Simplified Pacemaker

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***Abstract*— A significant portion of the world population relies on pacemakers to automatically regulate their heart rate and activity. This paper proposes and investigates a design for a ventricular pacemaker that is responsive to intrinsic heart activity. The design does so by first using a bandpass filter to process and amplify electrical signals generated spontaneously by the heart. It then determines if the spontaneous signal is sufficient in generating the desired heart rate using an amplitude detector circuit. Finally, an astable integrated circuit timer regulates pulse generation according to the output of the amplitude detector circuit. After designing and simulating in the Circuit Simulator Falstad, we have determined that this design can generate a desired output of 75 beats per minute in a variety of physiological cases. The proposed design is relatively simplistic, but effective, nonetheless. This design could be made widely available for patient use as it would be relatively low in cost and difficulty to produce or has the potential to be integrated into more complicated designs.**

I. Introduction

In the United States, heart disease is the leading cause of death across many groups, where an estimated person dies every 36 seconds [1]. The critical physiological problem behind several major heart diseases reside in the hearts inability to produce and maintain a proper heartbeat. We see this in conditions like tachycardia, an elevated resting heart rate, or bradyarrhythmia, wherein the heart produces slow heart rhythms. To address these improper pulses, there is the pacemaker, a popular and widely utilized bioengineered device. This device takes signals from the heart, determines if the pacing generated by the heart spontaneously deviates from a predetermined normal pacing range, and responds by creating corrected pulses to the heart. As seen in figure 1, leads create the direct connection between heart and pacemaker.

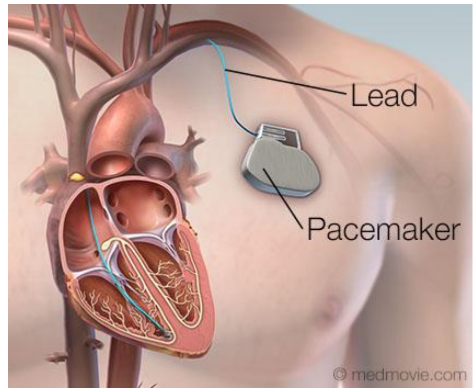

Figure 1: The visual depiction of the heart with the pacemaker leads directly connected into the left ventricle to the pacemaker unit [2]

This paper proposes a simplified version of a single-lead pacemaker that does not use battery life unnecessarily. A ventricular single lead was selected instead of a two lead since it addresses ventricular issues, which address the majority of heart issues witnessed. By having a pacemaker device that responds to intrinsic heart activity, it can extend the life of a battery more than the varied typical 5-15 years [4]. With the knowledge and conditions for our pacemaker design, we derive the essential electrical components to correct the heart's ill-produced heart beats. We determined our pacemaker must initially take signals through the leads as an ECG, or electrocardiogram, which visualizes pulses from the heart in a typical electrical pattern. From a usual QRS complex signal in an ECG, we isolated the R-wave as our input since it represents the pulse from the ventricular [5]. With our input signal, we then want to be able to process the signal, modifying appropriately. Afterward, we need a portion to detect the signal's range and determine if it needs a battery or not in order to then generate a corrected pulse to the heart. The pulse generation stems from a timing control, which can take inputs and create an output based on preset timing control values. These main functions are divided into a block diagram and depicted below in figure 2.

II. Methods

The overall design of our pacemaker circuit is represented as a block diagram in Figure 2. In this section, each block will be described in detail.

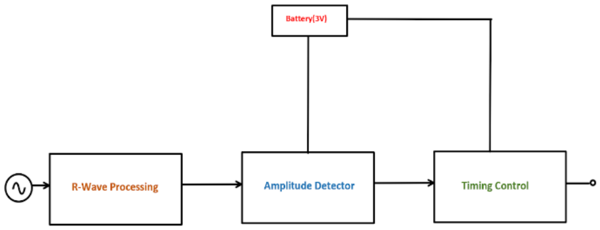

Figure 2: The Block diagram including: R-wave processing circuit, amplitude detector, and timing control. The input to the R-wave processing circuit comes from the lead placed in the right ventricle and the signal leaving the timing control will enter the same lead and stimulate the right ventricle into contraction.

A. R-Wave Processing Circuit Design

Once determining that a R-wave sensing and processing component is needed at the initial input of the design, as seen in many pacemakers we researched, we sought electronic components that would act as one [6]. Essentially, a R-wave processor senses the present R-wave signal and adjusts it to be interpreted accurately throughout the rest of the pacemaker circuit. The electronic component chosen was a bandpass filter with an operational amplifier since it can both filter and amplify our R-wave signal. Filtering the R-wave is crucial to exclude external signals from everyday devices that indirectly interfere with signals, such as phones or computers.

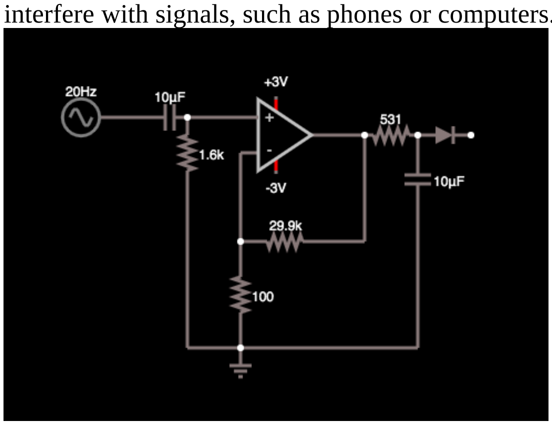

Figure 3: The R-wave processing block circuit design. From left to right, there is the input R-wave signal, the high pass filter, op amp, low pass filter, then diode.

It is determined from literature that the average value range of an R-wave is 10-30Hz and the volts between 5-25 mV [5]. Thus, the cut off frequencies for the low pass and high pass are respectively 10 Hz and 30Hz. Our band pass is able to isolate the pure R-wave signal. Amplification portion is necessary to map the R-wave lead amplitudes residing within small magnitudes to a larger amplitude. This allows us to later compare its amplitude to determine if the signal is at a proper value for a heart pulse in the later block components.

As seen in figure 3, following the bandpass, a diode at the end of the bandpass for peak detection and to ensure that the processed signal does not return to the filter but rather continues to the next circuit block.

B. Amplitude Detector Circuit Design

The next circuit block, as seen in Figure 4, primarily serves as a decoupler and amplitude detector.

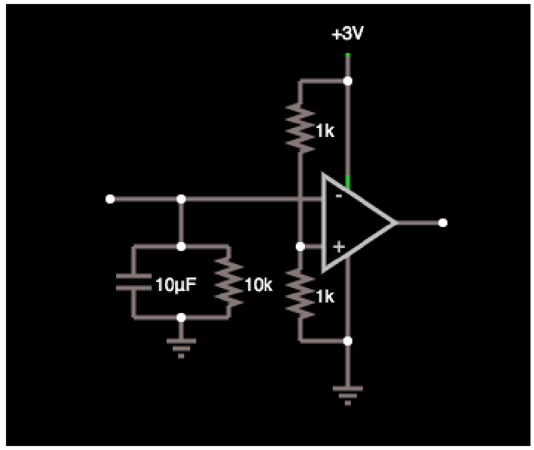

Figure 4: The amplitude detector circuit block. It receives an input signal from the R-wave processing block. It consists of a decoupler and a positive feedback comparator.

The capacitor and resistor in parallel going to ground decouple the signal received from the R-wave processing block. Decoupling refers to the elimination of AC noise of the received signal that may be present due to sudden or inconsistent voltage changes from the power source driving it [7]. This is made possible due to the capacitor needing time to charge and discharge, which allows it to store energy. In storing energy, the capacitor stabilizes the incoming signal: it will store excess energy if there is a voltage spike or provide energy to the circuit if there is a sudden voltage drop. The capacitor is in parallel with a resistor, which allows for the charge stored on the capacitor to leak to ground at a controlled rate [7]. This leakage allows the decoupling capacitor to continue to accept charge in the case of a signal spike. The decoupler as formed by the capacitor and resistor is necessary within the circuit because due to the nature of the R-wave, the received processed signal will not be a perfectly DC signal, which is better suited for the following comparator.

The following positive feedback comparator determines if the R-wave is sufficient for generating a heartbeat naturally. This is determined by comparing it to a value determined by the voltage source of the operational amplifier, which is 1.5 volts due to the presence of resistors within the circuit. The minimum R-wave voltage required to generate a heartbeat (5 millivolts, as previously stated) has been amplified to 1.5 volts by the R-wave processing block. Therefore, if the R-wave is sufficient to generate a heartbeat, the input voltage signal from the R-wave will be greater than the voltage provided by the operational amplifier source. If this is the case, the comparator will output the low voltage, or approximately 0 volts. If the R-wave is not sufficient to generate a heartbeat naturally, then it will not be greater than the threshold set by the comparator, and it will output the high voltage, or approximately 3 volts. This voltage output will go to the reset pin of the following astable timer.

C. *Timer Circuit Design*

The final stage of the circuit is a timer that creates pulses at a stable frequency. This stage can be seen in Figure 5.

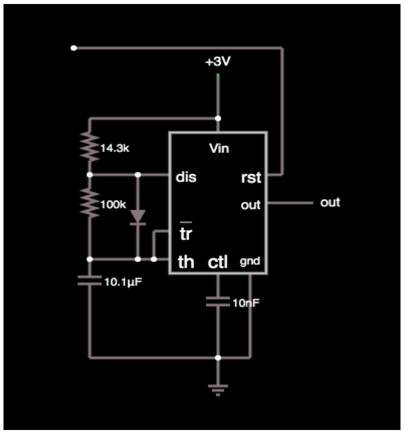

Figure 5. The astable timer circuit block. It receives an input signal from the comparator of the previous block, and

The desired pulse frequency for a pacemaker design is 75 beats per minute. An astable 555 timer was chosen to be the timer of choice. Astable 555 timers do not require a trigger to be able to create the pulse. This would be best in the case that an R-wave was missing, or that the heart is not generating enough R-waves to generate the desired heart rate. The total period of the heartbeat would be 0.8 seconds, which was a value obtained by taking the inverse of the desired frequency. A diode was added across the second resistor on the timer to improve the duty cycle and make the calculations more simple and T_{hi}(Time high) would solely be based off of the first resistor, rather than both of the resistors attached. From the research done on the QRS complex the R-wave had a frequency of up to 0.1 seconds, so this was used in the T_{hi} of the period and T_{lo}(Time low) would be the difference, 0.7 seconds [8]. The input of the reset is coming in from the comparator attached to the 555 timer, this causes the signal from the comparator to override the one coming into the flip flop from the internal comparators. When the signal from the comparator outside of the circuit is low, this will cause the output to be zero, or for the 555 timer to reset, giving the previous sections more control of the 555 circuit and when it should turn on. In order for the design to be safe, the output current should be less than 10 milliamps for safety, and after researching values the voltage should range from about 3 volts to 5 volts, which was achieved [8].

III. RESULTS

The complete pacemaker circuit, with component values, is pictured below in Figure 6. This section is dedicated to the determination of the pictured component values.

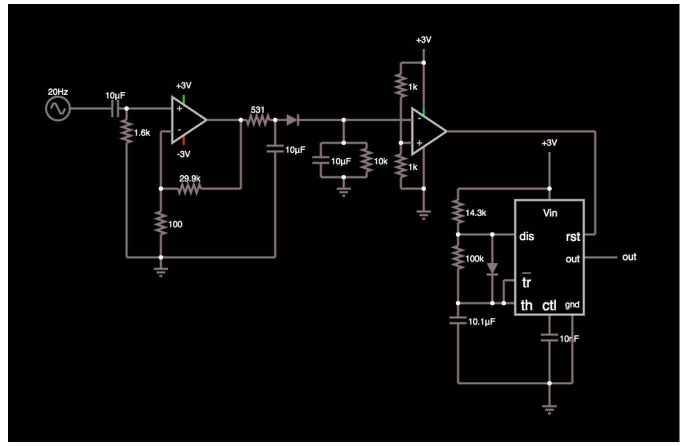

Figure 6. The complete pacemaker circuit, including all component values. Note that the representation of the R-wave input as a 20 Hz AC voltage source is for simulation purposes.

A. *R-Wave Processing Circuit*

The values for our bandpass filter are based on the previously stated desired cut-off frequencies, as determined by the range of typical R-wave frequencies, using equation 1.

$$f_{cutoff} = \frac{1}{2\pi RC} \qquad (1)$$

For the low pass filter, a cut-off of 10 Hz yielded the selected resistance R1=1.6 kΩ and C1=10 µF. We selected a resistance of 531 Ω and a capacitance of 10 µF for the high pass filter. Since the comparator threshold as provided by a 3-volt battery is 1.5 volts, the voltage from the R-wave needed a gain of 300 to increase the R-wave magnitude range of 5-25 millivolts to 1.5 volts and above. This gain is related to the resistor components using equation 2.

$$Gain = \frac{R_2+R_3}{R_3} \qquad (2)$$

Based on those values as our conditions, R2=29.9 kΩ and R3=100 Ω were selected.

After filtering and amplifying the input R-waves, the output voltage signal

Due to the filtering and amplification of the R-wave, the output voltage signal of the processing stage is expected to be near 1.5 volts and display peaks with a frequency between 10 and 30 Hertz. A simulation of this output signal can be seen in Figure 7.

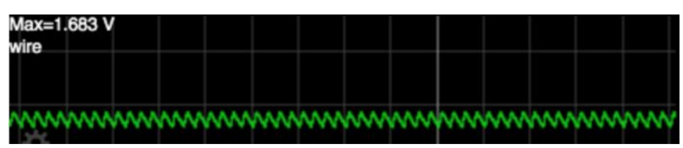

Figure 7. The output voltage signal of the R-wave processing stage simulated with Falstad Circuit Simulator.

B. Amplitude Detector

The value of the capacitor in the decoupler circuit is determined by examining the frequency of the AC noise that we would like to decouple. 3 volt batteries, such as the one used in the R-wave processing stage, generate AC noise of 50 Hz and above [9]. For this frequency range, it is generally accepted that a capacitor between 1Fand 100F is sufficient for decoupling [10]. We have arbitrarily chosen 10Fas our capacitor value. The parallel resistor value was determined using the time constant of the capacitor and resistor, as written in Equation 3, as the time constant dictates the rate of discharge from the capacitor.

$$\tau = RC \qquad (3)$$

We chose tau to be 0.1 seconds, as this provides sufficient time for the capacitor to discharge over the course of a R-wave pulse. The resulting resistor value is 10 kΩ.The resistors attached to the operational amplifier determine the voltage input into the operational amplifier, as written in Equation 4.

$$V_{in} = \frac{R_{top}}{R_{top}+R_{bottom}} V_s \qquad (2)$$

Where $V_s = 3V$, and we would like to select values such that $V_{in} = 1.5V$. Therefore, both resistors are chosen to be $1\ k\Omega$. The output voltage signal from the decoupler and comparator stage can be seen in figure 8.

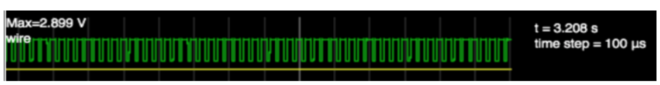

Figure 8. The output voltage signal of the amplitude detector stage simulated with Falstad Circuit Simulator.

As mentioned with Figure 7, R-waves will occur as pulses rather than waves. As the output voltage depicted here is reliant on the R-wave voltage, the changes in output voltage of the amplitude detector stage will also be less frequent than what is pictured in the simulation. With an accurate R-wave, the output voltage will mostly remain at its high voltage and occasionally fall down to its low voltage, synchronous with the peaks of the R-wave input signal.

C. Timer

Setting the T_{lo} and T_{hi} of the circuit was crucial in the calculations of the 555 Timer since the heart rate depends on it. The overall period of the timer is 0.8 seconds. The sum of the period of T_{hi} and T_{Lo} should be equal to the total period which is seen in the equation below.

$$T = T_{hi} + T_{lo} \qquad (2)$$

The diode added across the second resistor made the calculation simpler for the time low of the circuit. The period for time low is dependent on the first resistor and the capacitor, and the calculation for time high is dependent on the second resistor and the capacitor. The resistors and capacitors were set to be in an acceptable range for each, without out adding too much resistance or too small of a capacitance. The desired values were plugged into the calculations viewed below:

$$T_{hi} = R_1 C ln(2) \qquad (2)$$

$$T_{lo} = R_2 C ln(2) \qquad (2)$$

The duty cycle was determined to be:

$$Duty\ cycle(\%) = \frac{T_{high}}{T} * 100 = 12.5\% \qquad (2)$$

Using the determined values, the output signal of the timer, and complete circuit, displays 3V pulses occurring for 0.1 seconds within a period of 0.8 seconds, as seen in Figure 9 below.

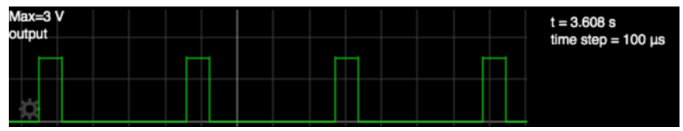

Figure 9. The output signal of the pacemaker circuit as simulated by the Falstad Circuit Simulator.

IV. Conclusion

In creating this design, the medical problem of heart disease was the motivation, mainly an issue discussed in the U.S as being a major contribution to the death tolls [11].The circuit designed is a simplification of a pacemaker circuit and was accomplished by incorporating an R-wave processor, amplitude detector, and timer. A bandpass filter was used to obtain a frequency within the range of 10Hz to 30Hz, the typical range for an R-wave [8]. The amplitude detector uses a decoupler and positive feedback comparator. The amplitude detector is used to reduce noise from the AC signal, and the positive feedback comparator is used to determine whether the R-wave is strong enough to carry out to the patient's heart, or if the battery needs to be used to create a pulse. The goal was to not overuse the battery and to utilize the body's own physiology to produce the R-wave. The next part of the circuit was the timer, applying an astable 555 timer was preferred since this would generate a pulse in the absence of a signal in the R-wave processor. The total period was set to be 0.8 seconds, given the target frequency was 75 beats per minute. The simplified circuit was a success in processing the signal and choosing the best outcome from either the battery or R-wave and producing the desired frequency and voltage amplitude.

Limitations related to this design are lack of functions that are related to modern pacemakers such as: tracking patient health and device data, MRI safe designs, greater battery conservation, and leadless designs that don't require openheart surgery[12]. Pacemakers typically are on a case by case basis and will not work for every type of heart condition. Candidates for pacemakers are those with heart issues such as bradycardia, tachycardia, congestive heart failure, or may have suffered from a myocardial infarction [13]. The significance of the design is to find ways to simplify these medical device's circuits to improve cost and using less components and materials in the design, making them more accessible to different demographics. There would also be less room for error or malfunction in the design with less constituents. This is a study of much importance and future research.

V. References

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