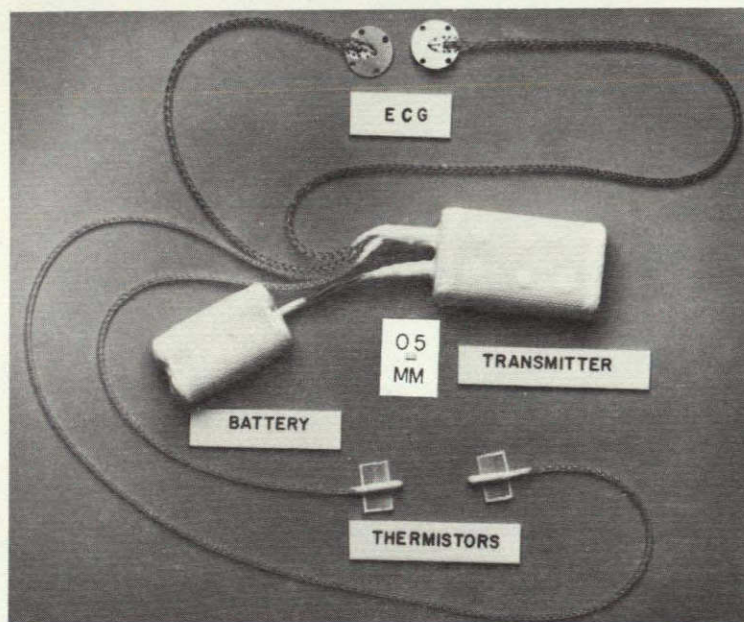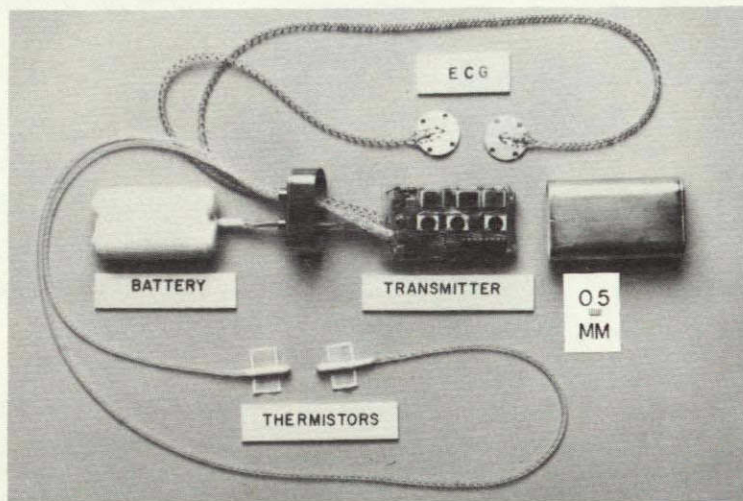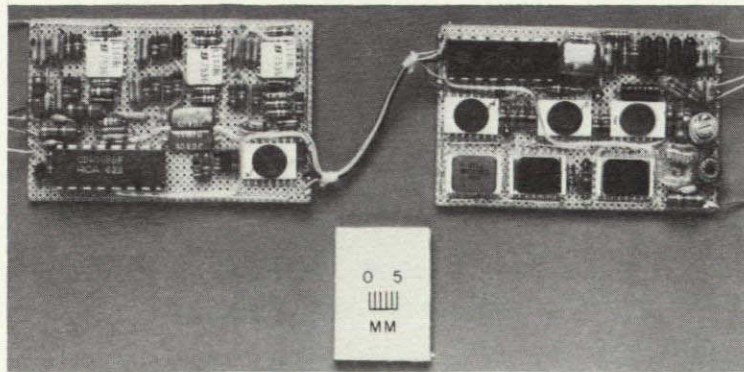
Figure 12.- Transmitter at various stages of prototype packaging.
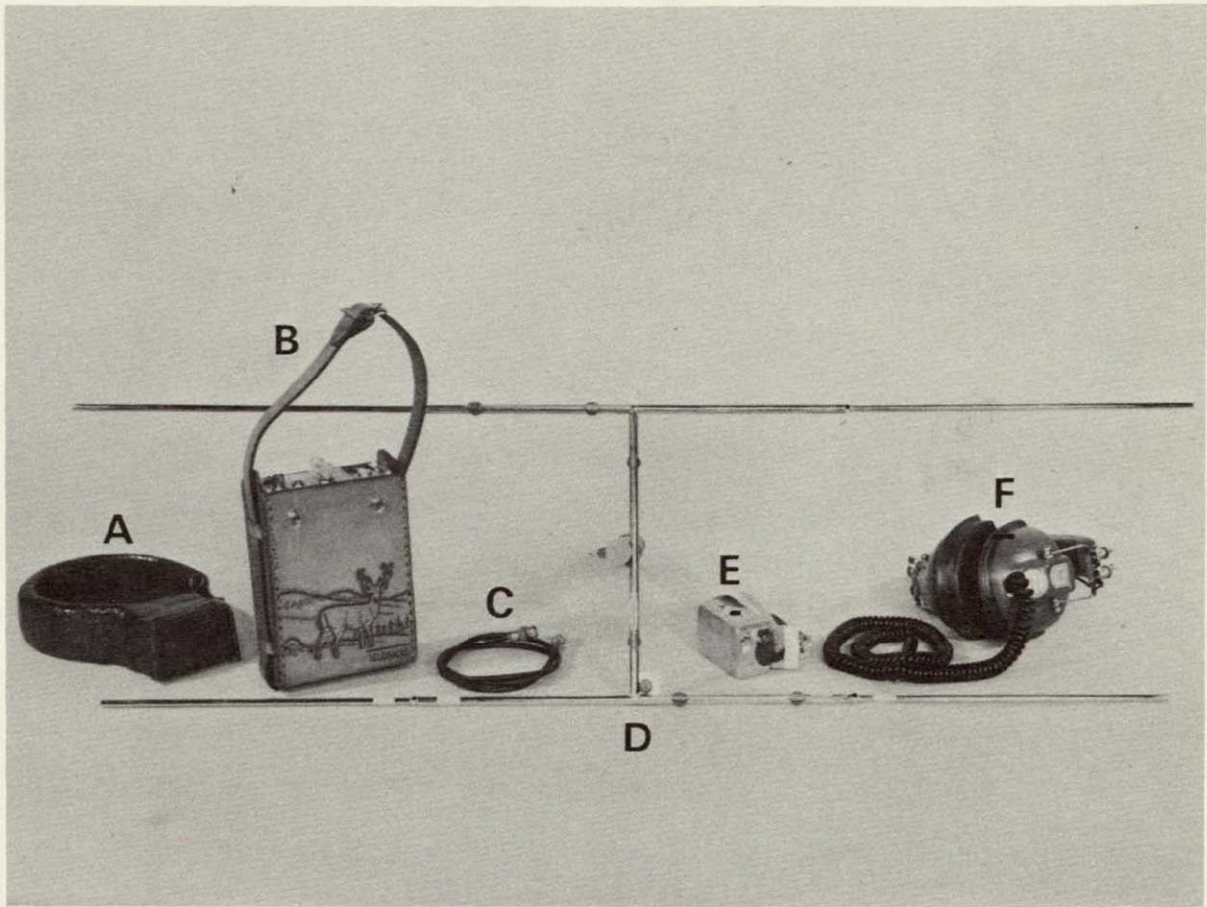
Figure 13.- Collar prototype and field receiver equipment.
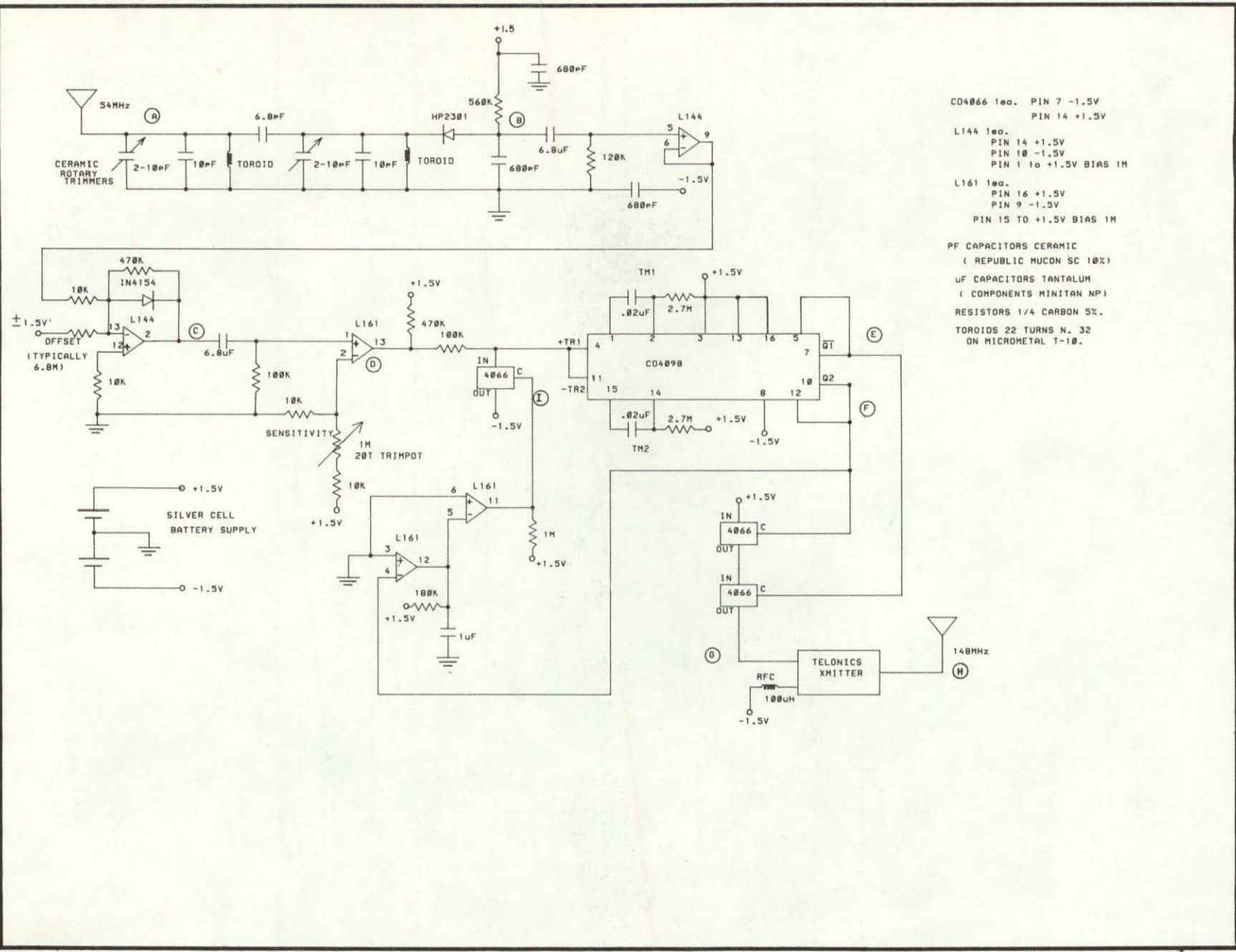
Figure 14.- Collar transceiver circuit diagram.

A — RECEIVED RF PULSES

B —

DETECTED

AMPLIFIED X 47

C —

LIMITED

5 msec | 10 msec

D —

E —

20 msec | GATE ONE OPENED | 20 msec

20 msec | GATE TWO CLOSED | 20 msec

F —

20 msec | CONSTANT 20 msec DELAY | 20 msec | 5 msec | 10 msec

G —

TRANSMITTED RF PULSES

H —

100 msec SQUELCH | 100 msec SQUELCH

I —
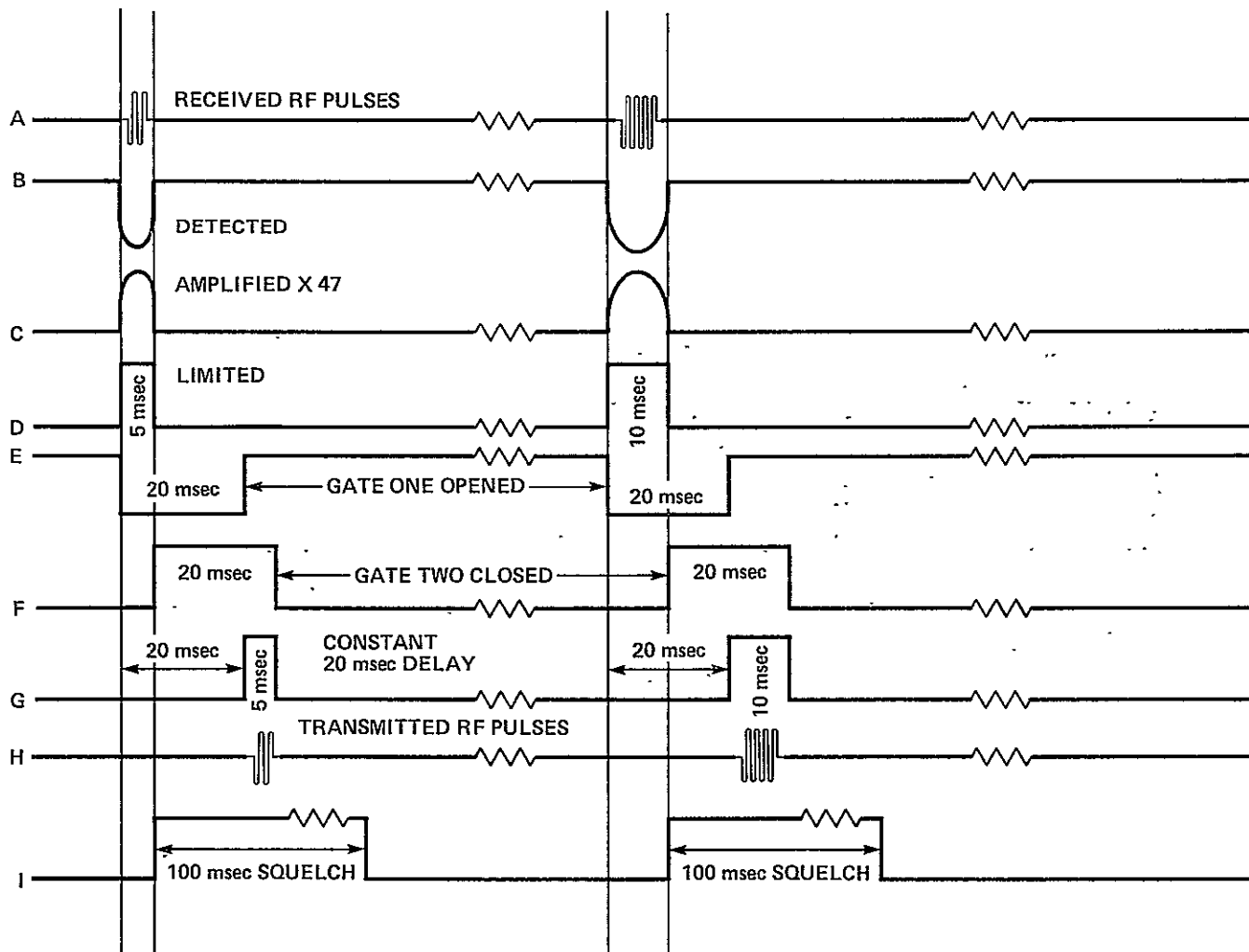
Figure 15.– Collar transceiver timing diagram.

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COLLAR STRAP

5 cm

27 cm

7 cm

RETRANSMITTER
MODULE

TRANSMITTING ANTENNA
TELONICS TUNED DIPOLE
(148 MHz)

RECEIVING ANTENNA
FOLDED DIPOLE
(54 MHz)
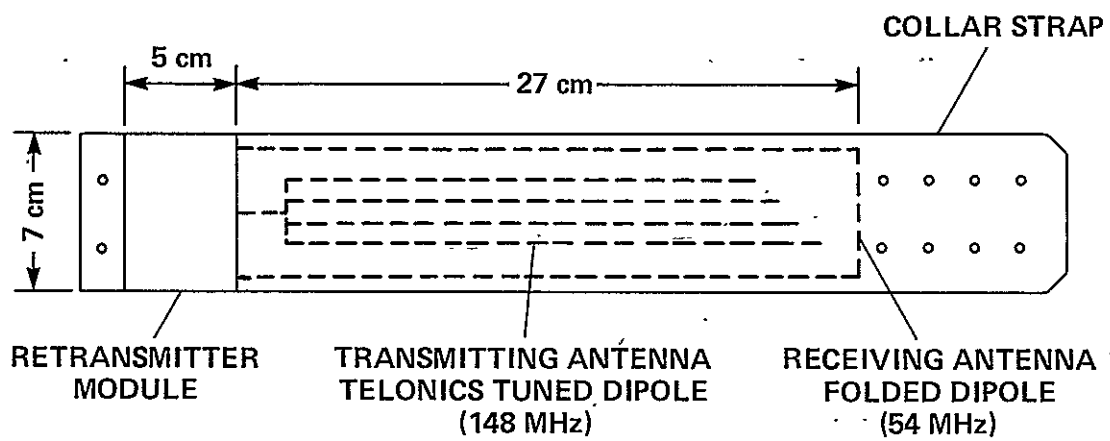
Figure 16.- Collar antenna arrangement.
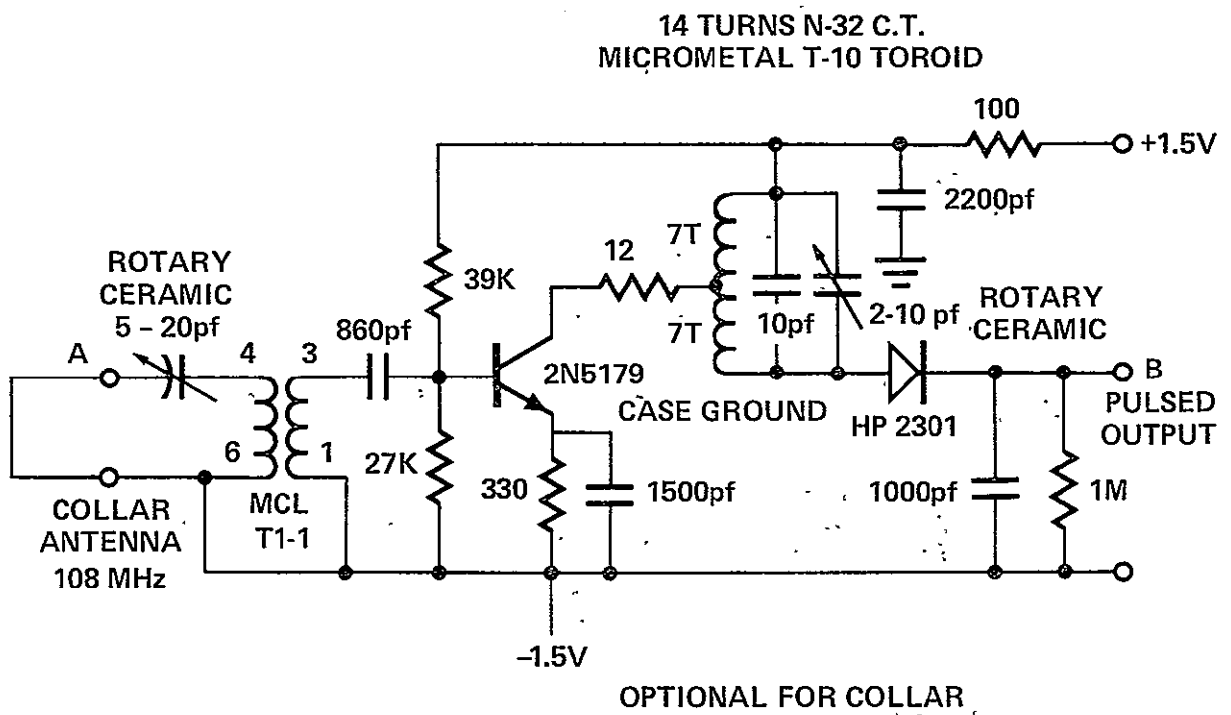
Figure 17.— Circuit diagram for active gain stage.
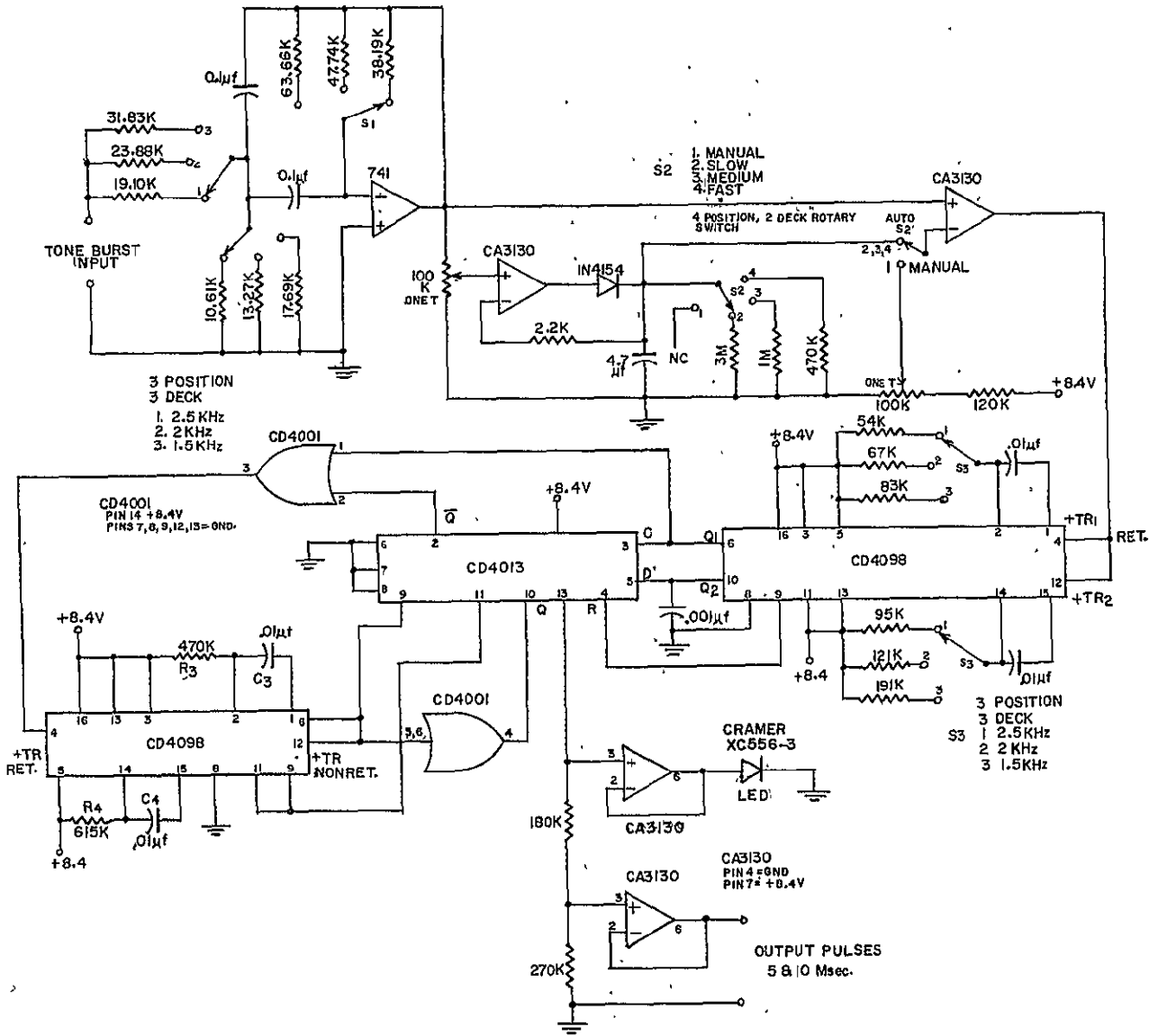
Figure 18.- Interface circuit diagram.
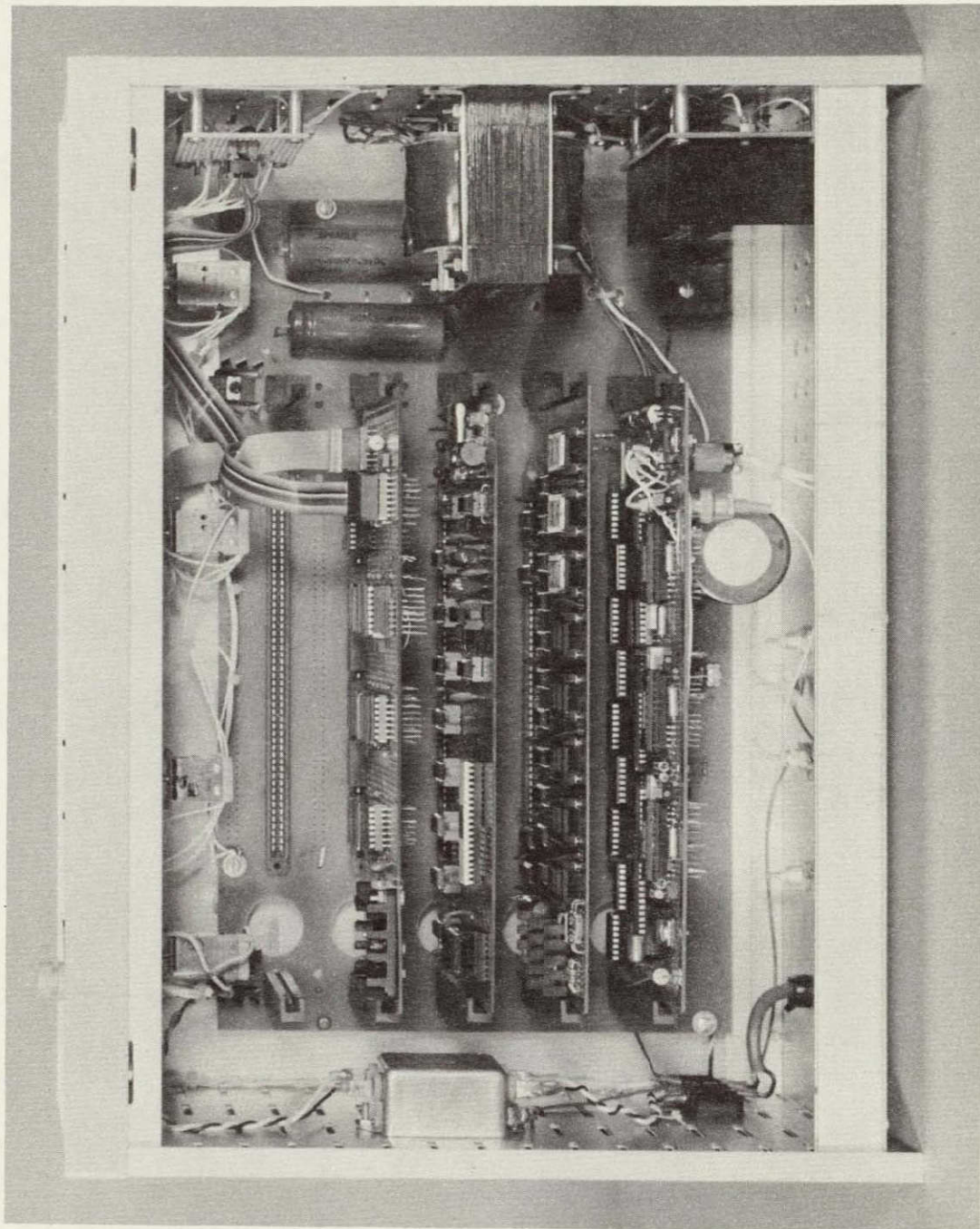
Figure 19.- Top view of demodulator.
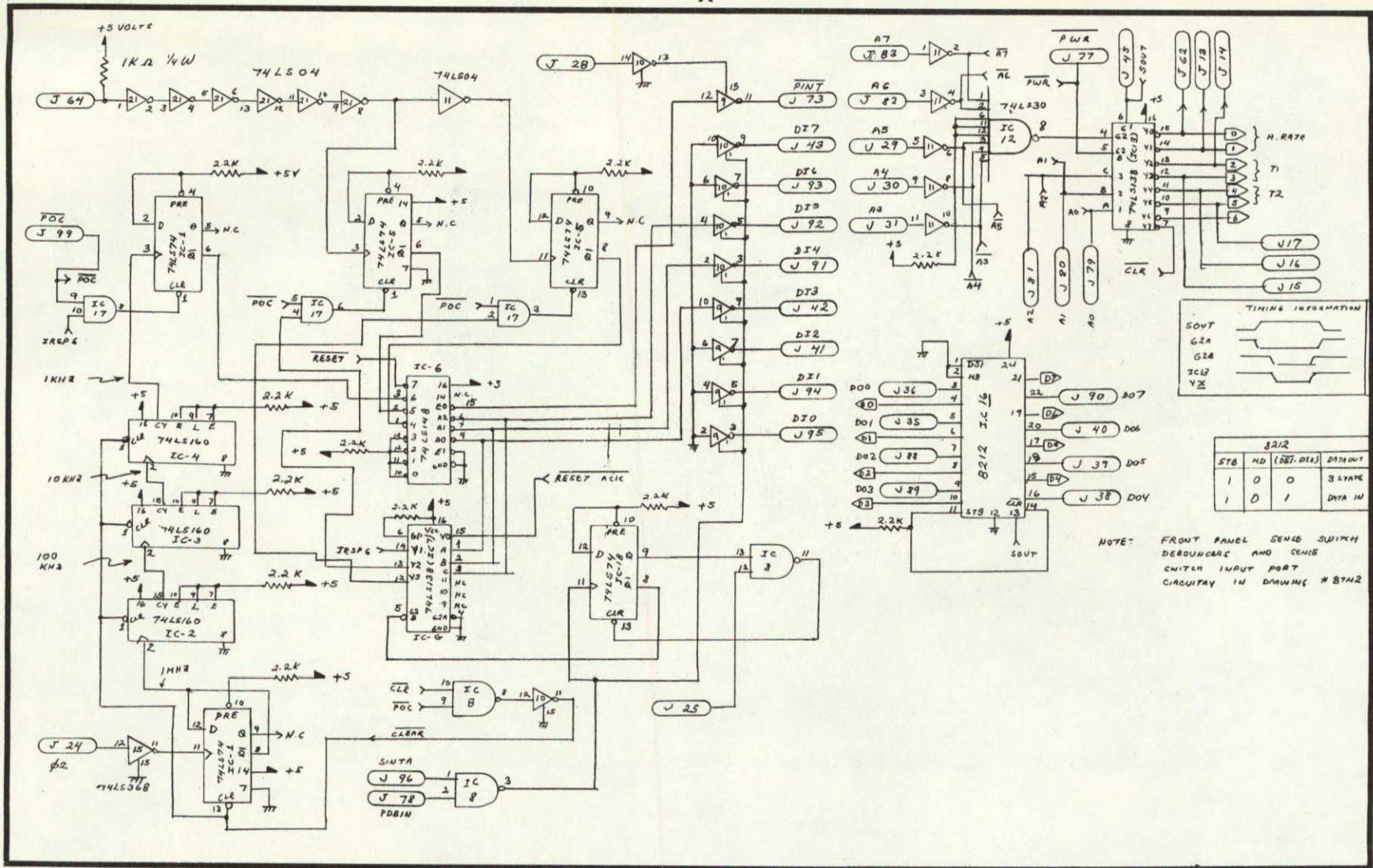
Figure 20.- Circuit diagram of demodulator.
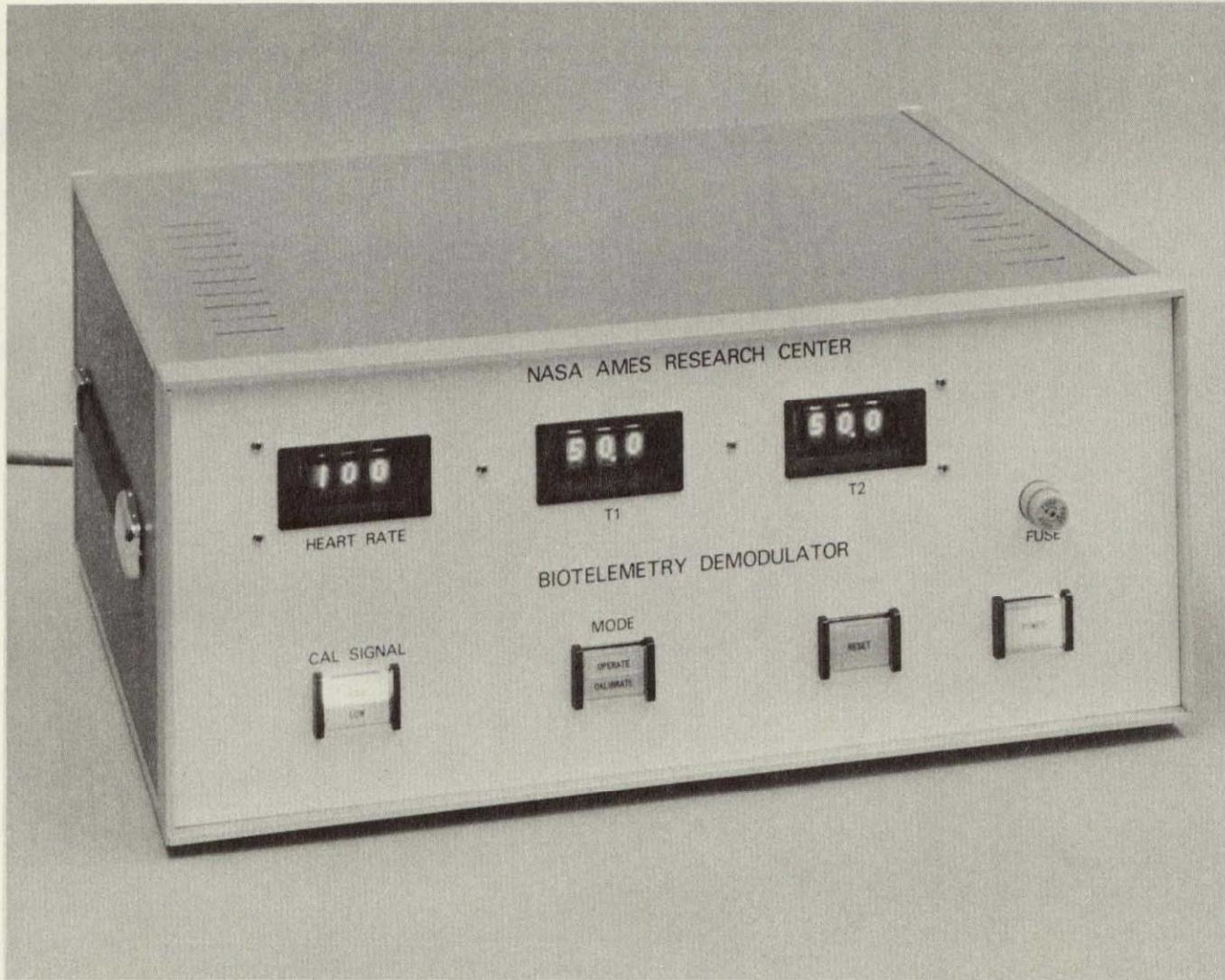
Figure 21.- Front panel of demodulator.
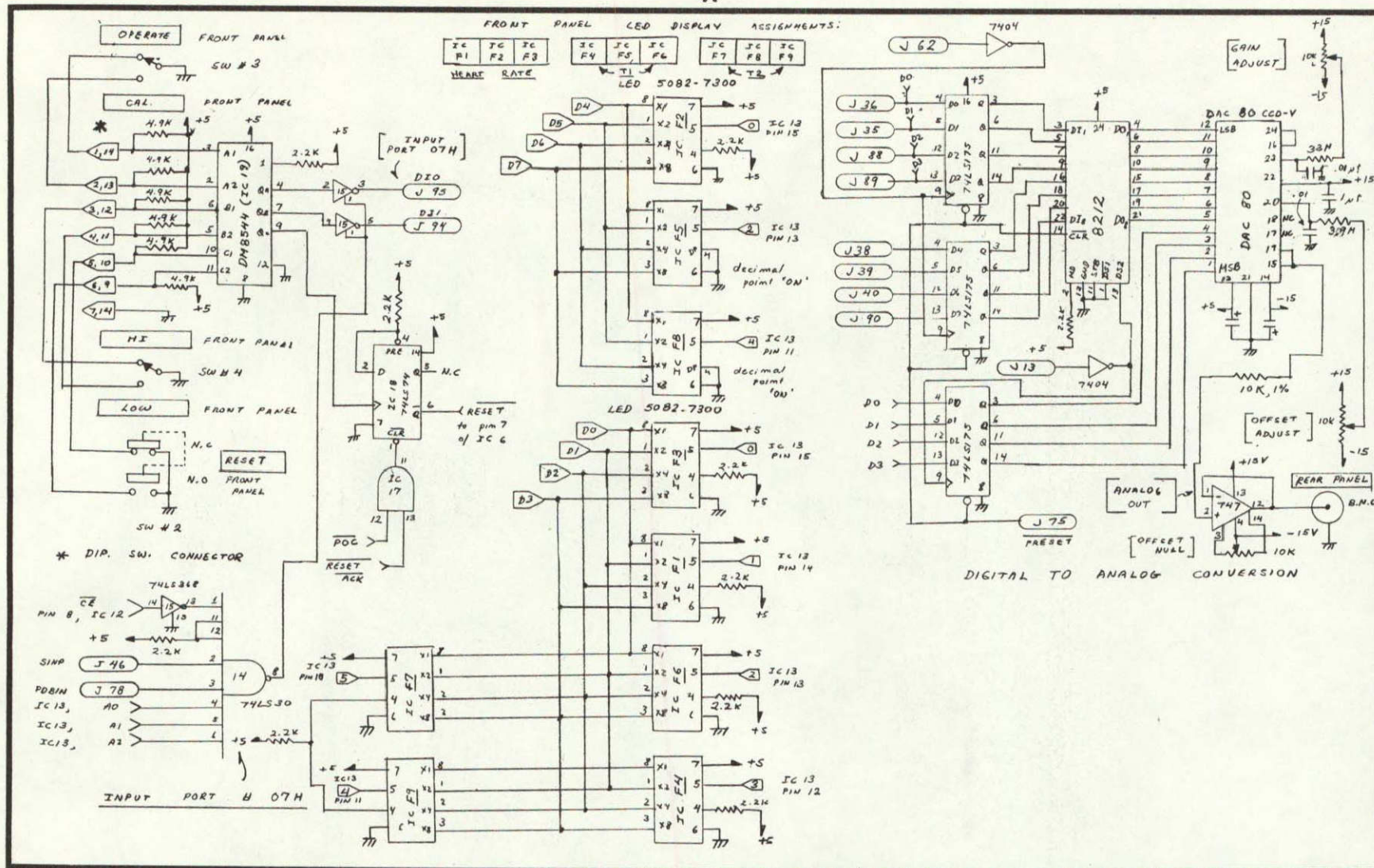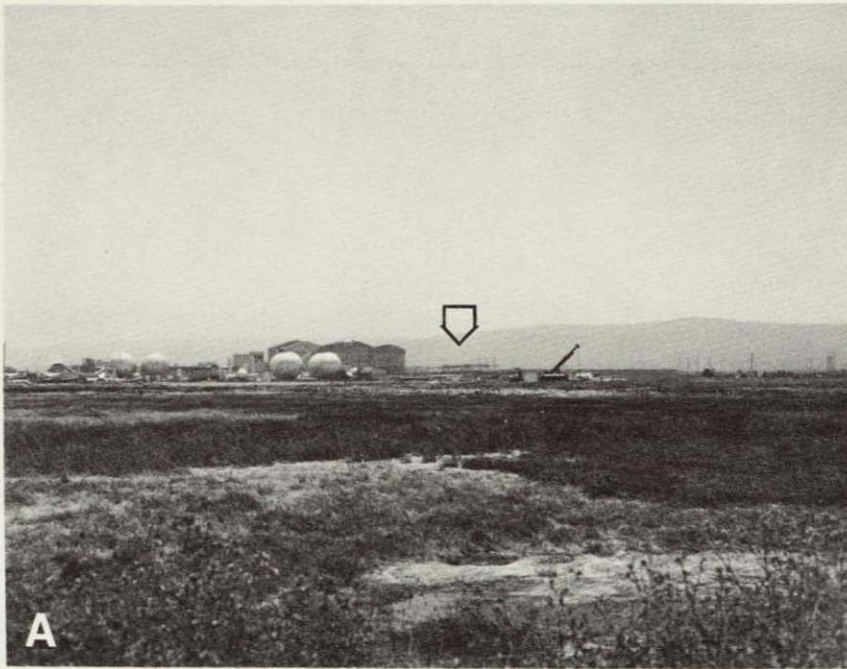
Figure 22.- Continued circuit diagrams of the demodulator.

Figure 23.- Views of field test station.

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16. Abstract

    A long-range and long-life telemetry system for heart rate and multiple body temperatures from free-ranging animals has been designed. This system includes an implantable transmitter, external receiver-retransmitter collar, and a microprocessor-controlled demodulator. The size of the implant is suitable for animals with body weights of a few kilograms or more; further size reduction of the implant is possible. The ECG is sensed by electrodes designed for internal telemetry and to reduce movement artifacts. The R-wave characteristics are then specifically selected to trigger a short radio frequency (RF) pulse. Temperatures are sensed at desired locations by thermistors and then, based on a heartbeat counter, transmitted intermittently via pulse interval modulation. This modulation scheme includes first and last calibration intervals for a reference by ratios with the temperature intervals to achieve good accuracy even over long periods. Pulse duration and pulse sequencing are used to discriminate between heart rate and temperature pulses as well as RF interference. The implanted transmitter might be used alone for experiments on animals that frequent particular locations within a large territory; on animals in virtually any laboratory situation; or on animals in moderate-sized enclosures, such as those in a zoological garden. The implanted transmitter is otherwise interfaced with the receiver-retransmitter collar that employs commercial tracking equipment to achieve the long-range transmission. Peak energy is consumed only during the short RF pulses so that average current drain of either transmitter is in the range of tenths of milliamperes. The RF pulses from either transmitter are processed by the microprocessor controlled demodulator for the characteristics of pulse durations, intervals, and sequence. The output provides analog beat-to-beat heart rate and periodically updated temperatures as well as digital display. Heart rates to several hundred beats per minute (BPM) and body temperatures within a range of zero to 50° C with 0.1° C in resolution of change or better seem feasible. The objective of the design was to achieve a high degree of experimental flexibility and overall high quality in performance. The system was tested in prototype form on a dog.

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