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# CARDIAC R-WAVE DETECTOR WITH AUTOMATIC SENSITIVITY CONTROL

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16. Abstract
An electronic circuit that automatically changes its sensitivity was developed for detecting the bioelectric signal resulting from activation of the heart's ventricles. Regulation of sensitivity was accomplished with two feedback channels that maintain the sensitivity level between an upper and a lower limit. These limits are proportional to the R-wave amplitude. Tests on an experimental circuit demonstrated a capability to reject unwanted signal noise, illustrated difficulties encountered without sensitivity control, and presented closed-loop transients which occurred for step changes in R-wave amplitude.

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# CARDIAC R-WAVE DETECTOR WITH AUTOMATIC SENSITIVITY CONTROL

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## SUMMARY

A new cardiac R-wave detector automatically changes its signal sensitivity. The instrument uses two feedback channels to control the sensitivity level of the basic detector circuit. The instrument was developed to improve the performance of heartbeat-monitoring equipment and for synchronization of heart-assist pumps.

An experimental circuit was tested with the use of electrodes on the right arm and left leg. Tests demonstrated that all unwanted signals except those generated by vigorous motion or extreme muscle tensions are rejected by the instrument. The data illustrated the difficulties encountered when operating without automatic sensitivity control. Closed-loop transients from step changes in R-wave amplitude are presented.

## INTRODUCTION

The electrocardiac R-wave detector is an instrument that detects the bioelectric signal resulting from activation of the heart's ventricles. Such detectors are used in intensive-care wards to monitor heartbeats of patients and to alert the medical staff to abnormal rhythms. Another application is synchronizing heart-assist pumps to the rhythm of the natural heart. Detectors are also used in research projects that record the heart rates of subjects doing strenuous exercises.

Dependable detection of the R-wave requires a circuit that does not respond to other waves present in the electrocardiogram (ECG or EKG) signal. For example, the familiar shifts of the ECG baseline produced by breathing, electrode movements, and physical contact with electrically charged objects could cause the electronic circuit to produce an output signal at the P-, T-, and R-waves of the ECG or to not trigger at all, depending on the direction of the baseline shift. Electrical signals produced by alternating electrostatic fields, electromagnetic radiation, and muscular activity also present a problem. Excessively noisy input signals mask the R-wave. Conventional noise filters generally are inadequate because the signal amplitudes produced by muscular activity can be high relative to the 1-millivolt amplitude of the normal R-wave.

During the past several years, a variety of electronic circuits have been designed to improve the reliability of detecting the R-wave portion of the ECG. These circuits use a combination of special signal processors to accurately detect R-wave signals in the presence of electrical interferences. A previously reported successful circuit (ref. 1) used a series of networks that provided high common-mode rejection, linearly filtered the ECG signal, detected amplitude, and blocked waves of shorter duration than the normal R-wave. Other successful circuits (refs. 2, 3, and 4) have included nonlinear amplification, slope discrimination, and phase detection of R-waves to improve their detection capabilities.

Sensitivity of the detector circuit is generally set to match the individual R-wave signal. The R-wave amplitudes usually change with time from physiologic effects and from artifactual changes. Consequently, the sensitivity must be periodically readjusted to minimize false output signals. To solve this problem, automatic control of the circuit's sensitivity was added to the basic R-wave detector. The new instrument was developed under the NASA Technology Utilization Program.

This report details the operation of the new R-wave detector and presents the schematics of all circuits used in the instrument. It also presents the results of the performance tests.

## CARDIAC R-WAVE DETECTOR

The cardiac R-wave detector produces an electrical output pulse which can be activated only by signals that duplicate the characteristics of the normal R-wave. The input to the detector is the electrocardiac biopotential obtained from surface electrodes placed on the right arm and left leg (bipolar standard lead II). Figure 1 shows the ideal ECG input signal without noise and the 100-millisecond output pulse from the detector.

Figure 2 shows the sequence of operation used to eliminate essentially all components from the input signal except the R-wave. The first section is a differential amplifier with high common-mode rejection for canceling equal signals at the two input terminals. The input terminals are electrically isolated from the circuit common to prevent grave dangers that can result from excessive leakage current. The second block contains the bandpass amplifier that amplifies the R-wave and suppresses the P-, T-, and U-waves.

After it is amplified and filtered, the signal is processed by a circuit whose output is the absolute value of the input signal. This circuit corrects for an inverted R-wave, and thereby makes the instrument independent of lead polarity.

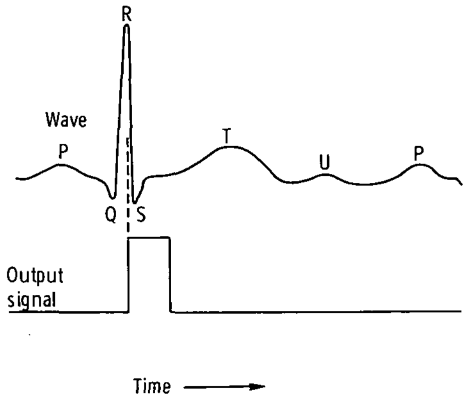



Figure 1. - Input-output wave characteristics.

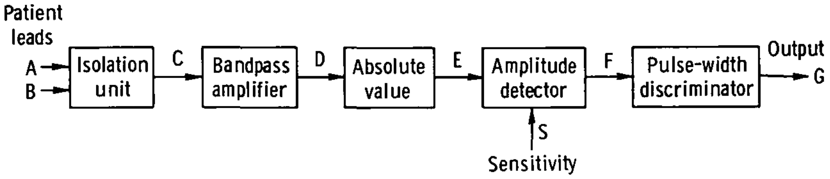



Figure 2. - Block diagram of cardiac R-wave detector without sensitivity-control circuit.

Next, the electrocardiac signal is converted into pulses for further analysis. The amplitude detector produces a pulse whenever the signal exceeds the level set by the sensitivity signal. These pulses have durations related to the durations of the original waves. Pulses are then subjected to a pulse-width discriminator which eliminates short pulses. Long pulses exceeding 10 milliseconds activate the circuit output. This technique inhibits most interferences from causing false outputs.

Best results are obtained when the R-wave detector is set at the lowest sensitivity value that still produces reliable R-wave detection. Low sensitivity means the amplitude detector can be triggered only by high-amplitude signals. Low sensitivity is desirable, since it minimizes the number of false outputs due to biopotentials from muscular activity and other electrical interferences.

## CARDIAC R-WAVE DETECTOR WITH AUTOMATIC SENSITIVITY CONTROL

In practice, the lowest sensitivity setting presents a problem. The detector misses low-amplitude R-waves that occur after a physiologic or artifactual change. To solve this problem, automatic sensitivity control was added to the basic R-wave detector circuit. The control process is shown in figure 3.

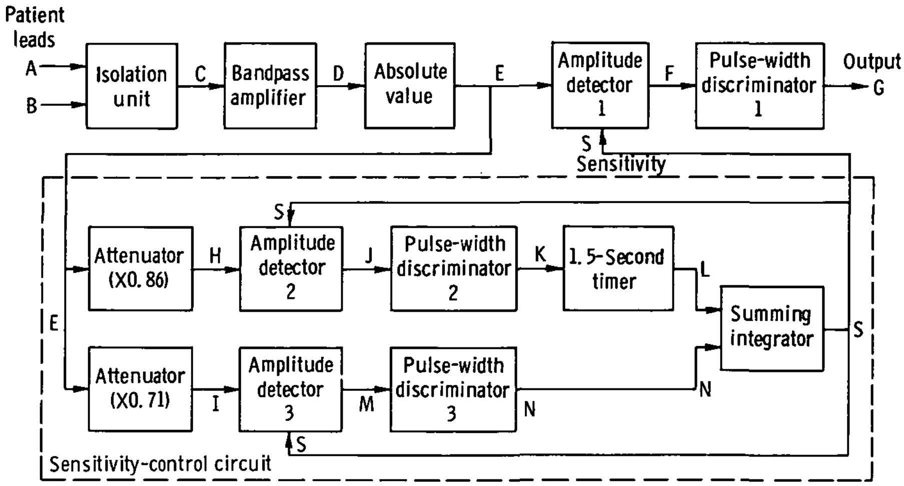



Figure 3. - Block diagram of cardiac R-wave detector with automatic sensitivity control.

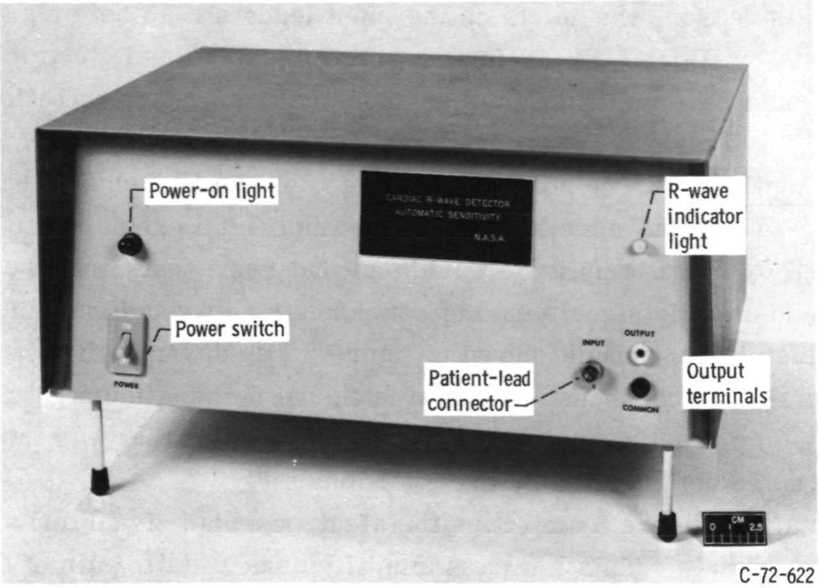
Too low sensitivity is determined by the circuit between E and L. First, signal E is made smaller by a factor of 0.86. The resultant signal H is then processed by an amplitude detector and a pulse-width discriminator identical to those of the basic R-wave detector circuit. Too low sensitivity is indicated when no pulses occur at K within a 1.5-second period. The timing circuit then switches L to a different voltage level. The new voltage at L causes the integrator to increase the sensitivity at a constant rate until a pulse at K resets the timer. At this instant, L returns to its normal level, and signal S becomes fixed at a new level that makes the instrument more sensitive to small signals.

The circuit between E and N determines the condition of too high sensitivity. Signal E is made smaller by a factor of 0.71 before being processed by the amplitude detector and the pulse-width discriminator. Sensitivity is too high if signal I can activate the pulse-width discriminator. Signal N then switches to a different voltage for 100 milliseconds. The new voltage at N causes the summing integrator to decrease the sensitivity at a constant rate. At the end of the 100-millisecond period, N resets to its normal level, and S becomes fixed at a lower sensitivity level. The process repeats until the sensitivity is driven down to the acceptable range.

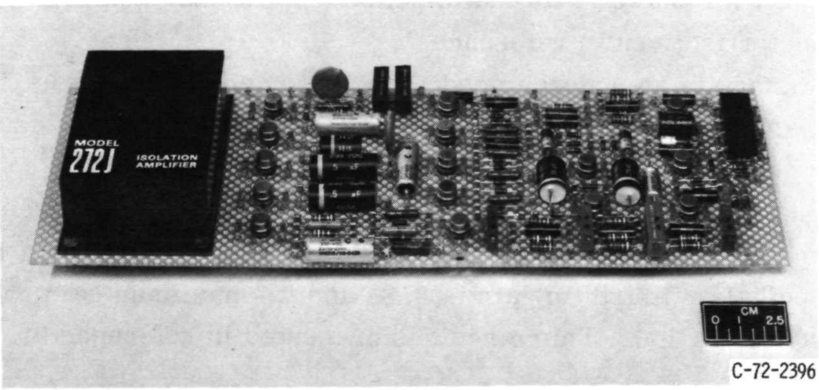
## EXPERIMENTAL UNIT

### Electronic Circuits

An experimental R-wave detector was built and tested. Figure 4 shows the instrument, which was fabricated from standard, commercially available components. Since the instrument is completely automatic, the cabinet has no control dials; it has only a




(a) Front view.




(b) Circuit layout.

Figure 4. - R-wave detector.

power switch, patient lead connector, output terminals, and indicator lights to display its operation. Complete details on the instrument circuits and test-signal circuits are given in this section. Definitions of schematic symbols and component specifications are given in the appendix.

Isolation unit. - The patient leads are connected to the input of an electrically isolated device (fig. 3) that transmits with no amplification of the input signal (unity gain). Its main function is to provide safety to the patient. Isolation characteristics that satisfied the safety standard recommended in reference 5 were obtained from a commercial amplifier.

To minimize 60-hertz pickup and other common-mode interferences, the input leads must be properly shielded. Grounded shields for off-ground differential-input units can degrade the signal by driving current through capacitive coupling into the signal leads (ref. 6). For this reason, the shield on the input leads should not be grounded but connected to either A or B (fig. 3). To further minimize unwanted electrical signals, the isolation unit should have an input common-mode voltage-rejection ratio of 1000 (60 dB), minimum.

Bandpass amplifier. - The normal QRS wave, shown in figure 1, has an amplitude of only 1 millivolt. A special selective frequency amplifier is required to convert the electrocardiac signal to a high-amplitude waveform that represents only the QRS complex. The circuit should amplify signals having components between 10 and 30 hertz.

The five-stage linear circuit shown in figure 5 was designed for the experimental instrument. Its frequency response is shown in figure 6. Maximum gain of 16 000 occurs at 20 hertz. The dip at 60 hertz results from a notch filter that was included to suppress any power-line noise not rejected by the isolation unit.

The first stage in figure 5 amplifies the electrocardiac signal and attenuates the higher frequency signals. This low pass amplifier has a static gain of 68, an attenuation rate of 20 decibels per decade, and a corner frequency (break point) of 64 hertz. The fundamental theory for this circuit and for other operational-amplifier circuits used in the R-wave detector is given in reference 7.

The second stage is an underdamped, second-order lag process. The relative damping coefficient is 0.7, and the corner frequency is 37 hertz. This circuit is described in reference 8.

The third stage is a 60-hertz notch filter that has an adjustable rejection ratio and an adjustable notch frequency. When properly adjusted, the circuit has a rejection ratio of more than 70 decibels. Its static gain is 0.8, and its maximum gain, which occurs above the notch frequency, is 1.0. This circuit is presented in reference 9.

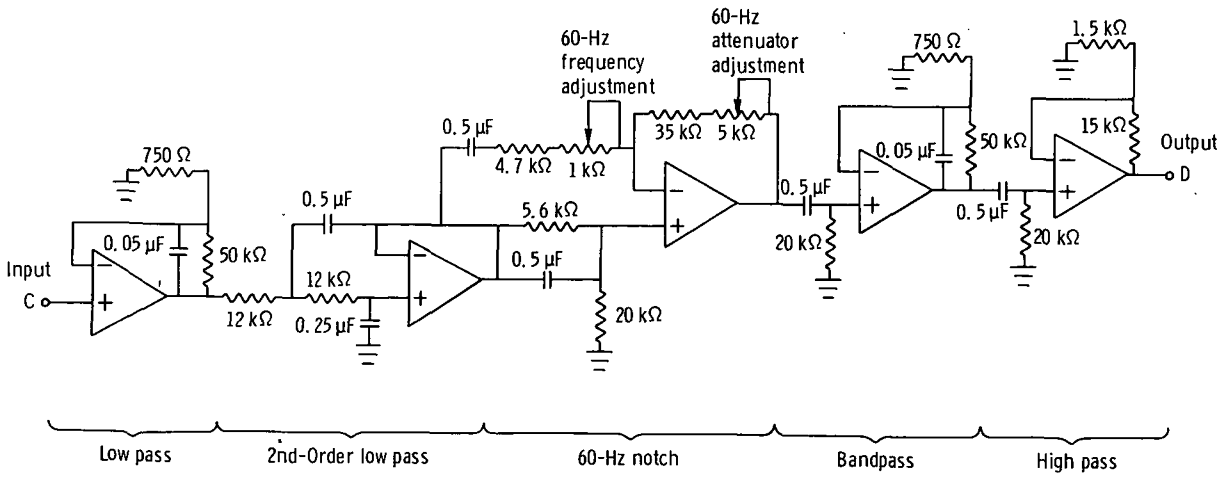



Figure 5. - Bandpass amplifier circuit.

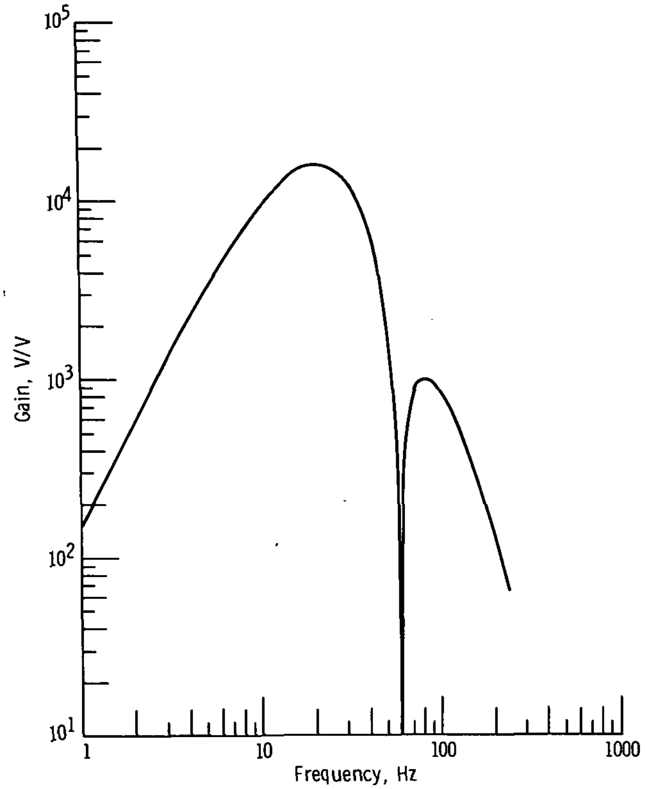



Figure 6. - Frequency response of bandpass amplifier of figure 5.

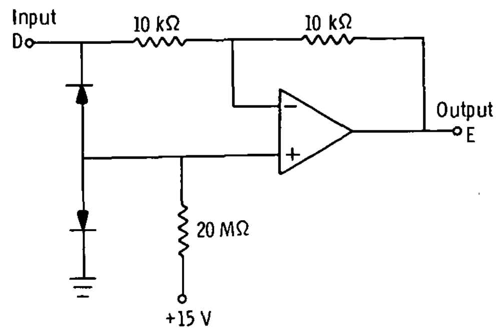



Figure 7. - Absolute-value circuit.

The fourth stage is a bandpass circuit that amplifies the components whose frequencies are near the fundamental frequency of the QRS wave. This circuit has a maximum gain of 54 at 32 hertz. The corner frequencies are 16 hertz for the lead process and 64 hertz for the lag process.

The last stage amplifies the remaining signal to an amplitude suitable for the amplitude detector. The circuit is a high pass amplifier that has an attenuation rate of 20 decibels per decade for frequencies below 16 hertz and has a maximum gain of 11. It eliminates zero shifts that may occur in the preceding circuit.

Absolute value. - The full-wave rectifier circuit in figure 7 makes the instrument independent of lead polarity. The diode arrangement directs positive input signals to the inverting portion of the circuit and directs negative inputs to the non-inverting circuit. There is a small bias in the output signal at E because of the forward voltage drop across the diodes. Thus, if the diode forward voltage drop is 0.5 volt, the signal at E will be +0.5 volt when D is zero. The net result from this circuit is an output that equals the negative absolute value of the input plus a bias voltage. The bias has no effect on R-wave detection; it only shifts the level of the sensitivity signal used in the amplitude detection.

Amplitude detector. - An open-loop operational amplifier provides amplitude detection. In figure 8, the sensitivity signal S (fig. 3) is applied to the positive input terminal of the operational amplifier, and the electrocardiac signal E is applied to the negative input. In this application, the reference voltage S is a negative voltage. Consequently, zero input voltage at E will place output F at the negative-voltage saturation level of the operational amplifier. When E exceeds S (i.e., E more negative than S), output F switches to its positive-voltage saturation level. Signal F returns to its negative state when E no longer exceeds S. The resultant pulse at F is then processed by the pulse-width discriminator circuit.

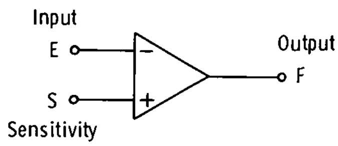


Figure 8. - Amplitude-detector circuit.

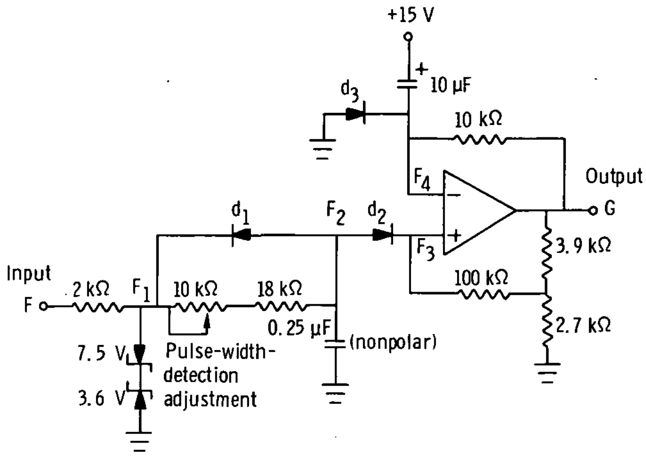


Figure 9. - Pulse-width-discriminator circuit.

Pulse-width discriminator. - The circuit shown in figure 9 prevents short-duration pulses from affecting output G. The normal states for input F and output G are negative voltages supplied by saturated operational amplifiers. In this operating mode, the potential at $F_1$ is approximately -8 volts. This value is unaffected by changes in the power supply or the operational amplifiers, since it is maintained by the zener diode circuit. When F becomes positive, $F_1$ changes to +4 volts. This shift from -8 to +4 volts causes $F_2$ and $F_3$ to increase exponentially, since diode $d_1$ blocks the current. When F returns to its normal state, diode $d_1$ conducts and quickly returns $F_2$ to its normal state.

If F remains positive for longer than 10 milliseconds, $F_3$ will build up to a value that is positive with respect to the voltage at $F_4$ and trigger output G to a positive voltage. The positive feedback circuit around the operational amplifier and the blocking action of diode $d_2$ keeps G latched at a positive value even though $F_2$ returns to its normal state. Output G remains positive until $F_4$ increases to a positive value greater than the voltage at $F_3$. One hundred milliseconds are required before G resets to its normal state. When G becomes negative, diode $d_3$ conducts and returns $F_4$ to its normal state. The circuit is then ready to detect another input pulse at input terminal F.

The R-wave detector with automatic sensitivity control (fig. 3) contains three pulse-width discriminators. Proper operation of the instrument requires that all three circuits be set exactly alike. The adjustment for setting the minimum detectable pulse width is made with the 10-kilohm trimmer potentiometer (fig. 9) while 10-millisecond pulses at a rate below 5 pulses per second are applied to F. A suitable test signal can be supplied by the pulse-generator circuit of figure 10.

Signal attenuators. - The automatic sensitivity-control circuit (fig. 3) uses signals H and I to determine if the sensitivity is too low or too high. These signals are obtained from the voltage divider shown in figure 11.

Timer. - The timing circuit in figure 12 is reset each time terminal K receives positive voltage from pulse-width discriminator 2. When K becomes positive, $K_1$ is raised

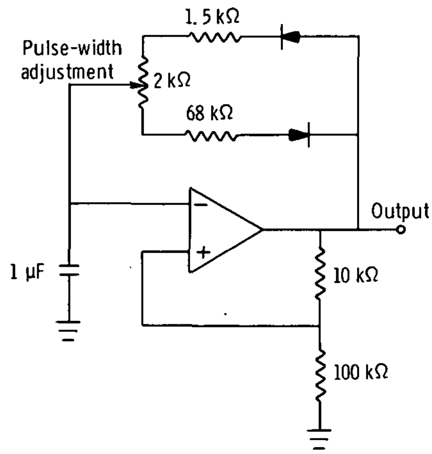



Figure 10. - Ten-millisecond pulse generator for adjusting the pulse-width-discriminator circuit.

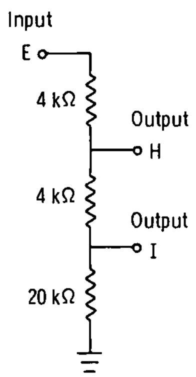



Figure 11. - Signal attenuator.

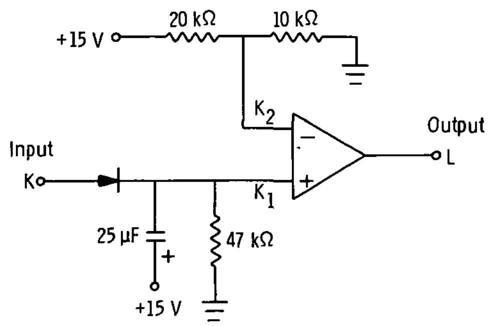



Figure 12. - 1.5-Second timer circuit.

to a positive potential which is higher than $K_2$. This condition places output L at the positive saturation voltage of the operational amplifier. Therefore, L is always positive immediately after pulse-width discriminator 2 has been activated.

The timing operation begins when K switches back to its normal negative state. The potential at $K_1$ then decreases exponentially, since the diode blocks the current. If K remains negative for 1.5 seconds, $K_1$ will decrease below $K_2$. Output L then switches to its negative saturation level, which indicates that the R-wave detector has too low sensitivity.

Summing integrator. - The purpose of the summing integrator is to (1) hold the output voltage constant when its inputs are in their normal states, (2) change the output at a positive rate when the instrument is too insensitive, and (3) change the output at a negative rate when the instrument is too sensitive. This function is accomplished with the circuit shown in figure 13. The operational amplifier with capacitance feedback provides the inverted time integral of the combined voltage $L_1$ plus $N_1$. Therefore, the operational-amplifier output changes at a rate proportional to the total input voltage. The proportionality constant is negative.

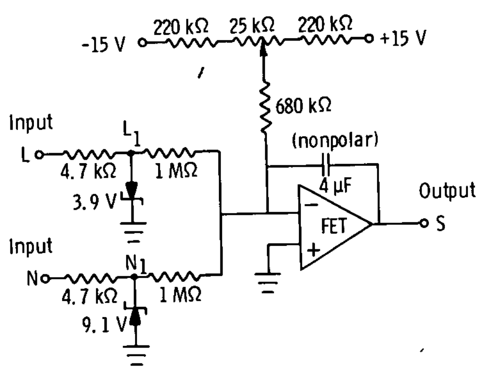



Figure 13. - Summing-integrator circuit.

Output S must be constant when the inputs are in their normal states. The normal state for L is a positive voltage that forward-biases the 3.9-volt zener diode. The normal state for N is a negative voltage that forward-biases the 9.1-volt zener diode. Since the forward voltage drop for the zener diodes is approximately 0.5 volt, the normal states for L and N result in low-level voltages at $L_1$ and $N_1$ that are nearly equal and opposite in sign. Integration of unequal potentials at $L_1$ and $N_1$ can be eliminated by supplying a bias current to the input circuit through the 25-kilohm trimmer potentiometer.

When the instrument becomes too insensitive for detecting R-waves, input L switches to a negative voltage, while N remains at its normal state. Voltage at $L_1$ changes to approximately -3.9 volts. The voltage at $N_1$ remains -0.5 volt. The combination of $L_1$

and $N_1$ (approximately -4.4 volts) changes output S at a positive rate, as required to make the instrument more sensitive.

For too high sensitivity, input N switches to a positive voltage that changes $N_1$ to approximately +9.1 volts. Input L remains at its normal state. The combination of $L_1$ and $N_1$ (approximately +9.6 volts) changes S at a negative rate, thereby making the instrument less sensitive.

Indicator light. - The R-wave indicator light shown in figure 4(a) turns on each time the instrument produces an output pulse. The rhythmic flashing light proved to be effective in demonstrating that the instrument was working properly. False outputs were indicated by rapid flashes, random flashes, or no flashes from the light. The indicator-light circuit used in the experimental instrument is shown in figure 14.

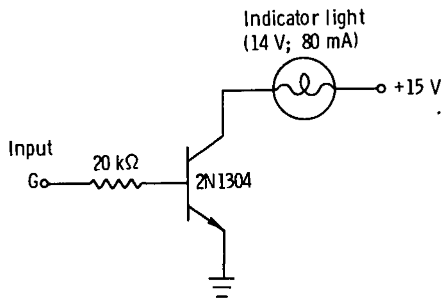


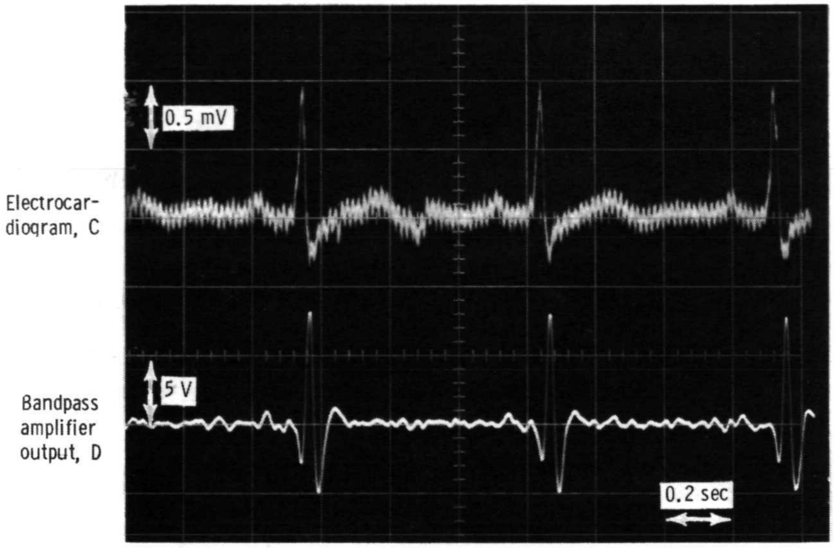

Figure 14. - R-wave indicator-light circuit.

## Test Results

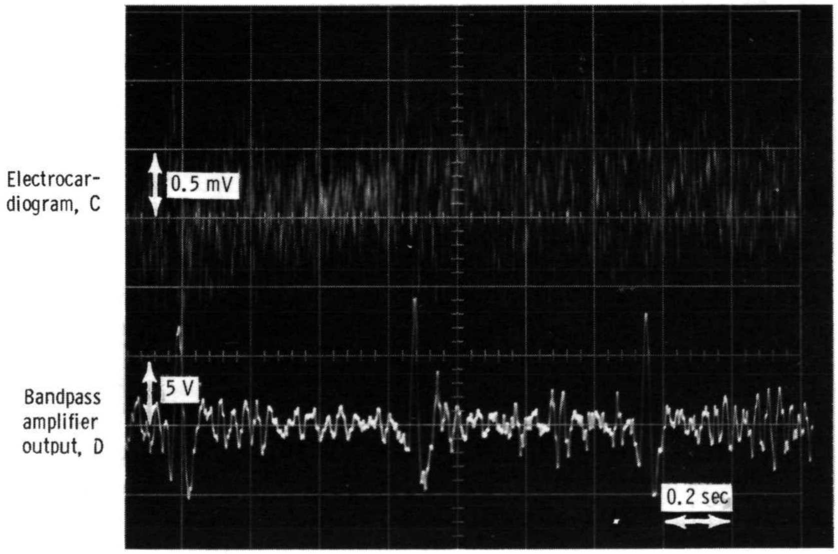
Experiments were conducted to verify the ability of the R-wave detector to reject unwanted noise, to demonstrate difficulties encountered during open-loop operation, and to record benefits derived from closed-loop operation. A human subject, with electrodes placed on the right arm and left leg, was used for the tests.

Noise rejection. - The bandpass amplifier circuit shown in figure 5 was checked for its noise-rejection capabilities. An oscilloscope recorded the signals at input C and output D. Figure 15(a) shows the results for a normal subject at rest. Output D contains only the QRS wave complex, with some baseline noise. The low-frequency P- and T-waves (see fig. 1) have been eliminated by the circuit.

Figure 15(b) shows signals that resulted when the subject tensed his right arm muscles. The ECG is hardly visible in the noise shown in the top trace. After filtering, the R-waves become quite distinct, for most of the low-frequency and high-frequency signals have been attenuated. Thus, the filter circuit provides a relatively noise-free signal for subsequent detection of the R-wave.




(a) Subject at rest.

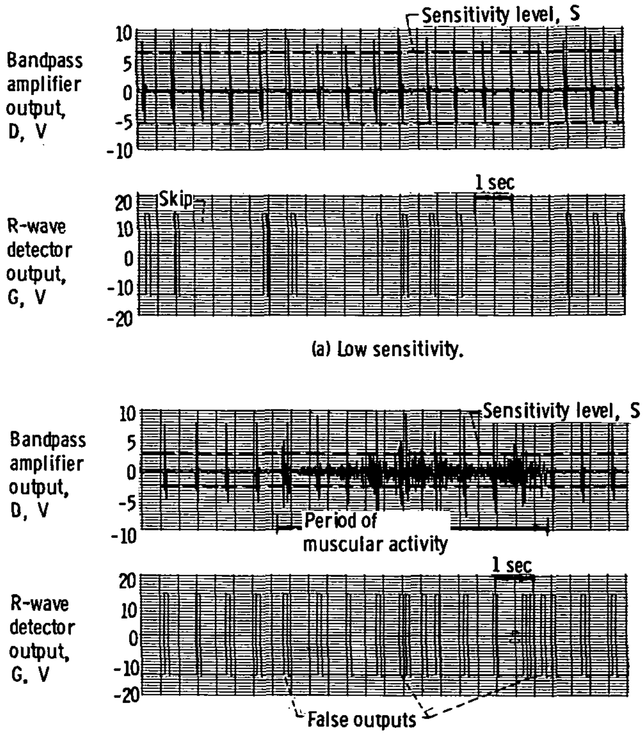



(b) Subject with muscles tensed.

Figure 15. - Noise-rejection capability of input filter.

Open-loop operation. - The disadvantages of operating without automatic sensitivity control were demonstrated by setting the sensitivity S at a fixed level. The results are illustrated in figure 16, which shows time traces of the filtered electrocardiogram D and the instrument output G.

The upper traces in figures 16(a) and (b) compare D with S. However, amplitude detector 1 (fig. 3) compares E, instead of D, with S. Signal D was recorded because it more clearly displays the R-wave. To illustrate the effect of E (i. e., absolute value of D), signal S in figure 16 is represented by two dashed lines. When D crosses either




(a) Low sensitivity.

(b) High sensitivity.

Figure 16. - Open-loop operation of R-wave detector.

line for periods longer than 10 milliseconds, output G is triggered.

In figure 16(a), signal S is 6 volts - a value that made the instrument quite insensitive to noise. In this case, the normal variations in R-wave amplitude were sufficient to cause the circuit to skip some R-waves.

Figure 16(b) shows the effects of reducing S to 2.5 volts. The higher sensitivity provided more reliable triggering for a resting subject but resulted in a condition more easily triggered by muscle noise.

The optimum sensitivity setting is between the two demonstrated extremes. However, it is difficult to manually determine the proper setting, because the R-wave amplitude and the various signal noises vary with time. Consequently, the automatic sensitivity control becomes a necessary feature that provides substantial improvement in the reliability of monitoring R-waves.

Closed-loop operation. - The transient behavior of the R-wave detector with its feedback loops closed was observed. Step changes in the ECG amplitude were simulated by step changes in bandpass-amplifier gain. Gain of the high-pass circuit (fig. 5) was decreased by switching a 13-kilohm resistor in parallel with the 15-kilohm resistor.

Figure 17 shows the case where signal reduction made the circuit too insensitive. The gain change and the corresponding reduction in ECG occurred at point 1 in the figure. The three amplitude detectors were then unable to detect the R-waves. Because of this

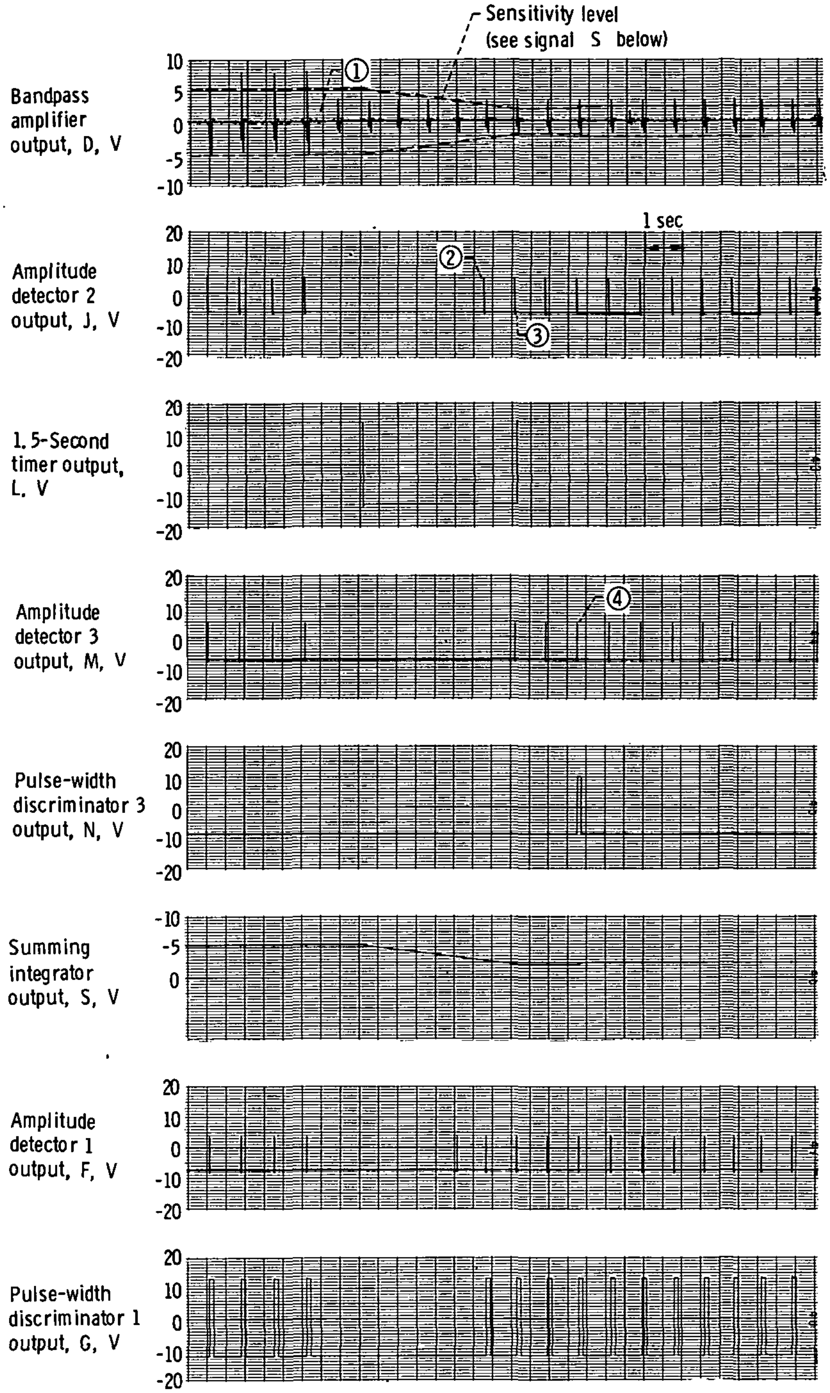



Figure 17. - Closed-loop transient due to a step decrease in R-wave amplitude.

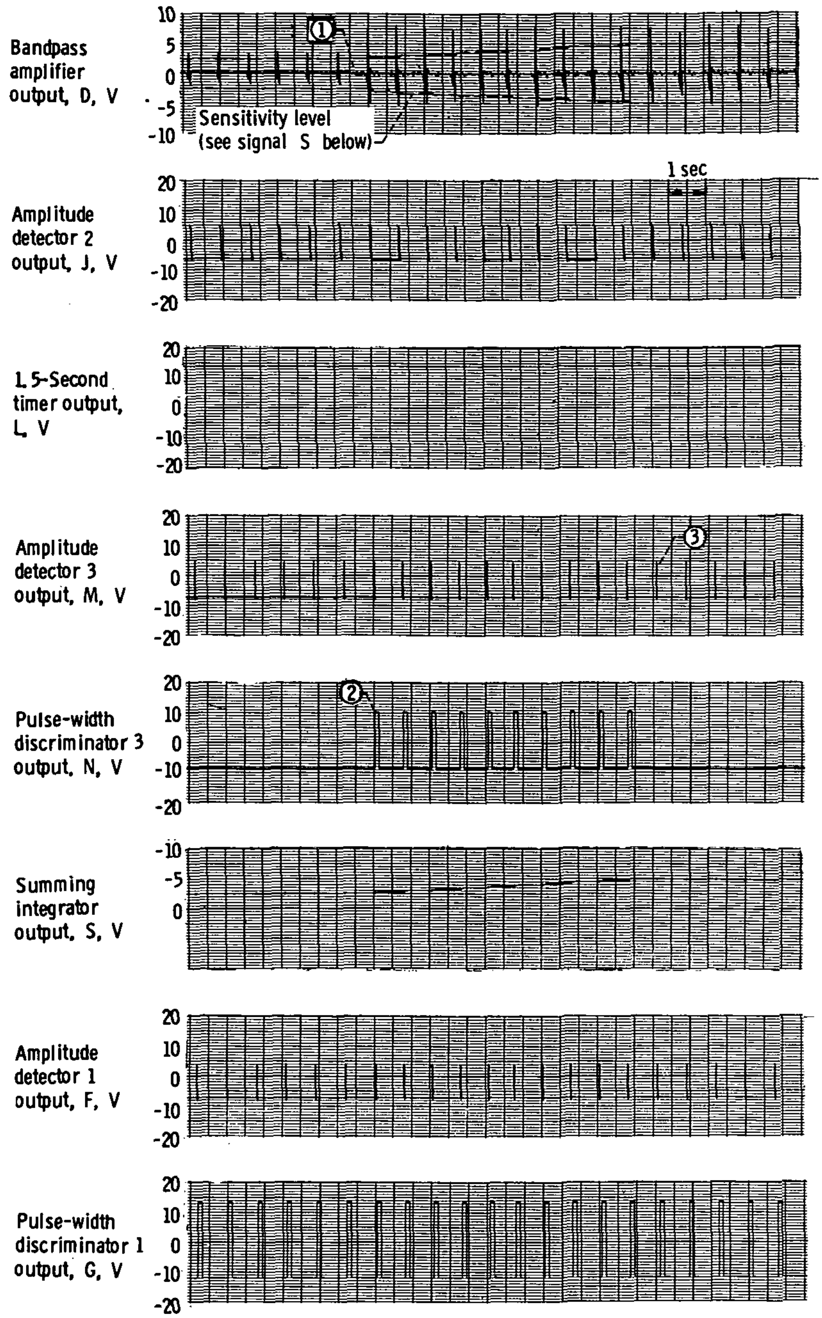



Figure 18. - Closed-loop transient due to a step increase in R-wave amplitude.

condition, the 1.5-second timer switched, which caused the integrator output to decrease the negative value of signal S. Signal S decreased at a constant rate until amplitude detector 2, J, detected a pulse that was wider than 10 milliseconds. In figure 17, the amplitude detector detected an R-wave at point 2, but the pulse-width discriminator did not reset the timer, since the pulse was shorter than 10 milliseconds. By the next R-wave, the sensitivity had increased enough to produce the required pulse width, which reset the timer at point 3 and stopped the integrator output S from further changes. Also at this point, the instrument output G resumed indication of R-waves.

A slight overshoot in sensitivity was indicated. At point 4, the sensitivity level was high enough to cause the R-wave to trigger pulse-width discriminator 3. The overshoot was soon corrected by the 100-millisecond pulse from N, which increased signal S by a discrete amount. With the control transient completed, S remained fixed in the zone that optimized the reliability of the instrument output.

The transient that occurred when the input signal was increased is shown in figure 18. The amplifier-filter gain was increased at point 1. This change resulted in pulses from the output M of amplitude detector 3 that were wider than 10 milliseconds. These pulses, which started at point 2, triggered 100-millisecond pulses from the pulse-width discriminator N. Each pulse from N increased S in a negative direction, thus decreasing the sensitivity. Pulses from N occurred on each R-wave until the sensitivity had been decreased sufficiently to make the pulses at M less than 10 milliseconds in duration (point 3). Signal S then remained fixed in the proper zone.

In figure 18, no interruption in the instrument output G had occurred during the test. False outputs could have occurred because of the initially high sensitivity setting if excessive noise had been present in the input signal.

Another example of closed-loop operation is shown in figure 19. This figure shows

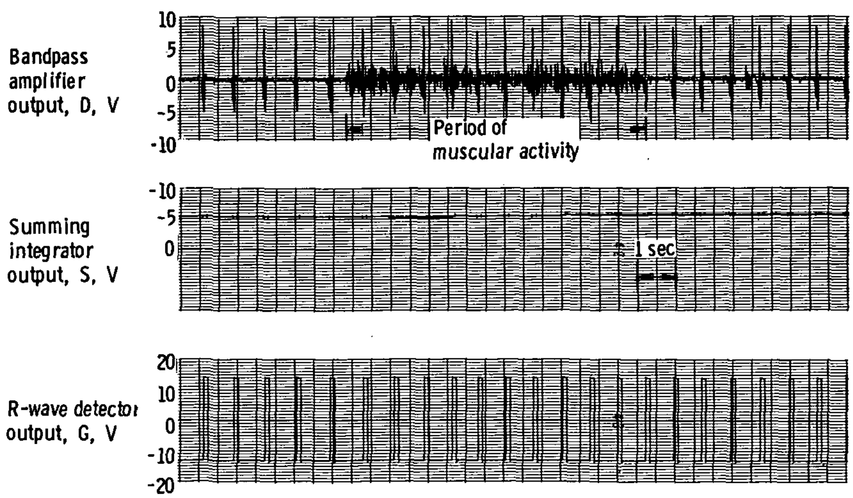



Figure 19. - Closed-loop operation of R-wave detector with noise in electrocardiogram from muscular activity.

effects of tensed arm muscles. The noise which is apparent in the amplifier-filter output D tended to add to the amplitude of some of the R-waves, which caused the automatic control to decrease the sensitivity slightly. This change was desirable, for it made the circuit less sensitive to noise. During this test, no false or missed outputs occurred in the output G.

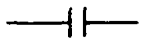
## SUMMARY OF RESULTS

Instruments for detecting cardiac R-waves use special signal networks that produce an electrical output pulse which can be activated by signals that resemble the normal R-wave. When they are properly adjusted, the processors separate the R-wave from the other signals produced by electrode movements, alternating electrostatic fields, electromagnetic radiation, and biopotentials from muscular activity. To minimize the number of false outputs due to interference signals, the instruments are generally set at the lowest sensitivity that still detects the patient's R-waves. Without automatic sensitivity control, these instruments must be readjusted whenever changes in signal amplitude result in irregular outputs.

An experimental R-wave detector with feedback circuits that controlled the instrument's sensitivity was built and tested. It operated reliably in the presence of abnormally high electrical noise obtained from surface electrodes located on the right arm and left leg. Tests demonstrated that automatic sensitivity control is a feature that improves the reliability and convenience of monitoring R-waves.

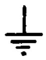
Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 17, 1972,
141-93.

# APPENDIX - ELECTRONIC-CIRCUIT SYMBOLS AND COMPONENT SPECIFICATIONS



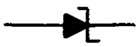
capacitor

resistor

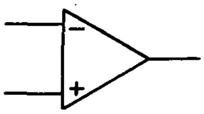


circuit common

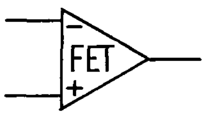
diode, IN459A or equivalent



zener diode, IN4700-series or equivalent




general-purpose operational amplifier: ±10-V output at ±5-mA output; open-loop total switching time $< 50\ \mu$sec; input resistance $> 1\times10^{6}\ \Omega$.




high-input-impedance operational amplifier: ±10-V output at ±5-mA output; input resistance $> 1\times10^{10}\ \Omega$.

Isolation unit

unity gain; 60-dB minimum common-mode rejection between inputs and shield; input currents less than 10 $\mu$A with 220 V ac impressed between any terminals; 1000-V common-mode voltage isolation from input to output terminals.

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