FOREWORD

This study was initiated by the Multienvironment Division, Biophysics Laboratory, 6570th Aerospace Medical Research Laboratories, Aerospace Medical Division, Wright-Patterson Air Force Base, Ohio. The research was conducted by Cutler-Hammer, Inc., Airborne Instruments Laboratory Division, Deer Park, Long Island, N. Y. as a part of research and development of advanced selective monitoring data systems under Contract AF 33(657)-10462. Mr. George W. Morton was the principal investigator for the Airborne Instruments Laboratory Division. Mr. Miles A. McLennan of the Multienvironment Division was contract monitor for the Aerospace Medical Research Laboratories. This work was performed in support of Project No. 7222, "Biophysics of Flight," Task No. 722203, "Specialized Instrumentation."

ABSTRACT

Often the most useful information contained in signals of physiological origin is the period or repetition rate of the waveform. This information is not directly apparent through inspection of the raw signal but must be derived by an additional counting or measuring operation. A review of methods of providing a direct indication of rate, including generating trigger pulses from periodic physiological waveforms and techniques for converting the wave-repetition period into a rate analog are presented. Particular attention is given to the electrocardiographic signals as a vehicle for demonstrating a recommended rate analog processor circuit.

PUBLICATION REVIEW

This technical documentary report is approved.

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Technical Director
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A STUDY OF RATE-ANALOG PROCESSING METHODS

INTRODUCTION

The application of selective monitoring techniques to physiological variables that may be measured during manned space-flight have been studied. Specifically the study concerned methods of deriving rate analogs of repetitive physiological phenomena such as heart-action and breathing. The objective of the study was to specify a means for converting raw output of cardiac or respiratory transducers into rate analog signal voltages compatible with the requirements of the monitored data system already constructed under an earlier contract (ref 11).

DISCUSSION OF RATE-ANALOG PROCESSOR DESIGN

The design of the rate-analog processor depends on the characteristics of the transducer output signals that are available for processing. A survey of the prominent signal sources from which cardiac and respiration rates may be derived is presented in Appendix A. Those that appear best suited for demonstration of the rate-analog processor are the electrocardiogram (ECG) and optical cardiac signals and/or a thermistor or strain-sensitive respiration transducer. The required ECG signal is thus fully acceptable. However for demonstration purposes the use of an optical pick-up will be tested for use as an alternative form of input to the system.

Methods of deriving a trigger pulse from periodic physiological signals are discussed in Appendix B. Raw amplitude sensing, combined, if necessary, with analog rate-of-change discrimination offers the best combination of simplicity and reliability for the intended application.

The rate analogs derived from cardiac or respiratory activity will be tested by preset selection criteria in the demonstration model Monitored Data System. This system is capable of making selections of input signal data on the basis of (1) absolute limits, (2) change in ongoing level, and (3) rate of change of level. With regard to criteria (2) and (3), changes in rate may more logically be defined in terms of percentage change in ambient rate (relative) rather than in terms of a fixed percentage of full scale as detected by the Monitored Data System. This form of selection could be provided by the Monitored Data System if the output of the rate-analog processor were logarithmically proportional to rate (or period). On the other hand for display purposes a linear rate analog characteristic may well be preferable. Therefore the rate-analog processor should have both linear and logarithmic outputs, the linear output being used for data transmission, and the logarithmic output being used for selection.*

*Because the Monitored Data System accepts the input signal by a separate path and performs a separate conversion for transmission of selected data values from those employed in selection, this can easily be done.

Techniques considered for the generation of a rate analog have included the following:

(a) Linear Filtering

This method assumes that the frequency components in the signal conditioner output are proportional to repetition rate. If such a signal is passed through a low-pass filter with cutoff frequency below the lowest expected signal frequency component, the rectified output of the filter should have a d-c component proportional to the ambient rate (for linear rolloff outside the filter passband). Although simple in construction, the basic assumption behind the operation of the device appears to be of dubious validity since changes in waveshape or duty factor of the signal conditioner output would give the appearance of changes in rate. The use of linear filtering does not therefore appear to offer a reliable means of generating a rate analog.

(b) Conventional Integration

A refinement of the linear filtering method of the preceding paragraph employs pulses of standard duration and amplitude derived from triggering techniques of the type mentioned in Appendix B. These would be integrated in a conventional analog integration circuit to afford a rate analog. For optimum performance the duration of the standard pulse should be the minimum required to fully charge the integrating capacitor. For linear rate integration the discharge time constant of the integrator should be several times longer than the longest expected beat interval. Because of the large integration time constant and the filter needed to eliminate beat by beat fluctuations, the response of this form of processor will be relatively sluggish, and irregularities in rhythm, such as extrasystoles, arrythmias, and bi- and tri-geminal beats, will normally be "averaged out."

(c) Pure Digital Techniques

Counting clock pulses during the interval between successive trigger pulses yields an output count directly proportional to period. This could either be monitored directly or converted to analog form by means of a digital to analog converter. A digital division may also be rapidly performed at the end of each trigger pulse interval to produce the reciprocal of the period which is the instantaneous rate. This value could also be converted to analog form. Such techniques are fast and can afford high resolution, but they are complex in terms of required hardware components.

(d) Ramp Integration (Period to Amplitude Processing)

The trigger pulse may start a ramp function generator (such as a Miller integrator) whose output is sampled immediately prior to each discharge and held until the next beat occurs. In this way a period analog is derived that is the reciprocal of the preferred rate analog. This technique is relatively simple and has been widely used in commercial cardiotachometers. Where only the relative changes in rate or period are of interest, a circuit of this type with a logarithmic output could be an indicator of small percent changes in either rate or period. For the Rate-Analog Processor application this circuit is thus useful primarily as a means to an end.

(e) Conversion from Period to Rate by Piecewise Linear Approximation

The hyperbolic relationship between period and rate can be approximated through the use of diode curve-fitting techniques. Berwin (ref 1) has devised a circuit to perform such computations and Gill (ref 7) has developed equations that explicity define the values and number of sections needed to achieve a desired accuracy. For relatively low accuracy (±10%) this method is worth further investigation. However other techniques offer higher conversion accuracies at a lower cost in number of components.

(f) Conversion from Period to Rate by Triple Integration (Gilford ref 6 Method)

If the output voltage of a period analog circuit is stored and serves as the charging voltage to a second ramp generating circuit, the voltage that this circuit exhibits as a function of time is

$$e = K_1 T_n t,$$

Where T_n is the period between consecutive events. The time t required for this second ramp to reach a fixed reference level is

$$t = e_{ref}/K_1 T_n = K_2/T_n$$

The voltage reached by a third ramp circuit charging linearly toward a fixed reference during the time t is thus inversely proportional to T_n, the period, or directly proportional to the rate. This third voltage may be sampled and held as the actual rate analog while the period analog generator is reset and started again. Waveforms illustrating typical operation are shown in figure 1.

(g) Conversion from Period to Rate by the Method of Hirsch and Hallden (ref 9)

This method employs two RC circuits with identical time constants. Circuit A is charged towards and initial reference of R volts and circuit B is charged towards an initial value of P volts, where P is a period analog voltage (greater than R). At t = 0, both circuits are permitted to discharge:

$$e_A\ (t) = Re^{-t/T}$$

$$e_B\ (t) = Pe^{-t/T}$$

Therefore,

$$e_A\ (t)/e_B(t) = R/P$$

and if e_A (t) is sampled at $t = T_R$, when e_B (t) = R, then

$$e_A\ (T_R) = R^2/P = K/p$$

The realization of this method is shown in figure 2. An operational integrator charges towards a reference voltage linearly with period. Immediately prior to discharge, the integrator C_1 is disconnected from its RC circuit, which is then

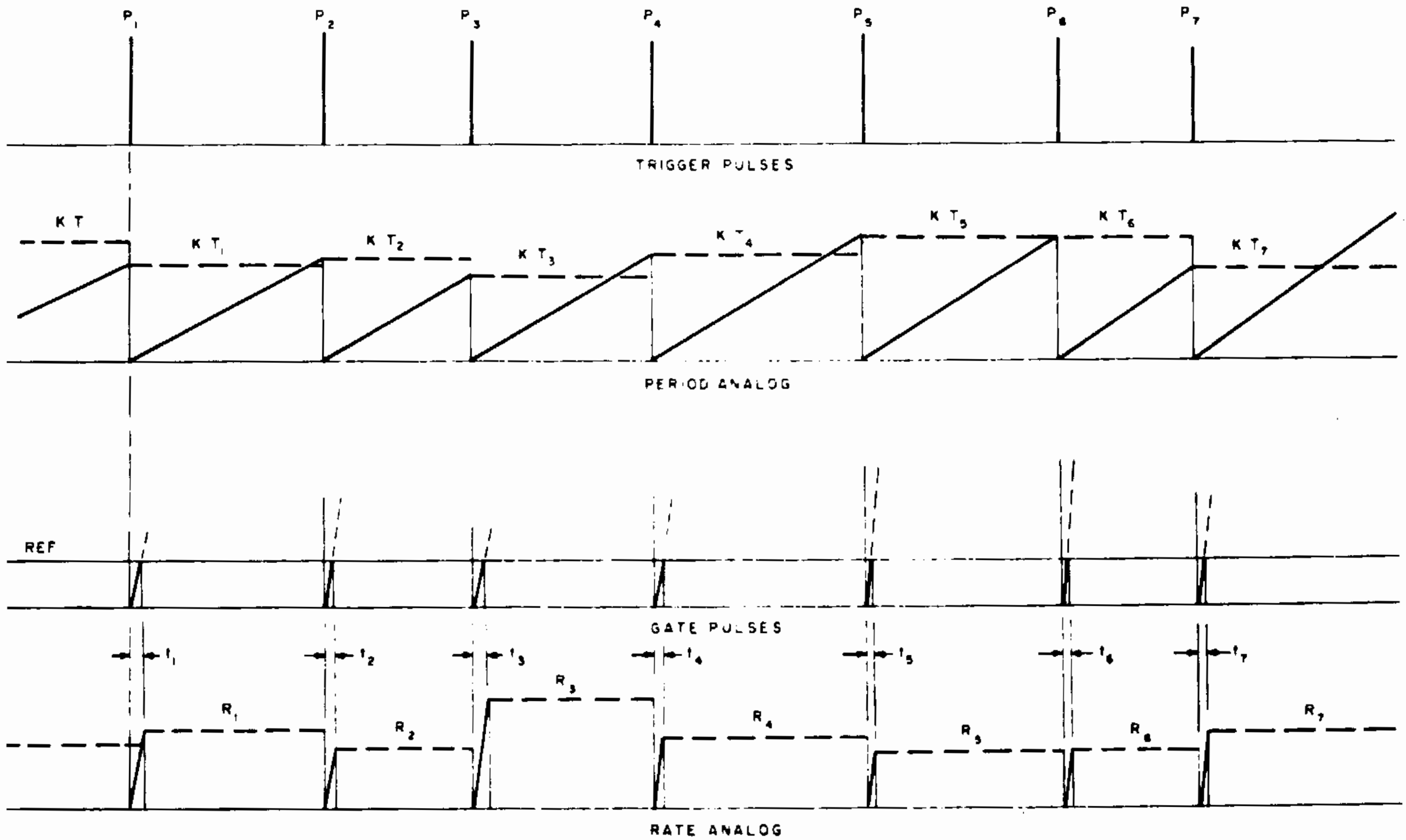

FIGURE 1 WAVEFORMS SHOWING RATE ANALOG GENERATION BY METHOD OF TRIPLE INTEGRATION

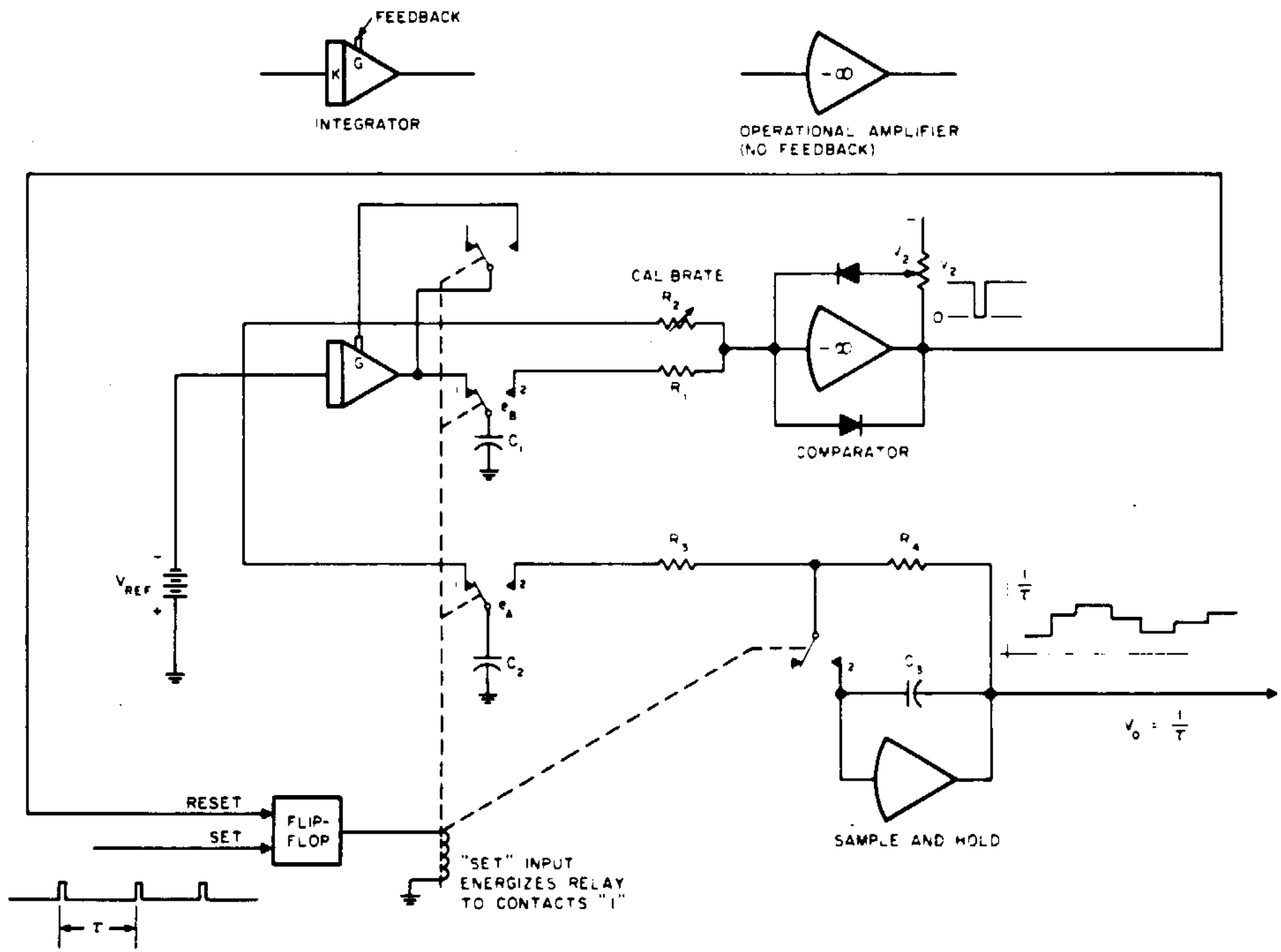

FIGURE 2 RATE ANALOG PROCESSOR CIRCUIT-METHOD OF HIRSCH AND HALLDEN

permitted to discharge at the same time as the other circuit C_2 is disconnected from its constant voltage source. When the comparator detects a preset voltage level in the RC circuit previously connected to the integrator, the sample and hold circuit, which had been reading the output of the reference voltage decay circuit, holds the voltage it sees until the next pulse. In a practical system solid state switches would be used instead of relays. Waveforms illustrating the operation of this circuit are shown in figure 3.

The system just described is simple, accurate, and highly linear, and is the type of circuit recommended for obtaining a precise linear rate analog.

(h) Conversion from Linear to Logarithmic Characteristic

The conversion of a linear rate analog to one with a logarithmic characteristic is realizable over a limited but useful range through the forward voltage-current characteristic of an ideal semiconductor diode. Hoyt (ref 10) shows an all solid-state amplifier capable of log-linear outputs over a 40 db range of input voltage starting at about 0.1 volts. This type of circuit would allow selection to be performed by the Monitored Data System on the basis of relative change of rate rather than absolute change of rate. As indicated in paragraph (d) above a (small) relative change in period would be equally valid as a criterion of selection. If this were used, the need for converting from period to rate analog would be eliminated.

SUMMARY

For test and demonstration purposes, the ECG with amplitude triggering or a combination of amplitude and slope triggering will be used as an input signal to the rate analog processor. A potentially simpler signal source that will be investigated further as a backup is the photoelectric ear-lobe heart-beat detector. If time permits, a nasal thermistor or a strain-sensitive belt transducer will be used to produce respiration signals for test purposes.

The rate analog processor will be designed to provide both a linear rate analog (by use of the method of Hirsch and Hallden) and a logarithmic rate (or period) analog. Its output voltage will be compatible with the input specifications of the Monitored Data System.

Circuit components will be solid state and compatible, so far as possible, with the power sources and packaging configuration of the existing Monitored Data System.

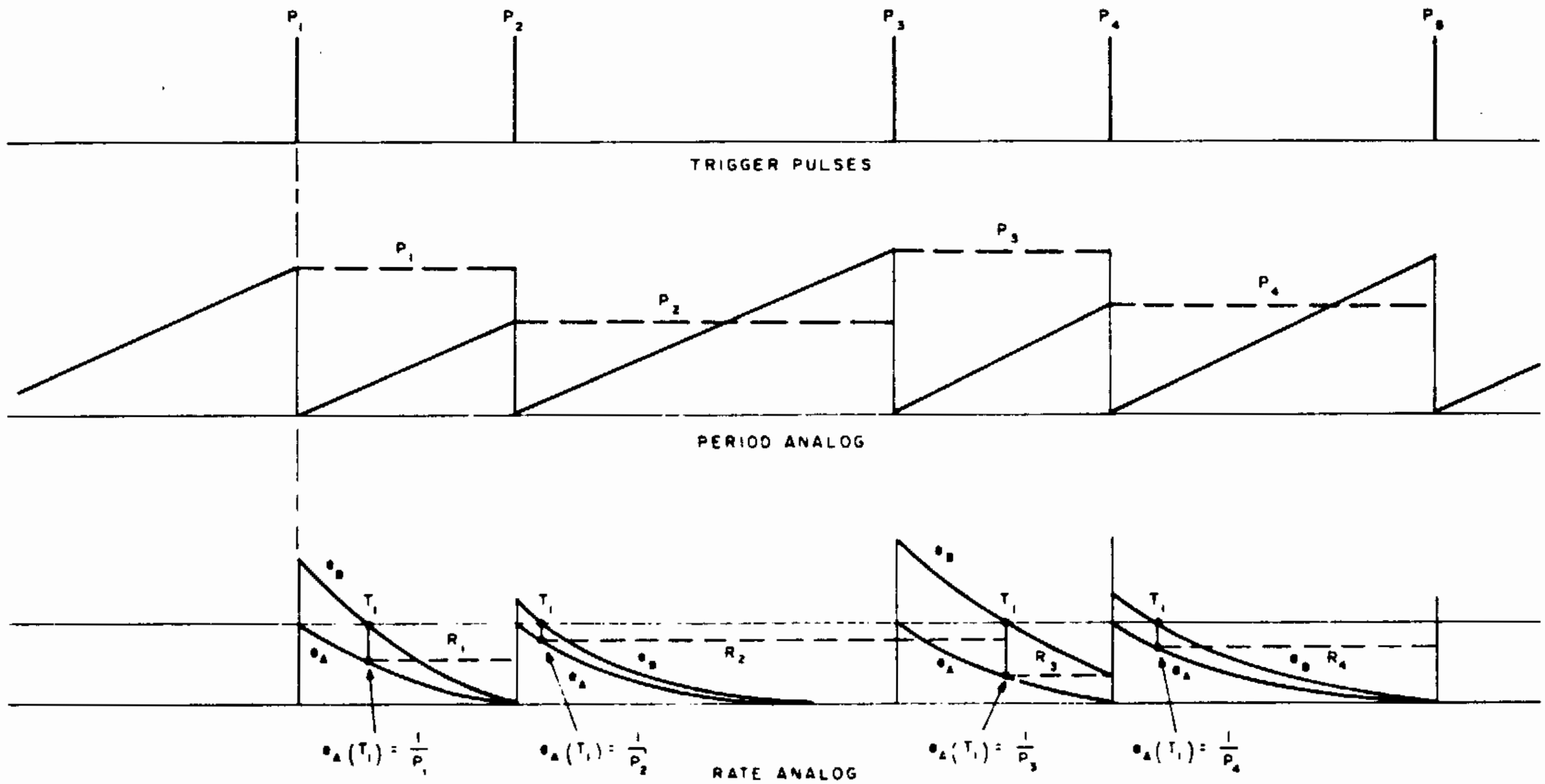

FIGURE 3 WAVEFORMS SHOWING RATE ANALOG GENERATION BY METHOD OF HIRSCH AND HALLDEN

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APPENDIX A

Survey of Cardiac and Respiratory Signal Sources

Among the more common methods of converting heart and respiration signals to electrical form are the following:

1. Cardiac

a. Acoustic

Rate information may be obtained from the phonocardiogram (PCG) appearing at the output terminals of an acoustic pickup. In this case it is necessary to filter the PCG so that the heart sounds can be isolated (for further processing) by suppressing other sounds and movement artifacts. Even with such filtering the PCG is relatively sensitive to artifact and for this reason is not ideally suited for rate determination.

b. Mechanical

The finger plethysmograph or sphigmomanometer cuff are sensitive to pulse pressure as blood volume changes in the confined area. With the addition of a pressure transducer they are capable of rendering an electrical output. These devices present undesirable restraints on subject movement, are ineffective in peripheral vasoconstriction or shock, and are quite movement-sensitive. They are therefore not suitable to the application in question.

c. Optical

The photoelectric ear lobe transducer described by Harten and Coroncal (ref 8) and marketed by Gilford* is relatively insensitive to subject motion and electrical interference, the former because of its placement on the ear lobe, and both the former and the latter because of the very narrow and noise-free (0.6 to 3.6 cps) bendwidth for photoelectric conversion of pulse signals. Although this type of device is ineffective in shock and peripheral vasoconstriction and will be affected by high ambient red or infrared radiation, neither of these limitations appears to severely impair its usefulness in the demonstration of a rate-analog device. The photoelectric pick-up therefore appears to merit consideration for the intended application.

d. ECG

The major disadvantage of ECG is its sensitivity to motion and EMG artifact. Several investigators have attacked this problem and suggested relatively

*Marketed by Gilford Instrument Laboratories, Incorporated, Oberlin, Ohio artifact-free electrode combinations 8,9,10,11, but the problem is by no means solved, and work in this area continues. The rich diagnostic values of the ECG makes its use as an input to the rate analog processor attractive in spite of its recognized limitations.

2. Respiratory

a. Pneumatic

Respiration rate may be derived via transducer from pressure or flow changes for a masked or helmeted subject breathing through a tube from an air supply. Implementation of this method for demonstration purposes would be somewhat cumbersome, however, and superior techniques are available.

b. Impedance Pneumogram

This technique has the potential advantages of using the same electrodes as the ECG. It remains to be seen whether electrode placement for an artifact-free ECG system is capable of also producing satisfactory pneumographic records. Due to the relative complexity of such a system, it does not appear suitable for demonstration purposes.

c. Thermistor Pneumogram

A small thermistor element with low thermal mass mounted close to one of the nares presents a simple means of measuring respiratory activity, provided the subject is not speaking or mouth-breathing. During speech the signal derived from such a device is meaningless but for mouth-breathers, the thermistor can be mounted near the mouth in much the same way as the microphone in a standard telephone headset. For demonstration in a controlled environment this method has the advantage of relative simplicity.

d. Strain-Sensitive Elements

A belt of conductive silicone rubber fastened about the chest presents a fairly large impedance change for changes in chest wall circumference. Such a system is simple to instrument, but sensitive to artifacts caused by arm movement (eg, changes produced by latissimus dorsi, pectoralis, and serratus anterior contractions). For demonstration purposes this method would probably suffice.

SUMMARY

ECG signals will be used for cardiac rate processing because of their diagnostic importance and relative freedom from artifact (using unconventional lead placements). Signals derived from the photoelectric transillumination transducer will also be tested, both because of the ease by which they can be obtained and their freedom from artifact. Respiratory signals will be obtained if time permits from a nasal thermistor.

APPENDIX B

Triggering Techniques for Physiological Variables

For optimum performance, the rate-analog processor requires the generation of an unambiguous standardized trigger pulse for each heart beat or each respiration cycle. In this Appendix the more prevalent methods of trigger generation are reviewed and evaluated for the intended application. Among these are:

(1) Amplitude Triggering

Triggering on a threshold of signal amplitude as, for example, the R wave of the ECG, is an accepted method of signal conditioning for rate measurement. When used on the ECG this method is susceptible to error in the presence of anomalous aperiodic or quasi-periodic events, such as EMG noise and baseline shifts at rates exceeding the low frequency cutoff of the system.

(2) Baseline Crossing

A special case of amplitude threshold triggering is that of baseline crossing which can be applied to a suitably filtered (or coupled) signal. This technique is particularly useful on the differentiated waveform as a means of detecting peaks independent of their amplitude. Suppression of secondary zero crossings in a wave complex can frequently be accomplished by combining inflection-point detection with absolute amplitude detection.

(3) Rate of Change of Amplitude

A third variety of amplitude triggering technique is that of triggering on rate-of-change of amplitude (amplitude of first derivative). This is frequently applied to the RS segment of the ECG. In such applications, a combination of absolute amplitude and ensuing rate of change of amplitude can afford increased discrimination against noise and artifacts.

(4) Integration, or Phase Comparison and Servo-Loop Control

In the range-gate type of system devised by Sawyer (ref 12), the PCG is filtered to pass the energy between 40 and 60 cps. It is then full-wave rectified and envelope detected. The range-gate operates on the envelope of the heart sound by attempting to keep it centered within the gate. Two servo loops are employed: one, a slow response loop, alters the basic repetition period of the gate generator to follow long-term changes in rate; the second (rapid response) loop adjusts the instantaneous phase of the opening time of the gate on the basis of the predicted time of occurrence of each beat. The error signal is derived from the integrated acoustic energy distribution between the "early" and the "late" halves of the gate. Once locked in, this system has the advantage of being able to track heart signals through a relatively high noise level and through large changes in signal amplitude. The output of the circuit is a standardized pulse coincident with the gate opening.

The inherent complexity of this system, plus the fact that it requires human intervention to reestablish tracking after loss of signal, limits this technique principally to research applications in a controlled environment.

SUMMARY

Of the foregoing methods the use of amplitude or zero-crossing detection, combined, if necessary, with signal differentiation appears to offer the simplest and most reliable method of generating trigger signals to drive the rate analog processor.