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An Experimental Investigation to Redesign A Pacemaker Training Board for Educational Purposes

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Abstract. An artificial pacemaker is a medical device that can generate electrical impulses which are delivered by electrodes to maintain the controlled rhythm of the heartbeats. Such a medical device can assist for extensive period of time and thereby regulates the pumping capacity of the heart. Usually, the need for a permanent pacemaker implantation arises from the occurrence of cardiac diseases such as failure of impulse formation (sick sinus syndrome) and/or conduction (A-V block). Functionally, a pacemaker comprises of at least three parts: an electrical pulse generator, a power source (battery) and an electrode (lead) system. This paper aims to provide a design of the trainer board of a typical pacemaker, which generates a QRS pulse and displays it on an oscilloscope which will help understand the basic components of the device for educational purposes. To do so, an extensive literature review was undertaken to comprehend the theory behind the design of a pacemaker. Further, the paper describes the practical methodology adopted in the design of the pacemaker and the achieved results of this study while making suggestions for future work.

1. Introduction

Heart is one of the most key body parts within any living organism. A human heart comprises of two pumps within an organ (Silverstein, 1994). It is estimated that, while resting, around 5 litres of blood is pumped within a minute in an average adult. This is based on an average beat rate of 72 times per minute. During exercise a healthy individual’s heart rate can reach 200 beats per minute (Mitchell, 2016).

The heartbeat is controlled by the body to ensure the requirement of Oxygenated blood by organs is maintained. This requirement is driven by any physical or mental activities undertaken by an individual. In the medical world multiple conditions have been determined where the heart fails to maintain the required beat rate. This condition is known as arrhythmia. It is currently estimated that more than 4 million Americans (USNews, 2019) and 2 million British (NHS, 2019) experience arrhythmias or heart problems.
The most common types of arrhythmia are bradycardia, tachycardia, fibrillation and heart block. Slow heartbeats rhythms are classified as bradycardia whereas abnormally fast heart rate, whilst resting, are regarded as tachycardia. The most common type of arrhythmia is fibrillation where heart beats abnormally at higher rate than normal. (NHS, 2019).

Heart rhythms are related to heart beats and to control the heart’s beats in a steady state, a small electronic machine called pacemaker is set in the chest. This machine is required for use when the heart beats too fast, too slow or not in a regular manner. Due to inefficient work of electrical impulses, the activity of a heart can be disturbed resulting in arrhythmia issues.

Types of heart beats can be classified as:

- Tachycardia
- Bradycardia

Tachycardia relates to the very fast beating of a heart while bradycardia is known as the very slow beating of heart. During bradycardia, various body parts may not get sufficient blood from the heart hence resulting in shortness of breath and tiredness, which is very common in patients suffering from such heart issues. Also, vital organs of the body stop functioning properly and sometimes loss of life may also take place due to extremity of arrhythmias.

In order to bring the heart beats back to normal, a pacemaker is a very effective option which allows the patient to experience a dynamic and energetic life without needing to worry about breathing issues (Campbell et al., 2006).

This study is aimed on designing a trainer board for a pacemaker, which generates a QRS pulse and displays it on an oscilloscope. This can assist in understanding the basic components of the device for educational purposes. To fulfill the aim, this paper provides a general introduction and background to the study in Section 1. Section 2 provides a review of the relevant literature while providing the theory behind the design of a pacemaker trainer as well as explaining the basic mechanism of a heart. The experimental methodology adopted in this study is provided in Section 3. Section 4 lists the results and provides a discussion of these results while Section 5 provides the proposed design of the trainer board. Section 6 lists the conclusions of this study while providing the suggestions for any future work.

2. Literature Review

The objective of a literature review in this study is to access useful published material for thoroughly analysing and understanding the experience of those patients who have pacemakers in their bodies. In
addition, it is also aimed that this review of the literature will assist in comprehending the lives of patients who use implantable defibrillators. This will also help in determining the problems which are faced by such patients.

Presently, humans are closely linked to technology. New fields of study are developing rapidly through which people are able to exchange information in order to satisfy the needs of people for knowing more about newer technologies. Demand for computers, mobile phones and the use of latest technology tends to increase the opportunities for more jobs. Engineers tend to be the backbone of technology therefore plenty of jobs are developing in different fields. Currently, the tremendous demand for electronic devices involves the competition in producing and developing more new and latest technology-based devices. The medical field has a huge potential for people interested in new technology. Al-Jumeily et al. (2016) claims that humans and in fact the whole society increases exponentially due to fast research in the medical fields along with the improvement in present products. Presently, machines are designed to interpret the test results and produce automatic computerised reports, which are then forwarded to physicians through the aid of excellent equipment. In addition, patients’ data is also saved in machines for further analysis along with follow-up comparisons (Bhunia et al., 2015). These machines are able to automatically analyse and interpret the results. However, there is always the need for an expert’s opinion such as the viewpoint of qualified and competent physicians, which cannot be eliminated. Also, it is possible that the results derived from machines including medical reports may not be able to suggest the best medical advice for patients who are in critical situations.

Figure 2: Possible improvement which can be made to the shape of the pacemaker device (Adapted from Defibrillator Machines, 2019)

2.1. General introduction to the heart

The four chambers present in the heart help it work as a pump with maximum productivity. The right side of the heart has two chambers and deoxygenated blood comes from the body towards the heart. After oxygenation, the blood is supplied to the lungs. The left side of the heart receives oxygenated blood and supplies it to different parts of the body. The blood from the atria (top chamber) supplies to the lower chamber, which is known as ventricles. This then allows for the blood to be supplied to other parts of the body. The blood comes in ventricles by the contraction of atria. This is a condition of a normal heart. The blood is pumped out to lungs and other body parts by the contractions of lungs (Taber et al., 2009).
Sinus Atrium (SA) node is a natural pacemaker positioned in the heart. The function of this SA is to transmit electrical signals by the contraction of atria. The top of upper chamber of heart (Atrium) is the place of this natural pacemaker. In normal functioning of heart, muscle fibres contract simultaneously. This is the reason behind the electrical signals passing quickly through the ventricles from the atria. When the blood from atria fully fills the ventricles, the ventricles contract after a while by the aid of electrical signals. The atrioventricular (AV) node located near the opening of coronary sinus delivers the signals to ventricles (Kotsakou et al., 2015).

In case the heart is not functioning well, the electrical system of the heart itself is usually disturbed and the heart beats are not maintained at a proper rate. In such a situation, the pacemaker works when the supply of blood to body parts is not enough due to slow beating of ventricles. The manmade pacemaker is fitted near the sick heart to maintain the correct rate of beats when the electrical system is disturbed. The use of pacemakers is recommended by physicians to enable the sick heart to work properly and smoothly (Moore et al., 2010).

2.2. Cardiac signals

The electrocardiogram (ECG) test is used for checking the electrical activity of the heart. The heart’s electrical activity is recorded by ECG on the body surface. The standard value of electrical signals is 2 mV and the bandwidth is 0.05 to 150 Hz. Such a test helps produce the required waveforms while checking the condition of the heart as the pattern of the waves shows the quantity of tissue activation. This test also mentions the direction, relative speed and electrode position. The use of a pacemaker is beneficial to the patient, but ECG tests are not capable of detecting potentials generated by small tissue mass. Overall, ECG waves are of three types: P waves, which show atria depolarisation and R waves and T waves, which show the ventricles depolarisation (Reed et al., 2008).

A typical pacemaker is used when electrical impulses are slower, which refers to the irregular or slow heart beats in a body. Also, in cases of ventricular conduction disturbances, the use and assessment of a pacemaker is suggested. In addition, one of the primary functions of an artificial pacemaker involve controlling tachydyss rhythms.

2.3. Components of a typical pacemaker
A typical pacemaker consists of two components; the electronic pulse generator and the pacemaker electrodes (leads). The former comprises of the relevant circuits and power sources needed to obtain the heart rate along with the intensity of the electrical stimulus which is delivered to the heart. The latter deals with carrying the impulses generated to the heart using the endocardial leads and epicardial wires (Banbury, 1997).

![Components of a pacemaker](Adapted from Addiscardiac.com, 2019)

### 2.3.1. Discussion on the types of pacemakers

<table>
<thead>
<tr>
<th>Temporary pacemaker</th>
<th>Permanent pacemaker</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Aimed for short term use, probably throughout hospitalization.</td>
<td>• Pacemakers that are intended for long term use.</td>
</tr>
<tr>
<td>• To support patients till recovery or till they receive permanent solutions.</td>
<td>• Consists of endocardial leads and the generator is implanted in a subcutaneous pocket.</td>
</tr>
<tr>
<td>• Epicedial wires and endocardial leads may be temporary.</td>
<td>• Last for approximately 6 to 12 years, depending on several factors.</td>
</tr>
<tr>
<td>• Positioned externally.</td>
<td>• Usually positioned internally</td>
</tr>
<tr>
<td>• The size of the temporary generator is comparable to the size of a small paperback book.</td>
<td>• Weighs less than 1 oz and the size is comparable to the size of a credit card.</td>
</tr>
</tbody>
</table>

### 2.3.2. Pacemaker chamber type

In terms of the single and dual chamber systems, the former includes the pacing lead being positioned either in the atrium or the ventricle. This is based on the chamber, which needs to be paced and monitored. For the dual chamber system, there are two leads. One lead is positioned in the atrium while the other is in the ventricle.

### 2.4. Complications associated with the use of a pacemaker
Certain complications can lead to a difficulty in the use of a pacemaker. For example, an existing infection at the entry location of the lead or at the subcutaneous site where the pacemaker will need to be placed can cause issues. Issues such as Pneumothorax and hem thorax along with bleeding and hematoma at the lead entry site for temporary pacing or at the subcutaneous site for permanent generator placement can also result in severe complications. In addition, any dispositioning of the leads may cause problems. Any irritations arising from the ventricular walls are also a reason for the complexities arising from the use of pacemakers (Stuart, 1990; Moses et al., 1991).

2.5. Assessment and prevention of a malfunction in a pacemaker

Three critical problems with a pacemaker can occur. These are usually due to a failure of pace, a failure to capture and a failure to sense properly. Failure to pace is a result of a lack of initiation of an electrical stimulus to when it should be primed to fire and can be identified easily by a lack of pacer spikes on the rhythm strip. A failure to capture is when depolarization is not noted after the electrical impulse is fired. A pacer spike is noted but consecutively is not followed by a p wave or a QRS complex on the ECG. A failure to sense is due to a lack of detection of the patient’s cardiac rhythm and still initiates an electrical impulse (Jeffrey, 1997).

2.6. Prevention of issues in a pacemaker

The condition of the temporary pacemaker needs to be monitored and checked regularly and documented in the patient's medical file. The ECG is also monitored carefully to detect any possibility of pacemaker malfunction. The V/S heart rate is monitored carefully as a malfunction may cause the patient to contract bradycardia. Signs and symptoms of pneumothorax, (hypoxia, and shortness of breath, pleuritic pain, and hypotension) are monitored. Dysrhythmias are assessed and treated. The patient is highly recommended to prevent or reduce physical activity to prevent possible lead dislodgment (Liao et al., 2016; Mulpuru et al., 2017).

2.7. Awareness and education of patients

Pacemaker batteries have a duration of 6-12 years and the replacement is performed by opening the subcutaneous pocket to replace the battery. The patient is advised to not raise the arm above the pacemaker level to promote healing and prevent displacement of leads. It is also advised to not shower to prevent infection and carefully washing the incision site and prevent using powder or lotion (Dayton et al., 2013).

2.8. Operation of a pacemaker

A pacemaker is a relatively small size device consisting of a pulse generator and weighs between 20-50g. The design of the pulse generator consists of a battery and a tiny computer circuit with wires that connect to the heart known as a lead. The pulse generator passes electrical impulses at a certain pacing rate. Modern pacemakers are programmed to adjust to the demands of the body. The closed feedback control system allows the pacemaker to send a signal when the heart is beating too slowly. This process is assisted with a sensor that measures the breathing rate of the patient. The discharge rate is sped up when the patient is active and is labelled by doctors as rate responsive (Mulpuru et al., 2017).

3. Methodology

3.1. Introduction
The pacemaker circuit was developed using multiple off-shelf electronic components. These components were assembled and integrated as part of this work. The most important part of the system was the ATmega328 microcontroller. The microcontroller was programmed during this task to compute and perform the required processes.

Pacemaker circuits are classified as relaxation oscillators. These oscillators produce a repetitive non-sinusoidal output. The output is maintained and monitored using a feedback loop.

The oscillators primarily operate by generating different frequencies using resistor-capacitor (RC) circuits. This method of operation differentiates them from communication circuits which comprise of Inductor-Capacitor (LC) circuit also known as tank circuits.

![Figure 5: AD8232 Heart Rate Monitor (Adapted from Sparkfun, 2019).](image)

3.2. Single Lead Heart Rate Monitor - AD8232

To effectively monitor the electrical activity of heart an AD8232 sensor was used. Monitoring the output from an ECG can be extremely noisy hence implementing this sensor ensured these issues were resolved. The AD8232 acts as an Op-amp to ensure a clear signal in received from the system. The sensor board also provided the ability to connect further signals for the arm and legs. With the onboard led indicator, the time required for debugging was extensively reduced.

![Figure 6: AD8232 Heart Rate Monitor (Adapted from Sparkfun, 2019)](image)
3.3. Arduino Uno

The key element of the entire work was the Atmega328 microcontroller. The microcontroller provided the work with the ability to interface with the AD8232 and the timer which in turn controlled the pacemaker. The ATmega328 was programmed using an Arduino breakout board. Using Arduino provided the compiler to program in a high-level language of C++. The compiler was later used to monitor the outputs on serial monitor and serial plotter.

A simple block diagram shown in Figure 8 shows the connections made between the AD8232 and ATmega328.

3.4. Hardware Timer 555

The output from the heart rate monitor were used to analyse the requirement of switching the timer on or off. The pacemaker was triggered and regulated using this timer. To produce a stable and effective signal a Timer 555 chip was used. The chip is commonly known as Timer 555, its manufacturers part number is NE555P. This chip has a wide range of operating voltage, +5 to +15 VDC. This feature made ensured the chip could be integrated in the circuit without any extra circuit requirements.
To simplify the process of testing the Timer 555 supplied in 8-pin DIP package was used. This chip is breadboard friendly and can be used on Printed Circuit Boards (PCB) hence was preferred for the system.

### 3.4.1. Timer 555 – Oscillator Circuit

The Timer 555 consists of an Astable multivibrator oscillator circuit. These circuits produce a continuous wave without the requirement of an external trigger such as crystal oscillator. The timer can be setup to produce a rectangular wave with varying frequency and duty cycle. For our circuit the values of the resistors, "R_A" and "R_B", and capacitor, "C", were calculated based on the frequency and duty cycle requirements. Figure 10 shows the circuit used to setup the Timer 555.

![Timer 555 circuit](image)

**Figure 10:** Timer 555 circuit connected for an Astable operation (Ti, 2019)

![Typical Square Wave](image)

**Figure 11:** Typical Square wave generated from a Timer 555.
Figure 11 shows a typical square wave and some of its critical aspects as such period (T), Time High (T1) and Time Low (T2). As mentioned earlier the period (T) and duty cycles (T1 & T2) were determined by selecting values for RA, RB and C. The output from the Timer 555 is obtained from pin 3. On Figure 10 the load is shown by RL. For this work the load is the pacemaker. To ensure any noise or dips in voltage are managed, multiple capacitors were used. The value of these capacitors ranges from 0.01 to 0.1μF.

3.5. Power Supply

To ensure the system had enough power a power converter was used. This power supply converted the domestic 230VAC to 12 VDC. The power supply was cable of delivering multiple amperes of current. The power supply required a standard IEC 10 connector. These cables are readily available ensuring there was no requirement to work at high voltage of 230VAC. The power supply was well built in a metal enclosure with sufficient ventilation. To ensure the power supply could be switched off a simple ON/OFF switch was also integrated.

Figure 12 shows the power supply used for the system. It can be noticed the supply has enough ventilation ensuring it can be used within an enclosed unit. The cables used to power supply were plug and play based. Figure 13 shows the entire architecture of the designed system.
3.6. Biomaterials in a pacemaker

To understand how a pacemaker operates it was necessary to split open an existing one. The pacemaker used for in deep analysis is shown in Figure 14. The electrodes connected to the pacemaker are not shown in this figure. It can be clearly seen as semi-coin cell battery is used to power the system. Most of the circuitry comprises of surface mount components which enables the system to require minimum space. To ensure a long life of the pacemaker the circuitry comprises of very efficient parts which consume minimum energy to prolong the battery life.

Figure 13: System interface diagram with Timer 555 and Power Supply included

Figure 14: Pacemaker with and without its casing
3.6.1. Casing Material

One of the key materials required for the construction of the pacemaker is Titanium. Titanium has a high modulus elasticity and very high resistance to corrosion making it a great contender for pacemakers. Other features of Titanium, such as high durability, strength and long lasting, also contribute to the long life of the pacemakers.

3.6.2. Battery

The battery life is the most critical aspect in determining the life of the pacemakers. A pacemaker which requires continuous maintenance on a higher frequency is unfeasible. At the same time the device will be installed in a very close proximity to the heart hence the no hazardous materials can be used. The pacemaker shown in Figure 14 uses a lithium-based battery which is resistant to corrosion and can last for extended periods of operation.

3.6.3. Connector Block

The pulses are generated by the pacemaker and transferred through the leads. To securely connect the leads, the pacemaker comprises of connector block. This block ensures the leads transfer the pulses effectively. The connector block is developed using Polyurethane. This connector block is identified in Figure 14.

3.6.4. Pacing Leads

As mentioned earlier the electrical pulses from pacemaker are delivered using the pacing leads. These leads translate and transmit electrical signals to deliver the fixation mechanism. Depending on a unipolar or bipolar installation the number leads vary. Most of the installations comprise of 2 leads being installed. In some instances, the leads can also transmit information on heart to the pacemaker.

Figure 15: An illustration of a typical pacemaker system with pacemaker leads (Reproduced from Hayes et al., 2013)
The pace leads have their entire body insulated with silicone rubber or polyurethane. This provides high strength and low coefficient of friction for the blood flow. This also ensures the leads can withstand any flexing caused by cardiac contraction.
The other end of the lead which interfaces with the pacemaker is show in Figure 16.

![Figure 16: Pacemaker lead connector pin (Reproduced from Helland et al., 2017)](image)

### 3.6.5. Effects of pacemaker’s materials on the skin

Advances in cardiovascular procedures would have not been possible without the concomitant developments in biotechnology. The application of biomaterials spans from prosthetic heart valves, ventricular assist devices, cardiac pacemakers and endovascular implants, to suture material and bio-adhesives. Materials and devices used for the restoration of anatomical and physiological circulatory properties are not without associated risks and potential complication, both in the immediate as well as the long-term period, following implantation within the recipient.

Implant building blocks vary from an array of metals and their alloys, polymers and ceramics. Naturally occurring materials such as collagen, hyaluronan and dextran are commonly used. Synthetic polymers used for the construction of implantable devices include polylactic acid, polylactic-co-glycolic acid, polyvinyl alcohol and others (Onuki et al., 2008). The majorities of implanted devices are composed of more than one type of material and are referred to as complex composition implants. Although these materials have been used extensively with good functional results, there are issues of biocompatibility. The need to surpass physical limitations and improve the biomechanical profile of metals has led to the development of novel metal alloys. In addition to superior physical and chemical properties regarding strength, durability and resistance to corrosion, certain alloys have unique properties. An example is nickel-titanium (nitinol) alloys that exhibit shape memory and super elasticity, making it one of the most widely used materials in medical prostheses.

The tissue response to implanted materials is a complex process. It entails a variety of pathways that may include the generation and activation of interacting humoral and molecular components. These processes may be acute, taking place over minutes, or long term, spanning many years (Mulpuru et al., 2017).

### 3.6.6. Microcontroller Programming

As shown in Figure 13, the ATmega328 is used in developing the system. The microcontroller was programmed using an Arduino breakout board and supported software. The software code used to programme the Arduino is attached below.

```c
1. /**************************************************************************/
2. //Programme developed Salwan Ali, Ali Abd & Mina Maan
3. //Supervised by MSc. Dina Raheem and MSc. Zainab Majid
4. /**************************************************************************/
5. int threshold=500;
6. void setup() {
7.   // initialize the serial communication:
8.   Serial.begin(9600);
9.   pinMode(10, INPUT); // Setup for leads off detection LO +
10.  pinMode(11, INPUT); // Setup for leads off detection LO -
11.}
12.} 
13.```

13
void loop() {
  ecg=analogRead(A0);
  if((digitalRead(10) == 1)||(digitalRead(11) == 1)){
    Serial.println('!');
  } else{
    // send the value of analog input 0:
    Serial.println(analogRead(A0));
  }
  //Wait for a bit to keep serial data from saturating
  delay(1);
  if (ecg>=threshold)
    { digitalWrite(9,HIGH);
      delay(800);
    }
  else
    {
      digitalWrite(9,LOW);
    }
}

4. Results and Discussion

The outputs captured from the Arduino analogue monitor is shown in Figure 17. The peaks at which the heart beats can be noticed on the output.

![Figure 17: Heart rate monitored using Arduino](image)

To more accurately monitor the output an oscilloscope was used. The output was captured at different states of the heart.
Figure 18: Output from the system for a healthy heart rate

Figure 19: Output from the system for an unbalanced heart rate.

Figure 20: Output from the system in case of consistent heart beat irregularity.
5. Training Board

To ensure the system could be used for further experiments a training board was designed and developed. The board displayed the schematic of the system with all the required input and output ports. The training board is shown in Figure 21.

![Figure 21: Pacemaker - Training Board](image)

6. Conclusions

As part of this work an entire pacemaker was developed from scratch using components off the shelf (COTS). The components were specified and integrated by the team. The final design was implemented onto a training to ensure it could be used for educational purposes.

As ATmega microcontroller was used to develop the system, a study to further develop the system could be initiated. Further inputs and outputs can be implemented to monitor different aspects of the patient. The process of debugging any problems and raise alerts can be eased. Inclusion of simple add-on such as Liquid Crystal Display (LCD) and LED indicators could help the users. The analogue signal from the system could be passed through filters to cancel noise and enhance the signal. To implement wireless charging of the pacemaker the system could be further developed. Pacemakers currently have long life batteries but still require replacing every few years. This adds a risk to the patient’s life. Wireless charging over 2.4 Ghz Wi-Fi signal would be the best way forward to extend the life of the pacemakers. Implementation of wireless charging could also enable the system to communicate wirelessly. This could enable the patient’s heart rate to be monitored wirelessly and any alerts can be passed onto the medical services in case of emergencies.

7. Acknowledgments

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