Specialized Ventricular Pacemaker to Detect and Treat Bradycardia

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***Abstract*— Cardiovascular disease is a leading cause of death in American adults, in part due to abnormal heart rhythms. This paper proposes a single-lead pacemaker to restore normal heart rates in patients with bradycardia. The design accomplishes this by first amplifying the inputted signal from the right ventricle of the heart. It then processes the signal, isolating the R-wave from a full ECG signal and formatting it into a signal which can be read later in the circuit. The timing of the heart is paced, checking that only low frequencies which correspond to dangerously low heart beats can continue through the circuit. These frequencies can then initiate a pulse, pacing the heart into a stable rhythm. This circuit was designed and simulated in the web-based program Circuit Simulator Falstad to confirm the feasibility and achieve its goal of attaining a heart rate of greater than 60 beats per minute. The design is simple, allowing it to both efficiently do its intended job and to be integrated into more sophisticated designs in future projects.**

Keywords*— *Pacemaker, Ventricular, Bradycardia

I. Introduction

Cardiovascular disease is the leading cause of death in the United States with 1 out of 5 deaths being attributed to an associated cardiovascular disorder. [1] The majority of these disorders can be attributed to the heart's inability to produce a reliable pace. This includes bradycardia where the heart beats at a rate below 60 beats per minute (BPM). [2]. A pacemaker is a medical device used to correct this abnormal pulse behavior. Specifically, pacemakers sense electrical signals from the heart, analyze if the pace is outside of what is considered a normal heart rate, and output correcting pulses that stimulate heart muscles to contract accordingly. [3] **Fig. 1** shows the placement and insertion of a pacemaker with respect to the physiological components of the heart.

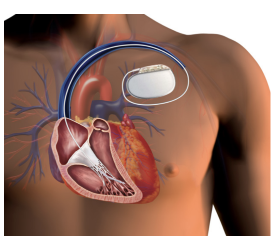

Fig. 1: The pacemaker is usually surgically implanted under the skin on the left side of the chest. The pacemaker lead is routed through the subclavian vein and lands at the bottom of the right ventricle [3]

This paper proposes a novel single-lead pacemaker which detects the changes in heart rate and shocks the patient if their heart rate is less than 60 BPM. For simplicity's sake, a single ventricular lead was selected for the design since most of the referenced cardiovascular disorders are inherently ventricular issues. Keeping these conditions and expectations in mind, we established the basic electrical components for the pacemaker. The single ventricular lead from the design will record signals from the heart via electrocardiogram (ECG) and create a visual representation of the pulse behavior. ECG readings are interpreted through various QRS complexes, but the design focuses on the R-wave component since it corresponds to ventricular pulse behavior. The next phase of the device processes the isolated R-wave and filters it accordingly. The output correction pulses are generated from a timing control apparatus within the circuit design that processes inputs and releases pulses based on calibrated values for timing control.

II. Methods

A general cardiac pacemaker is composed of four components: the power source, pulse generator, leads, and electrodes. The power source is usually a lithium-based battery that can provide the power needed to generate electrical impulses. Generating the pacing provides for the most amount of drain in a battery, so in order to make a long-lasting battery, the battery needs to have a high energy density and a low self-discharging rate. The pulse generator is responsible for generating the electrical impulses based on heart rate. The overall schematic of our specific pacemaker circuit can be visualized with the block diagram in Figure 2. The leads are responsible for connecting the pulse generator to the heart as referenced in **Fig. 1**. The lead follows through a vein into the heart and provides electrical impulses to the heart depending on the type of pacemaker. In a dual chamber pacemaker, one lead connects the pacemaker to the right atrium where the second leads connected to the right ventricle. However in a single chamber pacemaker, there is a single lead that connects to the right ventricle. Lastly, the electrodes are located at the ends of leads and directly deliver the electrical impulses to the heart muscle when the heart rate is too slow or irregular.

In a demand pacemaker, the pacemaker generates electrical impulses when there is an absence of natural heartbeats. The circuit is designed to be responsive to cardiac activity. When the sensor detects the PQRST wave, a non-inverting amplifier amplifies the signal. The R-wave will be processed and stabilized using a non-hysteretic comparator and a monostable 555 timer. To control the timing of pulses, a low pass filter checks the frequency of heart rates and induces a pulse using a 555 monostable timer when the heart has not beat for 1.4 seconds.

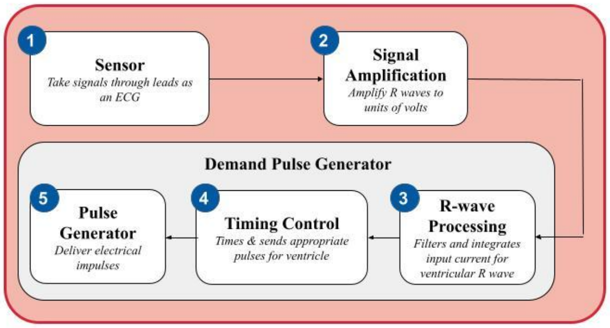

Figure 2: A block schematic of the five components of the pacemaker circuit: sensor, signal amplifier, R-wave processor, timing controller, and pulse generator

A. Sensor

To sense the electrical signals from the heart, the proposed ventricular pacemaker contains one lead. The lead has two electrodes: an anode and a cathode. The pulse generator applies a voltage difference between the anode and cathode which results in electrons flowing from the anode to the cathode. Those electrons then depolarize the myocardium and trigger an action potential throughout the myocardial tissue.

Each sensor has an acceleration sensor. A force transducer senses the vibrations from the heart which is sent to the acceleration sensor. The acceleration sensor processes the signal and outputs a voltage based on the linear relationship between acceleration and voltage [4].

B. Signal Amplification

Following the sensing portion of the schematic, the first objective of the proposed circuit for the pacemaker is to amplify the measured ECG signal. Typically, the R-waves of the ECG are measured in units of mV, which is somewhat difficult for the subsequent electrical components to utilize for the optimal performance. To facilitate the processing of the electrical pulses from the heart, the ECG signal from the initial sensor must go through a non-inverting amplifier. The chosen resistor values are referenced below in **Fig. 3**. Following this step, the amplified ECG signal is ready to be further processed so that waves of interest are isolated.

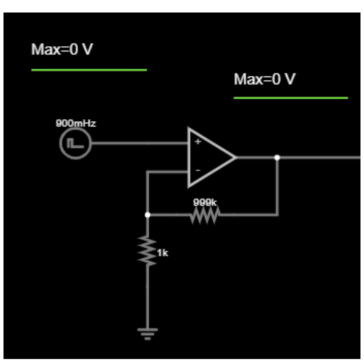

Figure 3: The non-inverting amplifier connected to a A/C source and connected to two resistors with values of 1 kΩ and 999 kΩ.

C. R-Wave Processing

After utilizing the sense amplifier to retrieve an ECG signal from the heart, the second step is to process the R-wave of the QRS complex. As mentioned before, the R wave of the QRS complex is of particular interest since the pacemaker analyzes and responds to the pulses based on ventricular behavior. To sense and process the R-wave, the first electrical component is a non-hysteretic comparator. Based on literature, the amplitude of R-waves vary from 5 to 25 mV. Keeping this information in mind, the comparator will compare the input R-wave with the threshold voltage established and calibrated within this specific range. Specifically, if the input signal is greater than 5 mV, the comparator will go "high." This amplification of the R-wave portion essentially isolates the ventricular related signal of interest from the PQRST complex.

As seen in **Fig. 4**, the second electrical component that is utilized for R-wave processing is the first 555 timer of the overall circuit. The desired pulse width of the R-wave is 0.1 seconds, and a monostable 555 timer was selected to set this value. Essentially, this component of the R-wave processing stage is implemented to refine the isolated and amplified signal for the upcoming electrical components in the circuit. The monostable 555 timer stabilizes the incoming signal from the non-hysteretic comparator to allow for simplified processing through subsequent low pass filter and the second monostable 555 timer.

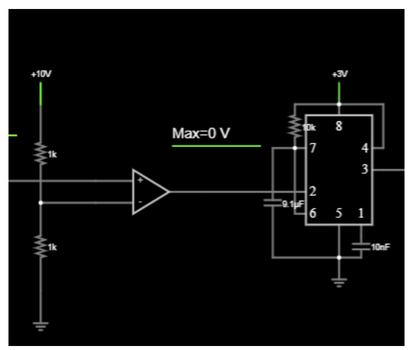

Figure 4: From left to right: a non-hysteretic comparator with resistances of 1kΩ each that is connected to a monostable 555 timer with a resistance of 10k Ω and two capacitors with values of 9.1μF and 10nF

D. Timing Control

As mentioned prior, the particular case of cardiac arrhythmia which is of interest for the proposed pacemaker is bradycardia. To detect the abnormally low heart rates, the stabilized R-wave signal will go through a low-pass filter. Since low-pass filters by nature allow only signals of lower frequency to pass through, it was considered optimal to detect bradycardia. Specifically, the designed low-pass filter makes sure that the frequency is less than 1 Hz. **Fig. 5** below references the chosen resistance and capacitance values for this specific filter. If there is a detected gap of 1.4 seconds between the R-waves, the circuit is designed to trigger the second monostable timer in the design.

The second monostable 555 timer itself is set to verify if there is no heartbeat present or if there is a sufficient time gap of 1.4 seconds between the R-wave signals. The above **Fig 5** denotes the chosen values for the resistors and capacitors associated with this specific monostable 555 timer.

Given that this time gap is present, the 555 timer is prompted to initiate a corrective pulse to speed up the subject's abnormally slow heart rate. The shock is delivered via electrodes inserted in the ventricle, and it is represented in the circuit diagram by the LED circuit. Specifically, if the LED switches on, it is representative of a corrective pulse being delivered by the pacemaker.

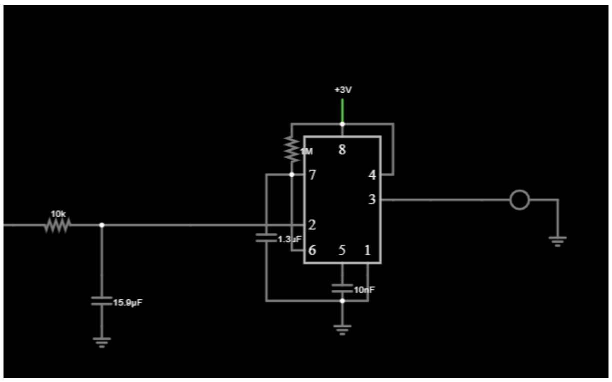

Figure 5: From left to right: low-pass filter with a resistance of 10k and a capacitance of 15.9 µF and a monostable 555 timer with a resistance of 1MΩ and two capacitors with values of 1.3µF and 10nF

III. Results

The complete circuit, shown in **Fig. 6**, uses a square waveform chosen to represent the shape of a PQRST wave coming in from the singular ventricular lead.

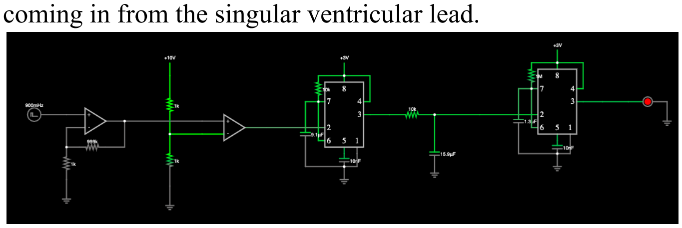

Figure 6: Complete pacemaker circuit, shown inducing a pulse by a red LED at the output of the rightmost monostable timer.

A. *Amplifier*

R-waves coming into the circuit are measured in units of millivolts. To prevent impossible values of resistance and capacitance later in the circuit, the non-inverting amplifier raises the magnitude of the signal to units of volts.

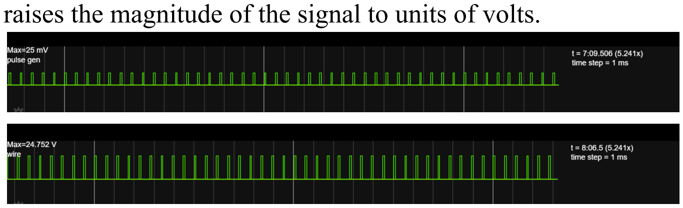

Figure 7: (Top) Incoming R-waves prior to amplification in units of millivolts. (Bottom) R-waves in units of volts

The gain of the circuit is calculated by:

$$Gain = \frac{R_1 + R_2}{R_2} \qquad (1)$$

where $R_1 = 999k\Omega$, $R_2 = 1\ k\Omega$

to raise the units of the signal from millivolts to volts.

B. *Non-hysteretic Comparator*

Since a square waveform was chosen to model the shape of the PQRST wave in the Falstad simulator, there are no visible P, Q, or ST segments in the pictured waveforms. To account for the P, Q, ST segments that would be included in the signal, a comparator is used to isolate R-waves from the PQRST wave. The comparator only initiates a signal when an amplitude of 5 V has been reached, as R-waves have been amplified and the minimum height of an R-wave would correspond to 5V in the comparator.

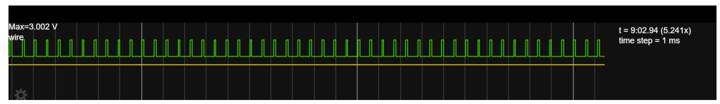

Fig. 8: Isolated R-waves coming from the comparator when the incoming signal has an amplitude of 5V

The non-hysteretic comparator will read the incoming voltage, and if it is greater than or equal to the $V_{reference}$ value of 5V, output a 5V amplitude signal. This is done by the voltage divider, which controls the output voltage of the comparator using the ratio of the component resistors. If the minimum amplitude of 5V is not reached, the comparator will simply output 1V. This is expressed in the following equation:

$$V^{-}_{ref} = \frac{R_3}{R_3 + R_4} V_s = \frac{1}{2} V_s = 5\ V \qquad (2)$$

C. *Non-hysteretic Comparator*

The output of the non-hysteretic comparator is taken as the input for the first monostable timer. When the output from the comparator goes high, the trigger goes low. In turn, this results in the a periodic voltage output governed by the monostable properties:

$$T = RC\ln(3) \qquad (3)$$

where R = 10 kΩ, C = 9.1 nF, resulting in a period of approximately 100 ms. The voltage output of this monostable timer can be seen in Fig. 9.

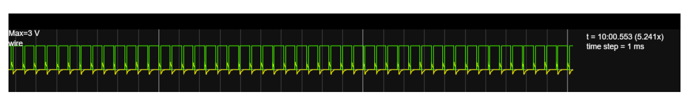

Fig. 9: The voltage output of the first monostable timer given a pulse input of 900 Hz.

D. Low Pass:

The voltage output from the first monostable timer is passed through the low pass filter, which has a cutoff frequency of approximately 1 Hz as found by the equation:

$$f_c = \frac{1}{2\pi(RC)} \qquad (4)$$

where R = 10 kΩ, C = 15.9 µF. This allows frequencies lower than 1 Hz to pass as the input of the final monostable timer. This value correlates to a heart rate of 60 bpm, meaning in bradycardic episodes, the output of the monostable times should produce an output that can be further processed by the final monostable timer.

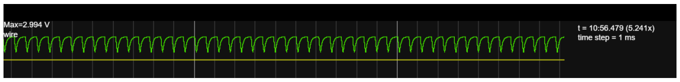

Figure 10: The output waveform procured from the lowpass filter for an input pulse with a frequency of 900 mHz

E. 555 Monostable Timer

Following the low pass filter, bradycardic frequencies are sent to the trigger of the final 555 monostable timer. The monostable timer will then check for the absence of a heart beat, and when there is a 1.4 second delay between heart beats, the timer will initiate a pulse. As such, when a frequency greater than our cutoff frequency of 1 Hz is propagated through the circuit, the monostable timer is not triggered, and no pulse is generated. Conversely, when a low frequency signal is put into the circuit, a pulse will be generated according to the time constant of:

$$T = RC\ln(3) \qquad (5)$$

Where $R = 1\ M\Omega$, $C = 1.3\ \mu F$

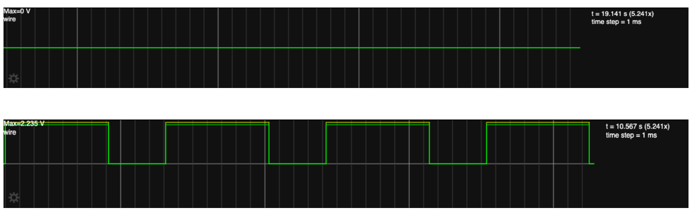

Fig. 11: (Top) 1.2 Hz propagated through the circuit, initiating no pulse. (Bottom) 0.8 Hz initiating a pulse when the heart has not beat in 1.4 seconds

IV. Conclusion

The primary goal of the single-lead pacemaker was to address the issue of bradycardia in adults. This design was motivated by the prominence of heart disease and pacing-related heart complications, which are significant causes of death for adults in the US. The circuit design has 3 main components: the signal amplifier, the R-wave processor, and the timing control mechanism. To bring the ECG signal from units of millivolts to volts, a non-inverting amplifier is used. The following R-wave processor is composed of a non-hysteretic comparator, which isolates R-waves from a full PQRST wave, and a 555 monostable timer, which stabilizes the R-waves for filtering and input to a second timer. After R-waves have been processed, the signal continues on to timing control. To accurately pace bradycardia, a low-pass filter prevents normal frequencies from continuing on to induce a pulse. Instead, only low frequencies, which would correspond to a heart rate below 60 beats per minute, trigger the final component. The final component is a 555 monostable timer. This monostable timer is used to check for the absence of a heart beat, and when no R-wave has been generated in approximately 1.4 seconds, a pulse is generated which will prevent the heartbeat from slowing to a dangerous rate.

This design is limited by its inability to track pacing history, its reduced accuracy compared to a dual-chamber pacemaker, and the specificity required for each patient and their pacing needs. The circuit design does not have the capability to record or store pacing history from the right ventricle, as it can only respond to ECG stimuli. Recording data would be useful in tracking heart rhythms over time in order to analyze the heart's condition and possibly diagnose complications which cannot be seen in single doctor's visits. Additionally, since the pacemaker only uses a single-lead sensor, it is less accurate than a dual-chamber design. A dual-chamber would have leads in both the right ventricle and right atrium, and be better able to optimize ventricular filling and cardiac output by synchronizing their activations [5]. Finally, this pacemaker is only tailored to deal with bradycardia. Heart arrhythmias are very complex and encompass more than just bradycardia. A range of pacing types are used to address patient-specific issues, necessitating pacemakers be calibrated on a case-by-case basis [6]. Future steps in improving the design could be addressing tachycardia, which describes when the heart is beating irregularly fast [7].

V. References

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