Designing Heart Rate, Blood Pressure and Body Temperature Sensors for Mobile On-Call System

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Electrical and Biomedical Project Report (4BI6)
Department of Electrical and Computer Engineering
McMaster University
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Electrical and Biomedical Project Report
Submitted in Partial fulfillment of the requirements
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ABSTRACT

There has been an exponential increase in health care costs in the last decade. Seniors have to make frequent visits to their doctor to get their vital signs measured. There is a huge market for non-invasive methods of measurement of these vital signs. The objective of this project is to design and implement a reliable, cheap, low powered, non-intrusive, and accurate system that can be worn on a regular basis and monitors the vital signs and displays the output to the user's cell phone. This data is also easily accessible by the physician through wireless network. This project specifically deals with the signal conditioning and data acquisition of three vital signs: heart rate, blood pressure, and body temperature. Heart rate is measured through an Electrocardiogram that is obtained by attaching skin surface electrodes on the patient's wrists and legs. Blood pressure combines the methodologies of Electrocardiography and Photoplethysmography to continuously monitor the systolic and diastolic blood pressure. Body temperature is measured inside the ear with a thermistor. The theory, design procedures, experimental results and discussions of these systems are presented.

ACKNOWLEDGEMENTS

I would like to sincerely thank my faculty advisor, Dr. Jamal Deen, and my project coordinator, Dr. Thomas E. Doyle, for the guidance and support on this project. I would also like to thank ECE's Electrical Shop's Technical Staff and the Machine Shop's Staff, especially Tyler Ackland, Steve Spencer, and Mark MacKenzie, for providing parts for the project.

I would also like to express my gratitude to my colleagues, Sandra Escandor and Kirsten Zernask-Cebek for their constant motivation and support.

Last but not least, I would like to thank my family for always encouraging me and supporting me throughout life.

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NOMENCLATURE

ADC: Analog-to-Digital Converter

BP: Blood Pressure

DBP: Diastolic Blood Pressure

ECE: Electrical and Computer Engineering

ECG: Electrocardiography; Electrocardiogram

IR: Infrared

LA: Left Arm

LED: Light Emitting Diode

LL: Left Leg

PPG: Photoplethysmography; Photoplethysmograph

PWTT: Pulse Wave Transit Time

RA: Right Arm

RL: Right Leg

RTD: Resistance Temperature Detector

SPB: Systolic Blood Pressure

INTRODUCTION

Background

Health care costs have risen exponentially in the last decade. Statistics released by the Canadian Institute for Health Information for 2008:

- Health care in Canada cost $172 billion or nearly $5,200 for every person in the country.
- Out of this, the third-biggest slice of the spending pie went to physician services, which totalled $23 billion.
- Health care for children under the age of one year cost, on average, $7,900.
- People 65 and older racked up an average bill of almost $10,000 in 2006, the last year for which age-specific data were available.
- Not surprisingly, patients between the ages of 85 and 89 cost the most in health services -- more than $21,200 on average in 2006. [1]

As observed from the statistics, individuals over 65 years of age have higher health care costs and a significant portion of these costs are a consequence of the services provided by the physicians.

Seniors have to make frequent visits to their doctor to get their vital signs measured. Regular monitoring of vital signs is essential as they are primary indicators of an individual's physical well-being. These vital signs include:

1. Pulse rate,
2. Blood pressure,
3. Body temperature, and
4. Breathing rate. [2]

Motivation

Traditionally, it was a custom to get these vital signs measured during a visit to the doctor. With advances in medicine and technology, this concept has adapted. There are many devices available in the market today that allow patients to monitor their own health on a regular basis from the comfort of their home. These devices are having a huge impact on health care costs as they are reducing the time and resources of medical physicians and facilities required by patients.

This is advantageous for both patients and physicians. Patients can monitor their health regularly and adjust their diet and physical exercise as needed to keep their vitals in balance. Health care professionals can access this information from their computers via wireless network and can check their patients' vitals at their own time. If they notice abnormalities, they can always schedule an appointment with their patients.

There are very few in-home monitoring devices in the market that are accurate, easy, and safe to use, while being of low cost to the customer. The objective of this project is to develop such a device.

Objectives

The goal of the main project is to develop a low cost, low power, reliable, non-intrusive, and non-invasive vital signs monitor that processes and analyses the data acquired from sensors to determine if they are within a "normal" range and to transmit this data to the user's cell phone using Bluetooth and store it there. This data can then be obtained by a health care professional anytime via wireless network.

The subproject that is under my responsibility is to design and build a sensing and data-conditioning system to acquire accurate heart rate, blood pressure, and body temperature readings.

The other two members of my group are working on the rest of the components of the project. Specifically, Sandra Escandor is responsible for the analysis and processing of data and Kirsten Zernask-Cebek is in charge of data transmission, storage, and output. Refer to Appendix A to see a block diagram of the whole project.

Scope

The scope of this project is to build a device for individuals over the age of 65 years. This limitation is added to simplify our project and ensure it is achievable with the restricted time and resources available. Since the target subjects for this device are individuals over 65 years of age, the most important feature of this device is that it must be easy to use.

Methodology

The methodology adopted for this subproject is to use non-invasive sensors to measure heart rate, blood pressure, and body temperature. The sensors used are inexpensive and are easy to use by the patient. Signal conditioning circuits are designed to filter and amplify the signals to provide desired output. All the components used in these circuits are low powered and inexpensive. The acquired data is real time and is sent to through the analog-to-digital converter (ADC) and into the microcontroller.

LITERATURE REVIEW

Initial research was conducted to determine the types of vital signs that are routinely measured during a visit to a doctor. These vital signs are: body temperature, pulse rate, respiration rate (rate of breathing) and blood pressure. As part of my project, I decided to design and build sensors that measured three of these vital signs.

Then, the market demand for this type of device was determined and research on similar monitoring devices that are currently sold was performed. According to a report from Berg Insight, the market for home health monitoring was worth about $11 billion in 2008 [3]. I found some current devices sold that offer similar monitoring capabilities as our main project.

Some examples of such devices are: i) “LifeGuard – A Wearable Vital Signs Monitoring System” developed by NASA AMES Astrobionics [4], ii) Spot Vital Signs LXi developed by WelchAllyn [5], and iii) CASMED's 740 Vital Signs Monitor [6]. These devices are compared in Appendix B in Table 2.

Major disadvantages with these devices are that they are not very easy to use, somewhat intrusive, and, of course, very expensive. From researching prices of similar devices on E-Bay, they cost anywhere from $500 to $5000 [7]. After considering these factors, a key goal of this project became to design sensors that would not only efficiently and accurately monitor the vital signs, but also be cost-effective.

Next, various technologies that were currently used to monitor these vital signs were examined and the most effective sensing techniques for this project was determined.

To measure the electrocardiogram (ECG), this project uses three unipolar leads, placed in Einthoven's triangle configuration. Lead I, Lead II, and Lead III are used. This method works accurately for the scope of this project as it is geared towards older individuals who are less active. Some different techniques that were researched are described in Appendix B in Table 3.

Next, different types of temperature sensors were compared. It was determined that the most effective way of measuring body temperature is by using a thermistor. The advantages and disadvantages of the various temperature sensors are provided in Appendix B, Figure 27.

Finally, various ways of non-invasive blood pressure measurement were reviewed. The two main ways blood pressure can be measured are using an oscillometric arm-cuff method and using photoplethysmography (PPG). These methods are compared in Appendix B in Table 4. This project uses the PPG method to measure blood pressure as it gives a continuous and real time measurement.

STATEMENT OF PROBLEM AND METHODOLOGY OF SOLUTION

Theory

ECG and Heart Rate

Electrocardiography measures the electrical activity of the heart. The activation of the heart starts at the sino-atrial node that produces the heart frequency, at about 70 cycles per minute. This activation propagates to the right and left atria muscle tissues. At the atrioventricular node, there is a delay to allow the ventricles to fill with blood from atrial contraction. The depolarization then propagates to the ventricles through the Bundle of His and spreads along the Purkinje fibers. Propagation of this activation through these fibers as a function of time is given in Appendix C, Figure 28. This activates the ventricles to contract and pumps blood to the aorta and to the rest of the body. Finally, repolarisation occurs and this cycle is repeated [8].

As the above cycle occurs, the transmembrane potential, which is the voltage difference between the internal and external spaces of the cell membrane, changes at each stage. These voltage differences can be measured using surface electrodes. The different peaks P, Q, R, S, T, and U are noticeable at these stages, as observed in Figure 1.

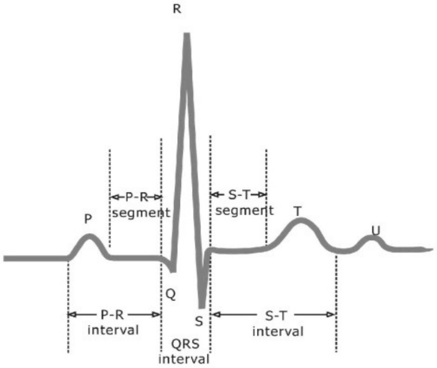

Figure 1: General ECG Waveform

The heart rate or pulse rate is the frequency of this heart cycle, and more specifically, the number of heart cycles that occur every minute.

Blood Pressure

Plethysmography measures the volume changes in an organ. Photoplethysmography is a plethysmograph obtained optically. PPG is obtained by a pulse oximeter. Light from a Light Emitting Diode (LED) is shone through

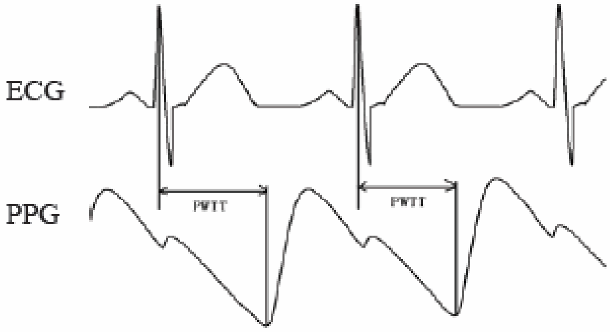

Figure 2: Pulse Width Transit Time (PWTT) Measurement

the skin and changes in light absorption are measured through a photodiode.

There are two types of techniques that can be used:

i) Transmission, which is shining light through the skin with LEDs on one side of the body part and placing the photodiode on the other side to obtain the characteristics of the light transmitted through the skin. This technique would work on finger or ear;

ii) Reflection, which is shining light through the skin with LEDs on one side of the body part and placing the photodiode on the same side to obtain the characteristics of light reflected from the skin. This technique would work on forehead or chest.

In the resulting signal, the DC component refers to the absorption by the tissue, and the AC component relates to the pulsatile component of blood volume that is directly related to the cardiac cycle.

After obtaining the PPG, the Pulse Wave Transit Time (PWTT), the time between the R peak of the ECG waveform and the minimum point on the PPG waveform, is measured, as illustrated in Figure 2. A linear regression is then determined and systolic blood pressure is estimated from that relationship.

Body Temperature

Human body temperature varies within a narrow range of values. Body temperature can be measured from different parts of the body, but for this project, temperature will be measured from the ear as it is one of the most accurate types of body temperature measurement.

Temperature depends on many things, including level of activity, time of day, and psychological factors. It also depends on whether the person is eating.

Statement of Problem

In this project, one of the tasks is to design and implement a device that will measure the ECG. Appropriate electrodes have to be chosen and placed at correct locations on the body. A signal conditioning block is to be designed to filter out noise and amplification is added to increase the signal to distinguishable levels.

The second task is to design and implement a system that will measure blood pressure. Pulse oximeter will be designed to measure the volume changes in the blood. The PPG and ECG will then be combined to give a blood pressure reading. The accuracy of acquiring blood pressure using this method has to be determined.

The final task of this project is to design and implement a temperature measurement system that will measure the ear's temperature. This has to be accurate to within ±0.2°C to have a reliable monitor.

Methodology of Solution

Three gold EEG electrodes will be used to get ECG signals using Lead I, Lead II, and Lead III electrode placements. These signals will be sent through a signal conditioning circuit that will filter out unwanted and noisy parts of the signal and output the desired signal. This output signal will be sent to the ADC and into the microcontroller.

For the PPG, red LED will used to illuminate the finger and the photodiode that measures this wavelength will be placed on the other side of the finger. Depending on the light transmitted, the photodiode will generate a voltage. This signal will also be sent through a signal conditioning circuit that will filter out unwanted and noisy parts of the signal and output the desired signal. This output signal will be sent to the ADC and into the microcontroller. Once this signal goes into the microcontroller, the PWTT and the corresponding blood pressure values are calculated using linear regression methods.

The thermistor will change its resistance depending on the body temperature. A simple circuit will be used to convert these changes in resistances to a voltage change. These voltage values will be sent to the microcontroller via ADC. The temperature will be determined by looking up the temperature corresponding to that specific voltage in the lookup table, stored in the microcontroller, which will be accomplished by another group member.

DESIGN PROCEDURES

ECG and Heart Rate

Electrode and Placement Selection

The first stage in building an ECG monitor is to select the electrodes and determine the placement of these electrodes.

For this project, Gold Cup EEG electrodes have been selected. These are reusable electrodes that provide consistent and superior quality signal and are well-suited for this application. Before attaching the electrodes on the skin, the skin is rubbed and cleaned with alcohol swabs to get rid of dirt and dry skin. A conductive paste is also applied to these electrodes before placing them on the body to reduce the noise in the signal. The paste used for this project is the Ten20 Conductive paste. After the paste has been applied, the electrodes are attached to the skin using adhesive tape.

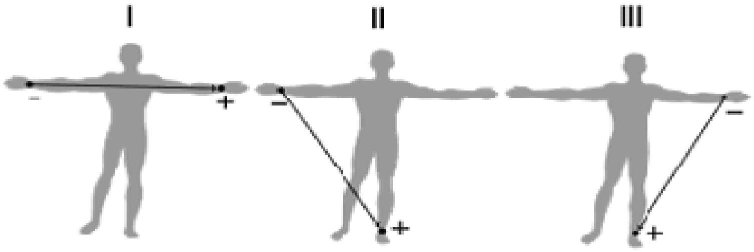

Figure 3: ECG Lead Configurations

For electrode placement, many techniques were reviewed, as demonstrated in “Literature Review” section, and the best placement configuration for this project is the Lead I, Lead II, Lead III configuration, as shown in Figure 3.

The Left Arm (LA) and Right Arm (RA) electrodes are placed on the palmar side on the wrists and the Left Leg (LL) and Right Leg (RL) electrodes are placed above the ankle and above the bony ridges.

Lead I placement: Right Arm (RA) is connected to the negative input terminal and Left Arm (LA) is connected to the positive input terminal.

Lead II placement: RA is connected to the negative input terminal and Left Leg (LL) is connected to the positive input terminal.

Lead III placement: LA is connected to the negative input terminal and LL is connected to the positive input terminal.

For all these lead configurations, the Right Leg (RL) is referenced as ground.

Signal Conditioning Circuit

The amplitude of the ECG signal varies anywhere from 0.1 mV to 5 mV. The frequencies of interest lie within the range of 0.05 Hz to 100 Hz. Since the line noise exists at 60 Hz, the affect of this noise on the signal has to be reduced.

The basic block diagram of the ECG signal conditioning circuit is shown in the Figure 4. All components use +2.5 V at their positive terminals and -2.5 V at their negative terminals, and reference voltage is set to 0 V.

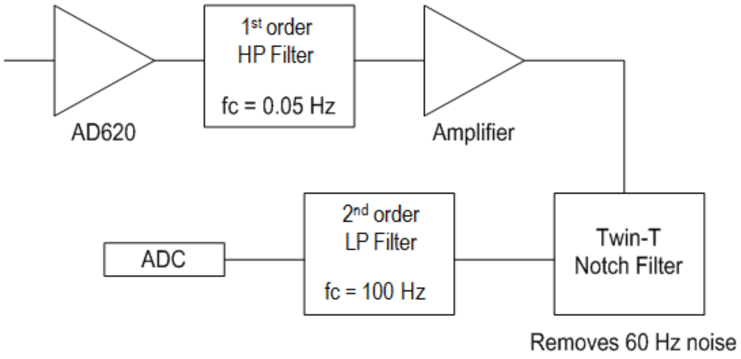

Figure 4: Block Diagram of ECG Signal Conditioning Circuit

The implementation of each of the above blocks is explained in detail below.

AD620 Differential Amplifier

The schematic of this head stage amplifier is shown below:

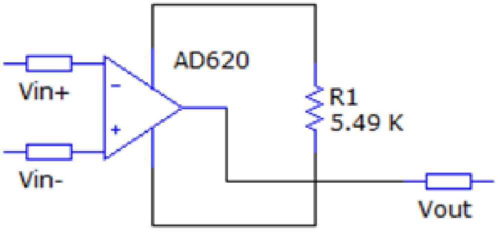

Figure 5: Schematic of Headstage Amplifier

By letting R = 5.49 kΩ, the gain of the circuit is set to 10. AD620 is a low cost, low power instrumentation amplifier with excellent DC performance and low noise. It is ideal for use in ECG and medical instrumentation.

This initial amplification is required to increase the amplitude of the signal so that filtering can be performed. The ECG leads go into the Vin+ and Vin- terminals. The RL ground is connected to the electrical ground.

First Order High Pass Filter

As we are only interested in the pulsatile part of the waveform, the next stage in the block diagram is a 1st order high pass filter that filters out DC components of the signal. It also rejects frequencies below 0.05 Hz, which is set as its cut-off frequency. Figure 6 shows the schematic of this circuit.

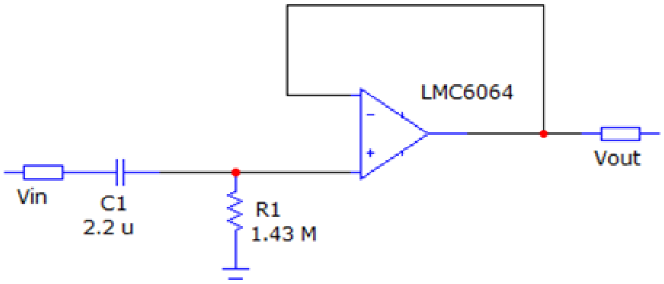

Figure 6: Schematic of High Pass Filter

The op-amp used here is the LMC6064, which is a precision CMOS quad micropower operational amplifier with low offset voltage and supply current and high voltage gain.

Second Stage Amplifier

Another amplification stage is added to the system to increase the gain of the signal further. The gain here is set to 10. The schematic for this amplifier is shown below:

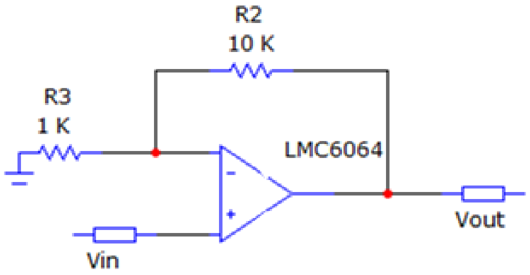

Figure 7: Schematic of Second Stage Amplifier

Twin T Notch Filter

The schematic for the notch filter is shown below:

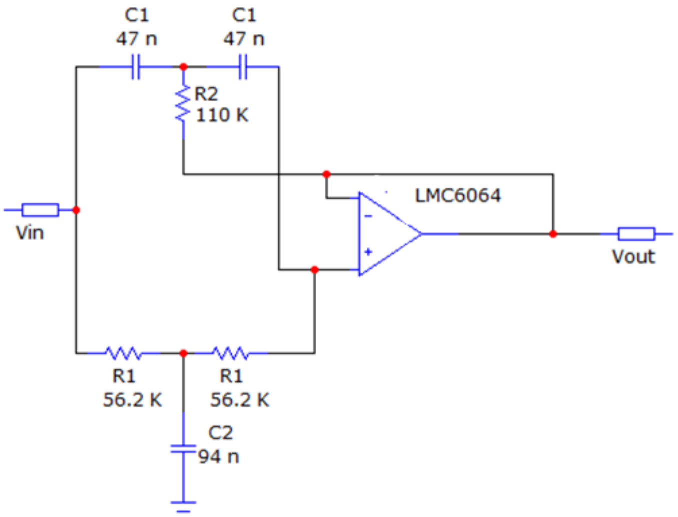

Figure 8: Schematic of Notch Filter

This filter is added to the output of the second stage amplification and it removes the 60 Hz noise.

Second Order Low Pass Filter

A low pass filter is added at the last stage of the ECG signal conditioning circuit. It is a second order Butterworth filter with a cut-off frequency at 100 Hz. Therefore, it rejects unwanted frequencies above 100 Hz, reducing noise.

Below is a schematic of the low pass filter:

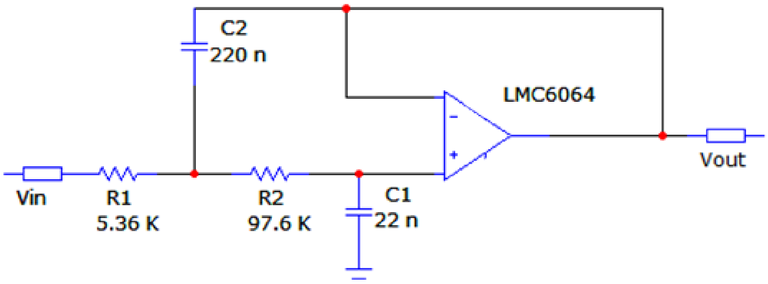

Figure 9: Schematic of Low Pass Filter

The output of the low pass filter is an ECG signal and it is sent through a 10 bit ADC into the microcontroller.

Blood Pressure

Selection of LEDs and Photodiode

To build a pulse oximeter, selection of appropriate LEDs and photodiodes are essential to obtaining a good signal.

A Red LED and an Infrared LED are normally used in a pulse oximeter to measure the blood volume changes that are used to determine the content of oxygenated and deoxygenated haemoglobin in the blood. For this project, the transmission technique is used on the finger to obtain the signal. Instead of using two LEDs, only one Red LED is used to measure the volume changes in blood. The photodiode captures the characteristics of the light transmitted through the finger and produces a current.

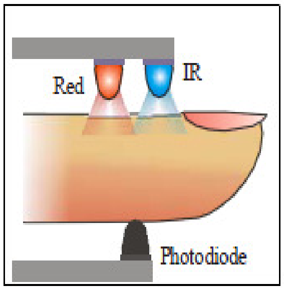

Figure 10: Transmission PPG

The Red LED chosen for this project is 5mm, 2800 MCD, SSL-LX5093SRC/E that generates light with wavelengths of 660 nm. A light-to-voltage optical sensor, TSL250R-LF is chosen to measure the light transmitted through the finger. This sensor combines a photodiode and a transimpedance amplifier, producing a voltage output. It has peak spectral responsivity at 750 nm; however, it also produces 100% responsivity at 660 nm.

Signal Conditioning Circuit

The amplitude of the light transmitted varies in the range of micro volts. The frequencies of interest lie within the range of 0.1 Hz to 10 Hz.

The basic block diagram of the PPG signal conditioning circuit is shown in the figure below. All components use 5 V at their positive terminals and the reference voltage and the voltage at negative terminals is set to 0 V (grounded).

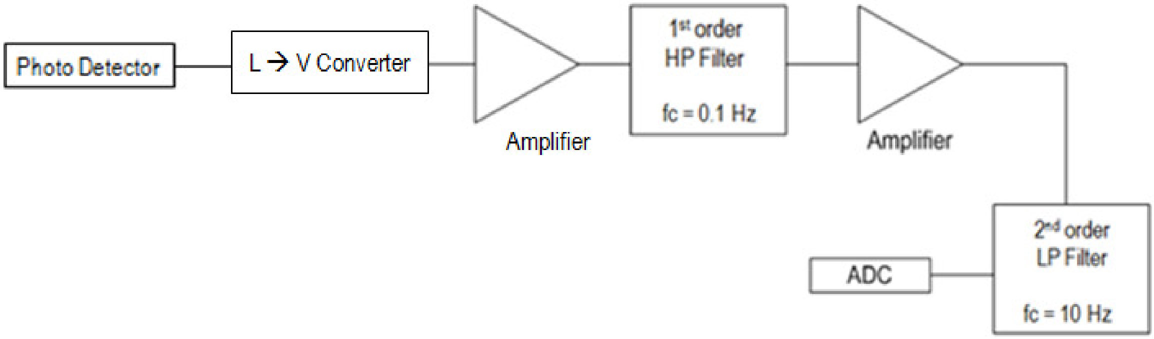

Figure 11: Block Diagram of PPG Signal Conditioning Circuit

The implementation of each of the blocks in Figure 11 is explained in further detail below.

Light to Voltage Converter

A 5 V DC voltage is used to turn on the Red LED. The light transmitted through the finger is converted to a voltage by the light-to-voltage sensor using the following circuit.

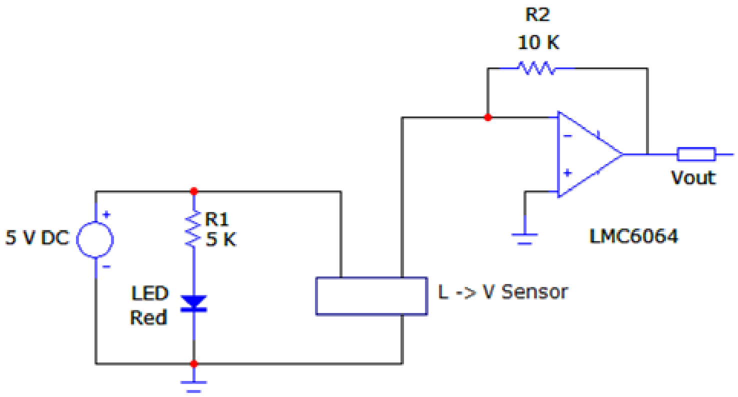

Figure 12: Schematic of Light to Voltage Converter

Head Stage Amplifier

The schematic of this amplifier is shown in Figure 13. The gain of the circuit is set to 1000:

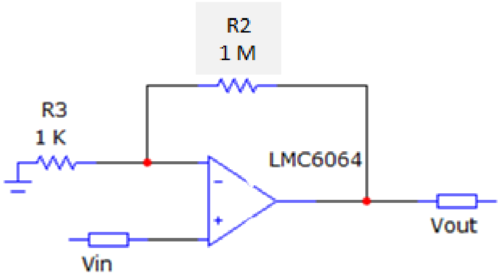

Figure 13: Schematic of Amplifier

First Order High Pass Filter

As we are only interested in the pulsatile part of the waveform, the next stage in the block diagram is a 1st order high pass filter that filters out DC components of the signal. It also rejects frequencies below 0.1 Hz, which is set as its cut-off frequency. The schematic of this circuit is given in Figure 14.

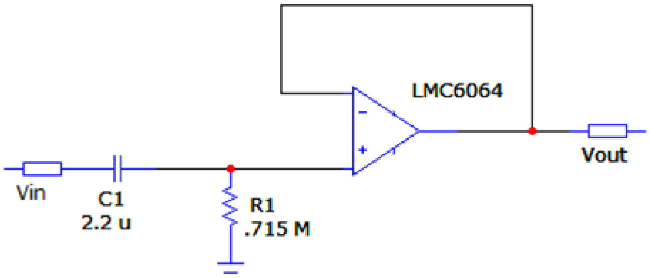

Figure 14: Schematic of High Pass Filter

Second Stage Amplifier

Another amplification stage is added to the system to increase the gain of the signal further. The gain here is set to 100. The schematic for this amplifier is shown below:

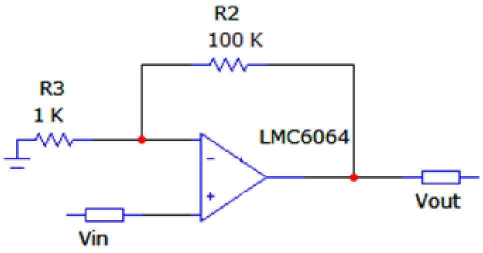

Figure 15: Schematic of Second Stage Amplifier

Second Order Low Pass Filter

A low pass filter is added at the last stage of the PPG signal conditioning circuit. It is a second order Butterworth filter with a cut-off frequency at 10 Hz. Therefore, it rejects unwanted frequencies above 10 Hz, reducing noise.

Below is a schematic of the low pass filter:

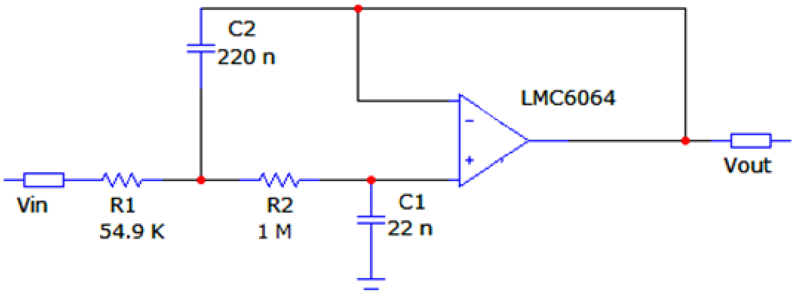

Figure 16: Schematic of Low Pass Filter

The output of the low pass filter is a changing blood volume signal which is sent through a 10 bit ADC into the microcontroller.

Estimation of Blood Pressure

After obtaining the PPG waveform, systolic blood pressure can be estimated. This can be done by determining the PWTT. PWTT is the time interval between two pulses measured on the same artery. More specifically, PWTT is the time interval between the R peak of the ECG and the minimum peak of the PPG. Since both PPG and ECG are measured from the same arm, these two modalities are combined to calculate the PWTT.

Referring to the figure on the right, the time between the two peaks in the pulses is measured, giving PWTT.

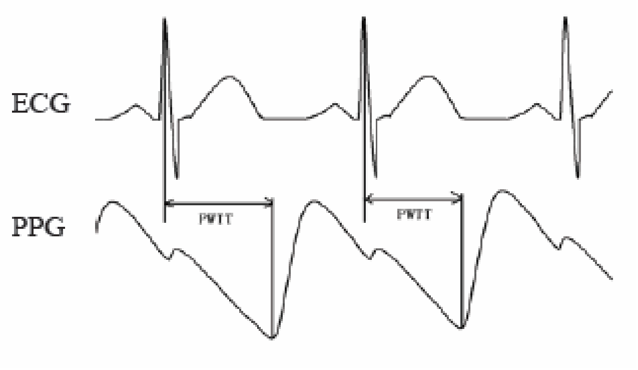

Figure 17: Pulse Width Transit Time (PWTT) Calculation

Through some research, a paper was *found where similar analysis of blood pressure was performed and they determined a linear regression that estimated the blood pressure using PWTT. Their final equation was* $SBP = -0.6881\times PWTT + 228.59$[1]*, where the PWTT is in milliseconds (ms) and SBP is in millimetres of mercury (mmHg). Due to time and resource limitations, the scope of this project did not involve determining this equation. Therefore, for the purposes of this project, this equation is accepted to be a reasonable estimation of blood pressure.*

Body Temperature

Temperature Sensor and Placement Selection

As explained in “Literature Review”, thermistor has been chosen as the temperature sensor for this project. General Electric’s MA300 10kΩ thermistor is a non-linear thermistor with tolerance of ±0.2°C. It can measure temperatures ranging from 0°C to 50°C and has a fast response time and low power dissipation, which makes it ideal for such medical application.

The sensor is small and can be placed anywhere on the body, however, its placement is chosen to be in the ear. Temperature measurements taken in the ear are accurate and relate closely to true core body temperature.

Normal temperature ranges in the ear vary from 35.8°C to 38°C [9].

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[1] The equation is adopted from “A LabVIEW Based Measure System for Pulse Wave Transit Time” by J. M. Zhang, P. F. Wei and Y. Li. The linear function is approximated from a data of 14 healthy individuals, therefore, the accuracy may not be very high.

Wheatstone Bridge

The following schematic illustrates the circuit used to measure the temperature:

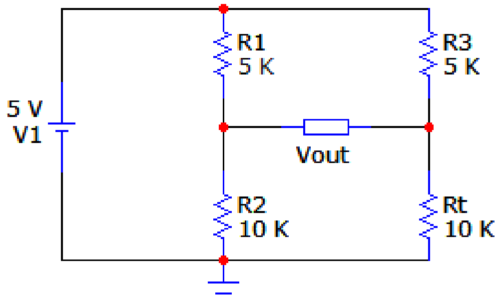


Figure 18: Schematic of Wheatstone Bridge

Rt is the resistance of the thermistor. The output voltage can range from +2.5 V to -2.5 V.

Change in temperature causes the thermistor's resistance to change accordingly. The relationship between this thermistor's resistance and temperature is non-linear. To measure this change in resistance, the circuit above is used. Four resistors are used in this configuration, one of them being the thermistor. When the thermistor's resistance changes due to change in temperature, the output voltage will change. The advantage of using a Wheatstone bridge is that it accurately measures small changes in resistances and produces a voltage output. This voltage output is sent through an ADC into the microcontroller.

Inside the microcontroller, there is a lookup table that has temperature values corresponding to voltage values. From this lookup table, the body temperature in degrees Celsius is determined.

RESULTS AND DISCUSSION:

Through various test procedures and techniques, many parts of this project were improved. Initially, basic features were tested to ensure that each component or block worked and then as testing progressed, modifications or adjustments were made to the circuits so they functioned well practically.

ECG / Heart Rate

While building each stage of the ECG signal conditioning circuit, each circuit block was tested. The component values used in the theoretical design of the circuits were not easily available, so components with values within 5% tolerances were used.

Initially, when building the ECG circuit, testing was performed using a sinusoidal wave. The power supplies used were +5 V and -5 V batteries for the positive and negative terminals. The input was set to 50 mV peak to peak voltage. The second stage gain was adjusted to 10 to give a total gain of 100. The results of these initial tests were as follows:

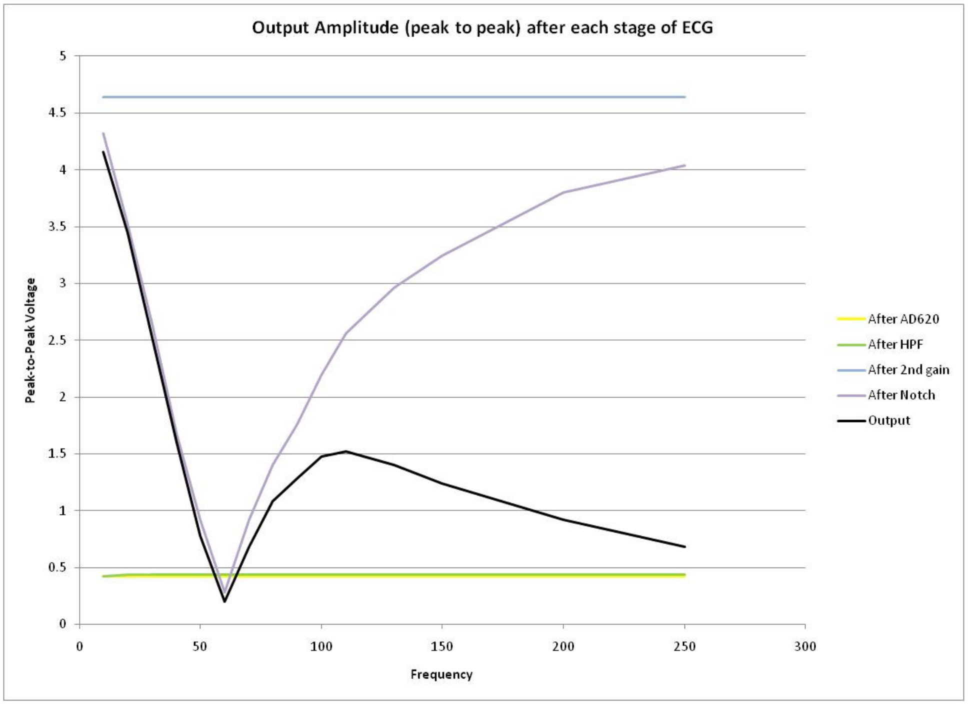


Figure 19: Amplitude Measurement after Each Block in ECG Circuit

From these tests, it was verified that each block of the ECG circuit functioned correctly. One disadvantage that was noticed was that the gain of the circuit at the output was greatly reduced due to the combined effect of the notch filter and low pass filter. However, for frequencies of interest, i.e. from 0.05 Hz to 100 Hz, the gain was sufficient to be sent to the ADC.

Next, this circuit was tested with a DC offset applied to its input. It was observed when this DC voltage was applied, there was an initial jump in the total output; however, after about 30 – 50 seconds, the output recovered to its original waveform (without the DC offset). This should have happened due to the high pass filter that blocked out all DC components.

This circuit was now ready for actual ECG testing. Increasing the second stage gain back to 100 to compensate for the small signals obtained from the electrodes, the gold cup electrodes were placed in all three lead configurations, and testing was performed on each configuration, in relaxed, standing, walking, and running modes.

Below is a chart that compares the 3 lead configurations, Lead I, Lead II, and Lead III, with each other.

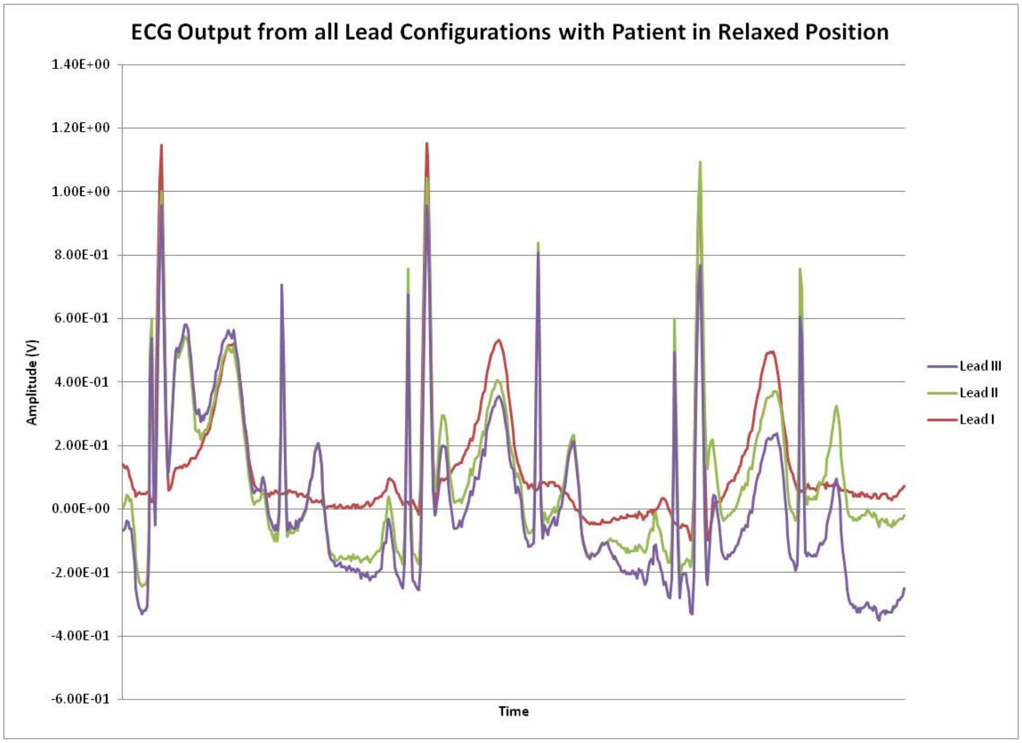


Figure 20: ECG Output from All Lead Configurations

As observed in the chart above, all lead configurations give valuable results. Each P, Q, R, S, and T peaks are distinguishable. However, in this case, Lead I configuration seems to give the most accurate representation of the signal. This cannot be said conclusively as data for each configuration was not acquired simultaneously, and hence, cannot be compared directly.

In the graph below, ECG measurements are taken at different stages of physical activity for Lead I configuration. It is clear that ECG signal for relaxed and standing positions looks similar to the desired signal and each phase in the cycle is distinguishable and noise free. However, when the level of physical activity increases, the peaks of heart cycle, the R peaks, are not as easily noticeable. Also, when the person is running, a lot of saturation occurs. The signals are noisier during these higher levels of physical activity due to all the motion artefacts.

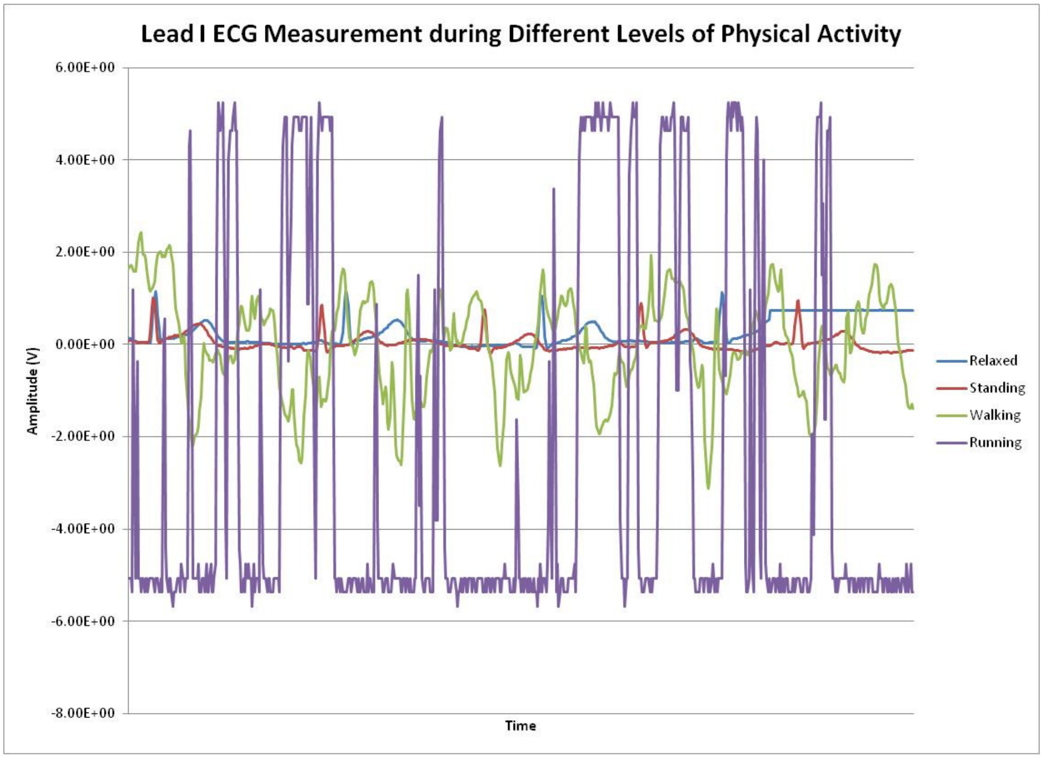


Figure 21: Lead I ECG Measurement during Various Levels of Physical Activity

Next, the power supply of the circuit was reduced to +2.5 V and -2.5V to get a higher resolution in the microcontroller when passed through the ADC. The second stage gain was reduced again to 10 to compensate for the saturation that occurred during running.

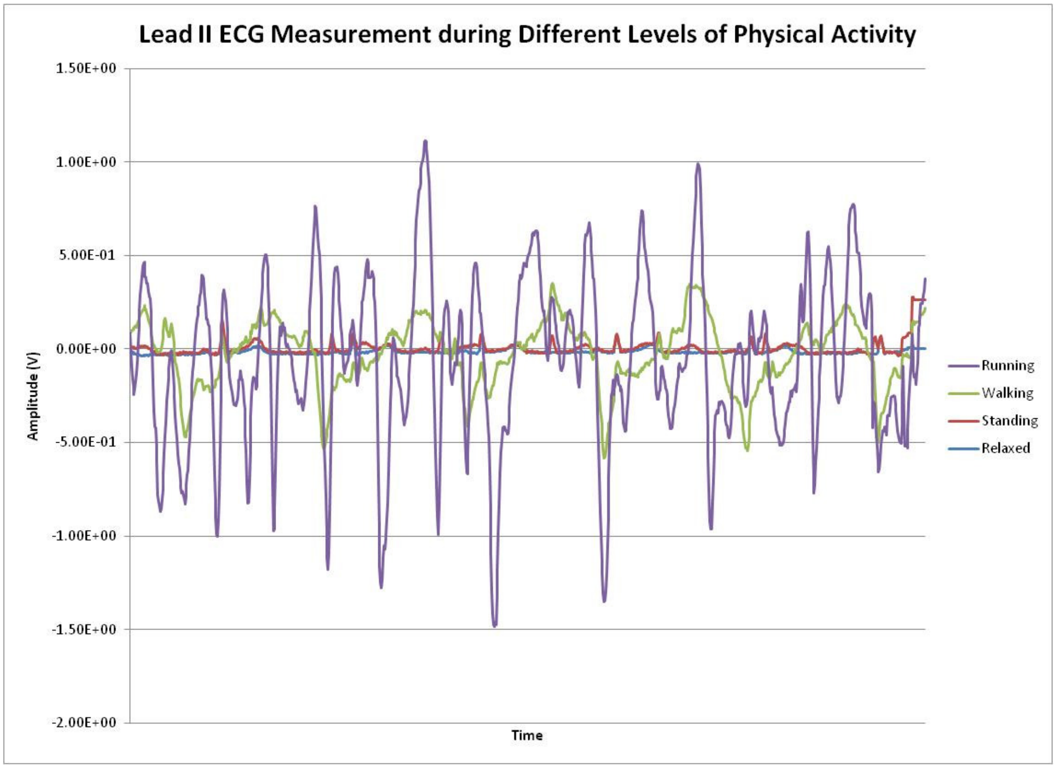


Figure 22: Lead II ECG Measurement with Various Levels of Physical Activity

The graph above displays Lead II measurement at various levels of physical activity. Similar observations are made as those above, however, this time, no saturation occurs during running. The R peaks in each case are distinguishable and heart rate can be determined by counting the number of R peaks that occur in a minute.

Although motion artefacts are present in ECG signals with high level of activity, these can be overlooked as this system is designed for older individuals, who are not as physically active.

Blood Pressure

After building the PPG circuit, it was initially tested with a sinusoidal input from a function generator. The voltage input into the circuit was 5 V for the positive terminal and the negative terminal was grounded. The input was set to 20 mV and the total gain of the circuit was reduced to 100 to prevent saturation. The results obtained from this test are shown in the graph below.

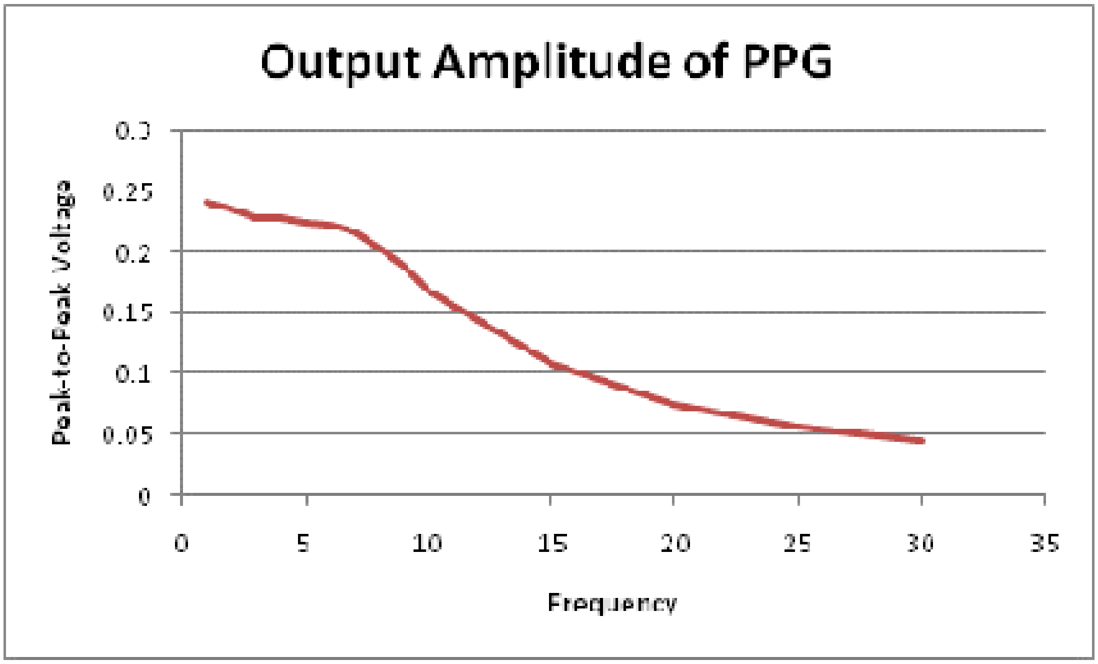


Figure 23: Amplitude Measurement at Output of PPG Circuit at Different Frequencies

As illustrated, the low pass cut off frequency of 10 Hz rejects frequencies above 10 Hz. When the input includes a DC offset, the circuit rejects the offset and allows only the pulsatile portion of the waveform to appear at the output.

Next, a small plastic casing is built. It has a large hole through the middle for the individual's finger. On one side, the Red LED is attached and on its opposite side, the light-to-voltage sensor is placed to measure the amount of light transmitted through. When the finger is inserted into the hole, the LED shines light on one side and the transmitted light is captured on the other side of the finger. This case reduces the interference from other light sources.

Then, the PPG circuit is tested on a subject. The subject is also connected to the ECG circuit through electrodes, as described in the "ECG/Heart Rate" section. Testing is performed using all three lead configurations for ECG. Blood pressure is also simultaneously measured by a blood pressure monitor on the other arm for comparison purposes.

Below is a graph of the results obtained using Lead I configuration for ECG. The index finger is used to obtain the PPG.

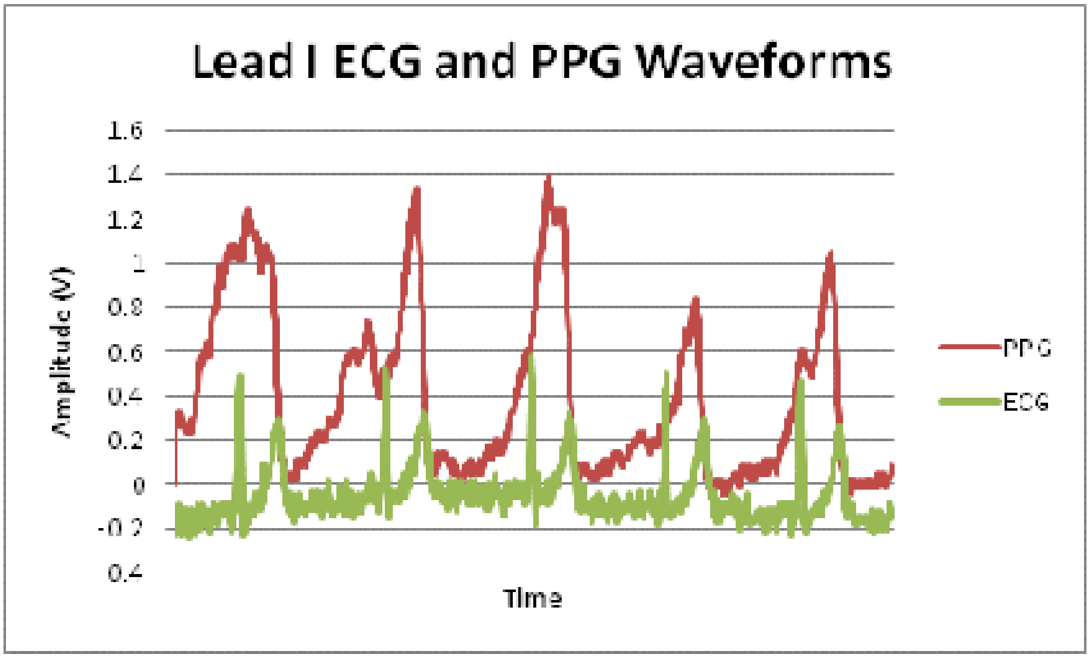


Figure 24: ECG and PPG Waveforms

As observed from the plot above, ECG and PPG are periodic at the same rate. This means that heart rate can be calculated using either PPG or ECG.

To calculate blood pressure, the PWTT is now measured. Through analysis in MATLAB, the PWTT is determined to be 300 ms. Therefore, the SBP $= -0.6881 \times PWTT + 228.59 =$ 70 mmHg. This value is not correct, because when measured using a commercially available blood pressure monitor, the SBP was determined to be 119 mmHg. This means that there is some factor that caused an error in the measurements. A potential reason for this may be the fact that only one LED is used to measure the PPG waveform. This may result in a different minimum value compared to that obtained from a PPG waveform of two LEDs. However, due to time constraints, this circuit was not further tested.

Body Temperature

The thermistor was initially tested to ensure that it performed according to specifications. A medical thermometer currently available in the market was used to compare the results with the temperature values of the thermistor. The calibrated medical thermometer used was BestMed's Deluxe Digital Thermometer.

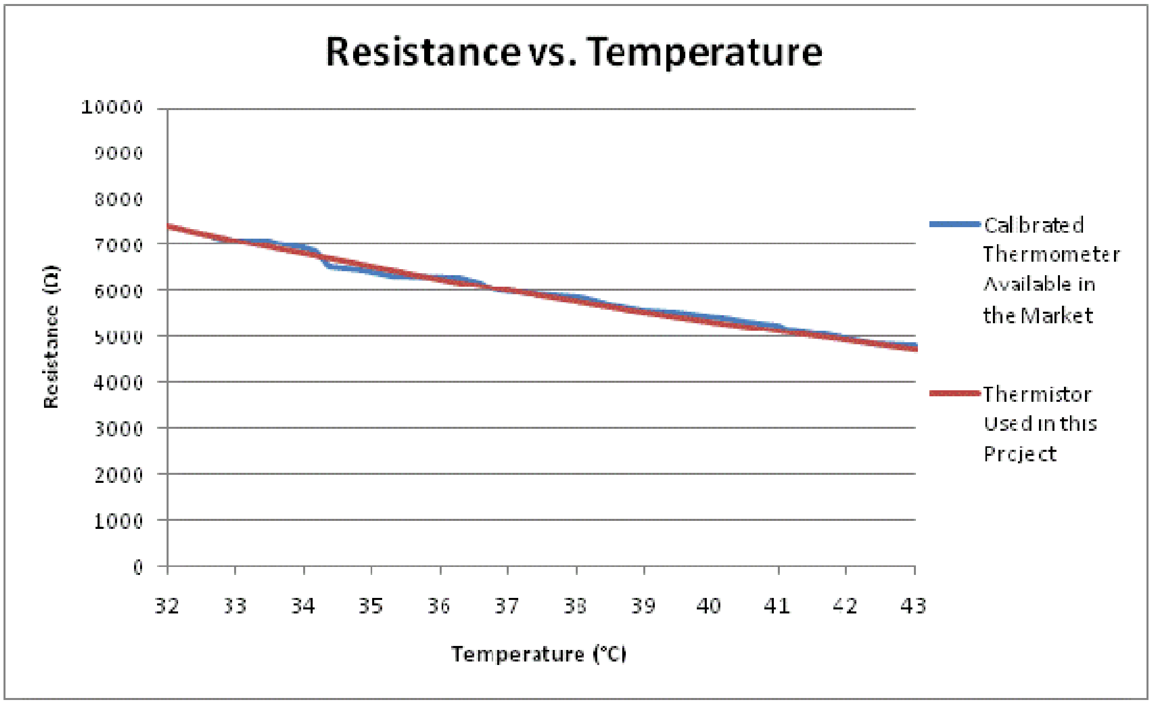


Figure 25:Resistance versus Temperature of a Calibrated Thermometer Against the Thermistor

The graph above is obtained by plotting the resistance versus temperature table provided in the thermistor's data sheet against the actual temperature measured by the thermometer. As observed, these plots line up very closely, and it can be deduced that the thermistor performs as desired.

Next, two circuits were designed to convert the changes in resistances to voltages. These voltages would then be converted to temperature values and compared with the real temperature measured by the thermometer. Two designs are compared and the best design is determined.

First design is that of a half-bridge circuit. The advantage of this design is that fewer components are used to build the circuit. The schematic of the design is presented below.

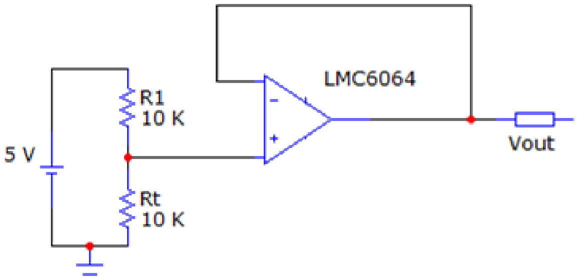


Figure 26: Schematic of Half-Bridge Temperature Measurement

Results obtained from this circuit are illustrated below.

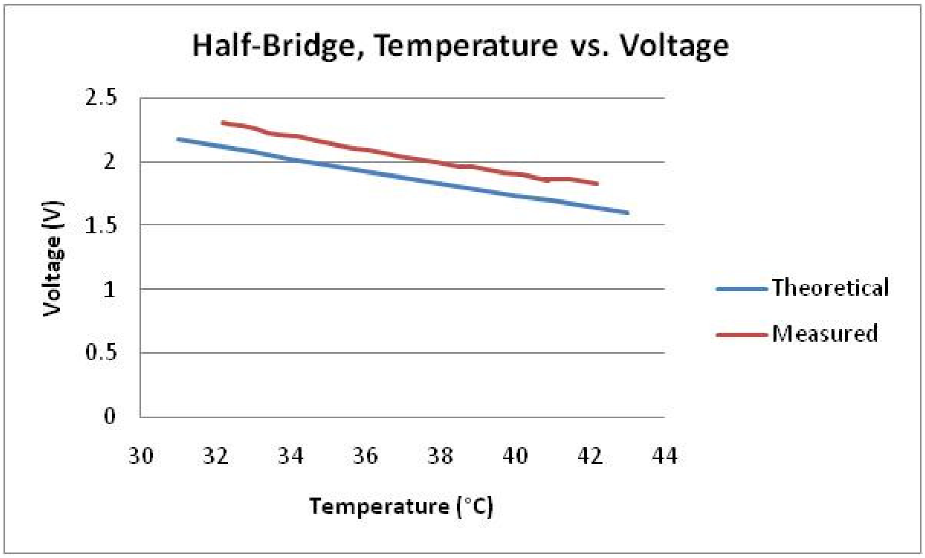


Figure 27: Temperature versus Voltage for Half-Bridge Circuit

As observed, the half-bridge design measures temperature accurately. However, there is an offset that is visible from the graph. This is mainly due to heat generated by the resistor and the op-amp. This can be compensated by adding an appropriate offset to the measured value to align it with the theoretical values. Since the offset is more or less constant throughout the range of temperature values, voltage values at any temperature can be chosen to compute the offset.

At 36°C,

$$Offset = Measured\,Voltage - Theoretical\,Voltage = 2.09 - 1.93 = 0.16\ V$$

When this offset is subtracted from the measured values, the theoretical measurements match the measured values. A problem with this design is that due to the use of an op-amp, this circuit would dissipate a lot more heat after running continuously for a few hours.

The second design was that of the Wheatstone bridge, which is already explained in the "Design Procedures" section of this report. The graph displays the temperature obtained from this design compared against the true temperature.

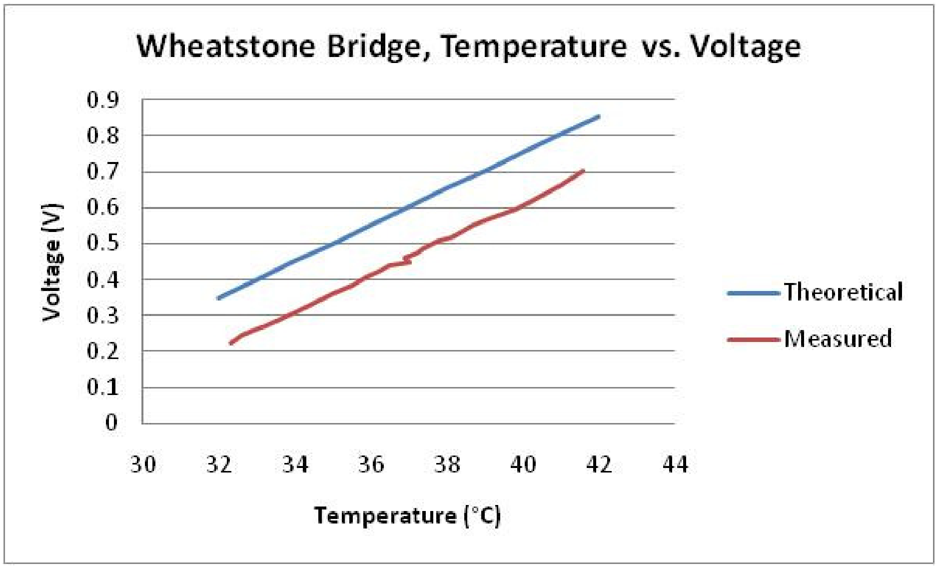


Figure 28: Temperature versus Voltage for Wheatstone Bridge Circuit

A Wheatstone bridge accurately measures small changes in voltages. The temperature values obtained using this method closely relates to the true values after the offset is applied. The offset in this case is calculated to be:

$$Offset = Measured\ Voltage - Theoretical\ Voltage = .665 - .804 = -0.139\ V$$

When this offset is subtracted from the measured values, the theoretical measurements match the measured values.

This design is chosen to be the acquisition circuit to monitor temperature as it is slightly more accurate than the half-bridge circuit (after applying the offset). Also, cheaper components are used to build this circuit, making it cost effective as well as low power.

Hardware Cost

The costs for all the parts used in the design and implementation of the vital signs sensors are listed below. The costs outlined below are for only the parts used to build the actual circuits. Additional costs related to other parts used in older models of these circuits are not attached.

Table 1: Cost Breakdown

Part	Quantity	Total Price ($)
AD620ANZ-ND	1	7.50
Red LED	1	0.50
TSL250R-LF	1	3.00
LMC6064IN-ND Op-amp	3	15.00

The ECG leads, ECG paste, thermistor, resistors, capacitors, and breadboards used in this project were obtained from the ECE department at no cost. The total value of these components if they were to be purchased would be around $50.00. Also, the casing for finger PPG cost around $20.

The total cost of all these sensors can be estimated to be around $100.

CONCLUSIONS AND RECOMMENDATIONS

The objective of this project was to build a low power, low cost, reliable, non-intrusive, and non-invasive monitoring system that would accurately measure the vital signs. A reliable and continuous vital sign monitoring system targeted towards older individuals has been successfully built. The resulting system was also low in power and cost, non-invasive, and provided real time monitoring. It is also easy to use and provides accurate measurements.

Given the scope of this project, the ECG and temperature measurement circuits accurately measure the heart rate signal and body temperature. The system to measure PPG was built; however, the blood pressure calculation was not tested fully due to time limitations.

This project can be improved and expanded in numerous ways. First of all, the target group for this product can be expanded to include people of all ages. To achieve this, noise resulting from motion artefacts in the signals has to be reduced. Currently, the signal conditioning circuits for these sensors are in analog form on breadboards. These can be made in Printed Circuit Boards (PCBs) and digital filtering can be added to further reduce noise. Also, the sensors used for measuring ECG can be upgraded to stick on electrodes. All these sensors should be wirelessly connected to the phone and microcontroller, making it comfortable and non-intrusive for the user to wear.

Some recommendations on future work would be to add the fourth vital sign monitor to this system, which is measuring the oxygen level in the blood. This can be achieved through PPG. Since the PPG is already being used to measure blood pressure, it can easily be extended to measure the oxygenation of blood. Adding this last sensing component would make this system a complete vital signs monitor.

In conclusion, with refinements to the design, the Mobile On-Call System measuring ECG, blood pressure, and body temperature would make a great competitor against other products that currently exist in the market.

APPENDICES

Appendix A: Project Overview

The diagram below illustrates the major components of the main project:

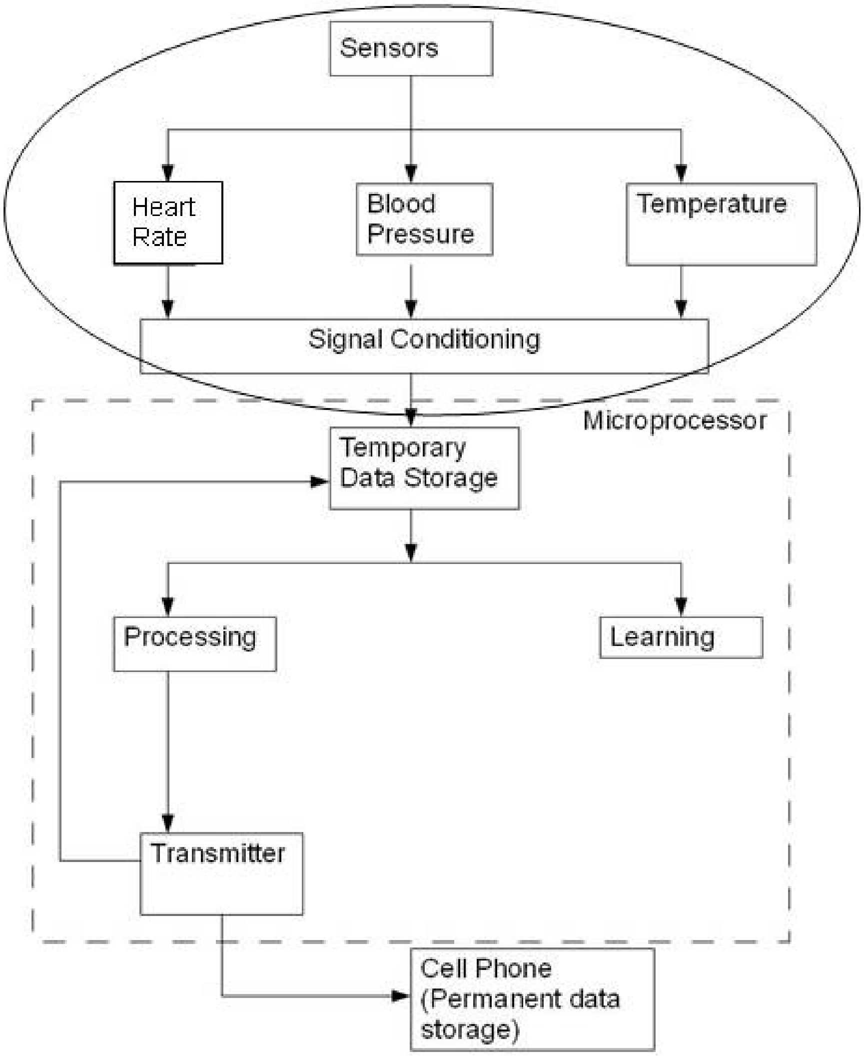


Figure 29: Block Diagram of Project

This project consists of three group members. I am responsible for the components displayed in the circle above.

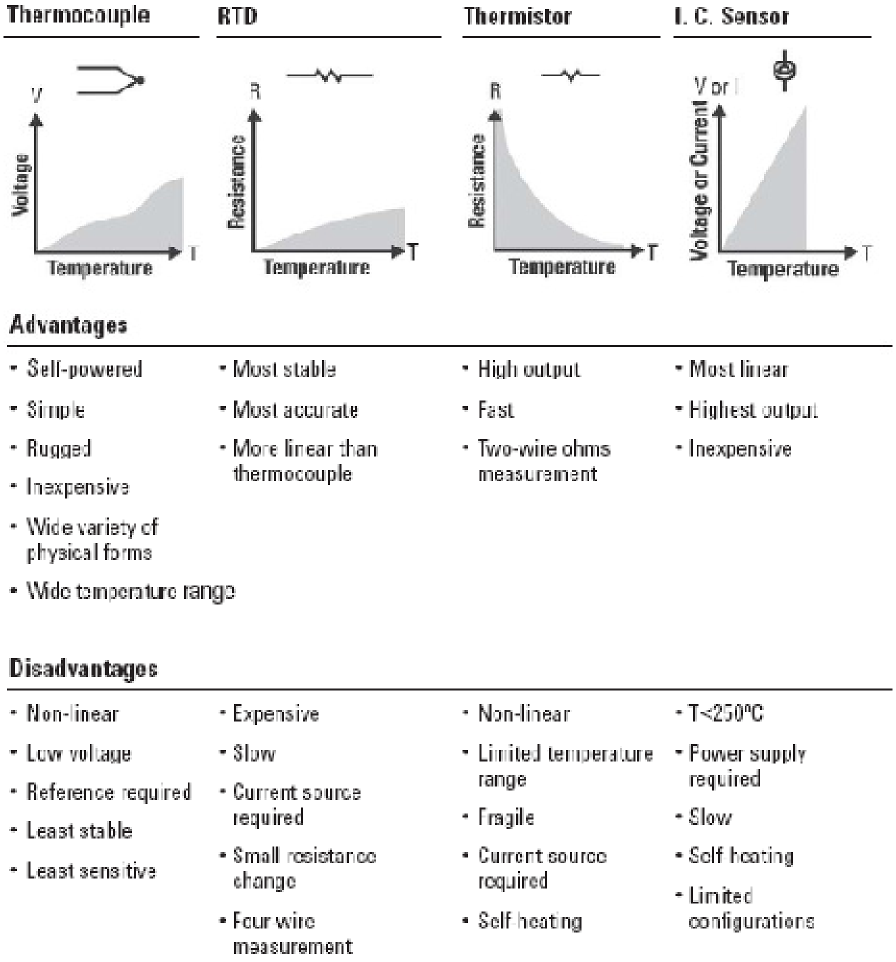
Appendix B: Detailed Literature Review

Table 2: Comparison of Different Types of Devices Available in the Market

Device	**Advantages**	**Disadvantages**
LifeGuard	- Monitors ECG, respiration, activity, temperature, heart rate, SpO2, and blood pressure - Used for multiple applications and designed for extreme environments - Can send data to a computer via Bluetooth	- Sensors are hard to put on and somewhat intrusive - Can only log upto 8 hours of data - Not actually for sale commercially
Spot Vital Signs LXi	- Measures temperature, respiration rate, pulse rate, blood pressure, BMI, SpO2 - Able to wirelessly transmit vitals to hospitals	- Cuff method to measure blood pressure, which is intrusive
740 Vital Signs Monitor	- Measures blood pressure, SpO2, and temperature - Reduces problems of motion in blood pressure measurement	- Cuff method to measure blood pressure, which is intrusive - No capability of wireless transmission of data

Table 3: Comparison table for different types of ECG configurations

ECG Configuration	**Advantages**	**Disadvantages**
Standard 12-lead	- Accurate - Gives a good signal as it is close to the heart - Fewer motion artefacts	- Have to shave chest hair to obtain a clean signal - Increased difficulty in placing electrodes
Unipolar Leads	- Accurate for low activity periods - Easy to place electrodes	- Motion artefacts skew results
Bipolar chest leads	- Accurate	- Have to shave chest hair to obtain a clean signal - Motion artefacts



Thermocouple	RTD	Thermistor	I. C. Sensor
Advantages			
• Self-powered • Simple • Rugged • Inexpensive • Wide variety of physical forms • Wide temperature range	• Most stable • Most accurate • More linear than thermocouple	• High output • Fast • Two-wire ohms measurement	• Most linear • Highest output • Inexpensive
Disadvantages			
• Non-linear • Low voltage • Reference required • Least stable • Least sensitive	• Expensive • Slow • Current source required • Small resistance change • Four wire measurement	• Non-linear • Limited temperature range • Fragile • Current source required • Self heating	• T<250°C • Power supply required • Slow • Self heating • Limited configurations

Figure 30: Comparison table for different types of temperature sensors

*Source: Agilent Technologies. *Practical Temperature Measurements*, Application Note 290, March 2008.

Explanation for choosing thermistor for this application: The advantages of using thermistors are that they are cheap, have a fast response time, and are pretty accurate. RTD's are more accurate than thermistors; however, they are also expensive and have a slow response time. Also, a major disadvantage of thermistors is that they are non-linear; the way this problem is resolved is to have a lookup table inside the microcontroller that will match the voltages with their corresponding temperatures. This will be obtained using the thermistor's datasheet. Other disadvantages such as limited temperature range and self-heating will not play a significant role for this application as we need to measure temperature between a small temperature range and will be using low power devices to power this project. Therefore, after considering various tradeoffs and weighing the importance of cost, accuracy, and response time, thermistor was determined to be the most effective sensor for this project.

Table 4: Comparison table for different types of blood pressure systems

Blood Pressure Techniques	Advantages	Disadvantages
Arm-Cuff Osillometric Method	- Easier implementation - Accurate if placed correctly on arm	- Intrusive - Hard to use - One measurement every 5 minutes
PPG	- Real time and continuous measurement - No cuff used - Less intrusive - Easy to use	- Harder implementation - Calibration required

Appendix C: Theoretical Details

The figure below illustrates the propagation of the activation in the heart fibers.[8]

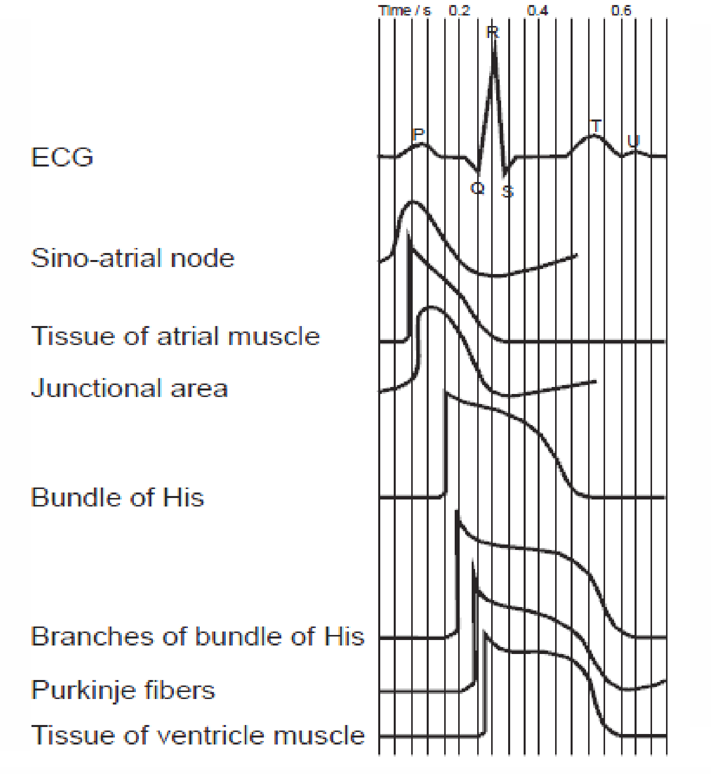


Figure 31: Propagation of the Activation in the Heart Fiber

The points outlined on the ECG graph, P, Q, R, S, T, represent the various stages in the heart cycle.

P = atrial depolarization

QRS = depolarization of right and left ventricles

T = repolarization of ventricles

U = follows T wave, not always seen

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