Photoplethysmography (PPG) Scheming System Based on Finite Impulse Response (FIR) Filter Design in Biomedical Applications

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***Abstract*—Photoplethysmography (PPG) is a non-invasive technique that measures relative blood volume changes in the blood vessels close to the skin. This research work intends to design a real-time filtering system. There are two main parts in this heart rate detection system: the data-gathering portion and real-time processing. Both processing includes preprocessing and filtering in which PPG signals derive from the pulse sensor in the data-gathering stage. It filters from PPG signal in real-time processing. In the data-gathering stage, the PPG signal is first derived from the pulse sensor, and then it is preprocessed to remove noise and enhance the signal quality to collect the paired-pulse index (PPI). After the signal has been preprocessed, the PPI is extracted from the signal, and this signal with features is collected as a data point to give an input signal for Raspberry Pi to draw the heat rate plot. In this system implementation, the pulse sensor is used to detect the heart-beat information of blood stream. This computer-aided system may also help patients save their time being spent waiting for doctors' decisions. Biomedical analysis, digital signal processing, image processing, and data analysis become important factors for the automatic diagnosis system.**

***Index Terms*—Biomedical circuit, biomedical signal processing, digital processing, finite impulse response filter, photoplethysmography (PPG)**

I. Introduction

Photoplethysmography (PPG) [1], [2] is an unpretentious and not expensive optical scheme that can be used to perceive the changes of blood volume in the tissue microvascular bed. It is often utilized non-invasively to make measurements at the skin surface. The PPG waveform comprises a pulsatile physiological waveform attributed to cardiac synchronous changes in the blood volume with each heart-beat and is superimposed on a slowly varying baseline with several lower frequency components recognized to respiration, sympathetic nervous system activity, and thermoregulation. Although the PPG signal components' origins are not fully implicit, it is generally established that they can provide cherished information about the cardiovascular system.

PPG analysis emphasizes the importance of early evaluation of the diseases. The technology of PPG has been applied in a wide range of commercially available medical devices to measure oxygen saturation, blood pressure, and cardiac output, assess autonomic function and detect exterior vascular disease. The exploratory sections describe the straightforward norm of operation and interaction of light with tissue, early and recent history of PPG, instrumentation, measurement protocol, and pulse wave analysis.

It is a technique for detecting blood volumetric changes from skin perfusion. The principle depends on the fact that the blood and surrounding tissues have different absorption ability to light emitted by the light emitting diode (LED). The reflected or transmitted light will be received by a Photo-Diode (photodetector), and the difference between the emitted and received light is related to the blood volume. That changes will generate small voltage signals proportional to the relative amount of blood existed in that region and time, and a PPG signal is then generated. Two different kinds of measuring systems are generally applied to record the PPG signal, namely, reflection mode and transmission. The transmission mode system is applied to perfuse tissues between the source and the detector, e.g., detecting the PPG by clipping on the fingertip or the earlobe. The reflection mode system has the emitter and the sensor on the same side and attached on the perfuse skin, e.g., forehead and the wrist. It is significant to monitor the perfusion of circulation. The utmost essential parameter for cardiopulmonary is blood pressure, but monitoring it is problematical. A second imperative parameter is blood flow, which is connected to blood pressure. The blood perfusion in large vessels can be monitored using ultrasound devices, but it is not practical to use them characteristically. More than a few devices for monitoring blood perfusion have been reported in [3], but inappropriately, it is challenging to find a real-world device. However, blood flow perfusion and blood pressure can be determined easily using a pulse rate monitor with an FIR filter. The photoplethysmography (PPG)-based wearable pulse rate sensors have become increasingly popular, with more than ten companies producing these sensors commercially. The principles behind PPG sensors are optical detection of blood volume

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changes in the microvascular bed tissue. The sensor scheme comprises of a light source and a detector, with small variations in the tissue blood perfusion and provides information on the cardiovascular system, particularly the pulse rate. Due to this device simplicity, wearable PPG pulse rate sensors have developed with Finite Impulse Response (FIR) filter and Short-Time Fourier Transform (STFT).

Light traveling through biological tissue can be absorbed by different substances, including pigments in the skin, bone, arterial, and venous blood—most changes in blood volume mainly in the arteries and arterioles. Arteries contain more blood volume during the systolic phase of the cardiac cycle than during the diastolic phase. PPG sensors optically detect changes in the blood flow volume of microvascular bed tissue via reflection from or transmission through the tissue. The Direct Current (DC) component of PPG waveform corresponds to the detected transmitted or reflected optical signals from the tissue and depends on the tissue structure and the average blood volume of arterial and venous blood. The DC components change slowly with respiration. The Alternating Current (AC) component shows changes in the blood volume between the systolic and diastolic phases of cardiac cycle. The fundamental frequency of AC component depends on the heart rate and is superimposed onto the DC component [4], [5].

The main process of the research is to design the FIR filter in the heart-beat detection system and reduce motion artifacts in a light-based measurement system. It consists of software and hardware implementation. The core target of this research work is to progress a FIR filter in the detection of the defective heart sound and reduce any background noise, thereby producing a perfect heart-beat signal for analyzing the heart failure, and to verify the ability of the filter in performing a better utility than the medical electrocardiogram (ECG or EKG) measuring device without any side effect on the people, is the aim of this work. The PPG signals are determined as impulse response ($h(n)$) of a specific system, where the decision is made based on the linear predictive coding coefficients of impulse response of a heart.

The rest of the paper is organized as follows. Section II presents the overall system. Section III mentions the implementation of the system with the design of the FIR filter for PPG. Section IV gives the results and discussions. Finally, section V concludes the research works.

II. Overall System

There are two main parts in this heart rate detection system: the data-gathering portion and real-time processing. Both processing includes preprocessing and filtering in which PPG signals are derived from the pulse sensor in the data-gathering stage. It is filtered from PPG signal in real-time processing. In the data-gathering stage, the PPG signal is first derived from the pulse sensor, and then it is preprocessed to remove noise and enhance the signal quality to collect the PPI index. After the signal has been preprocessed, the PPI index is extracted from the signal, and this signal with features is collected as a data point to give an input signal for Raspberry Pi to draw the heat rate plot. In this system implementation, the pulse sensor is used to detect the heart-beat information of blood stream. This pulse sensor adequate over a fingertip and utilizes the expanse of infrared light reflected by the blood circulating intimate to do just that. The sensor the aforementioned comprises of an infrared emitter and detector mounted side by side and pressed closely against the skin. The sensor has two sides; on the front side, the LED is positioned lengthways with an ambient light sensor, and on the back side, some circuitry have installed. This circuitry is in control for the work of amplification to and noise cancellation from the signals. The LED of the sensor is located over a vein over a human body. This can either be the fingertip or the ear tips, but it should be placed directly on top of a vein. When the heart pumps, blood pressure upsurges abruptly, and so does the amount of infrared light from the emitter that gets reflected in the detector. The detector passes more current when it receives more light, which causes a voltage drop to enter the amplifier circuitry. The light emitted from the LED, which fall on the vein unswervingly. The veins will be full of blood flow inside them only when the heart is pumping, so if the monitoring of the flow of blood, the monitoring of the heart-beats. If blood flow is detected, the ambient light sensor will pick up lighter since they will be reflected by the blood; this minor change in received light is analyzed over time to determine the heart-beats [6]-[10].

The pulse sensor is directly connected to the Arduino Uno analog part to convert the analog heart-beat information signal into digital form. The Raspberry Pi used as the main controller in this research work. The digitalized heart rate information signal is forwarded to the Raspberry Pi to perform the digital filtering process. The digitalized heart rate information is kept as comma separate value (csv) format in Raspberry Pi. The Raspberry Pi is read the csv file to filter the signal through the FIR filter. The Butterworth FIR filtering process is designed with MATLAB programming language and implemented with Python programming language in Raspberry Pi.

A PPG signal needs to be split into small segments (30 seconds ∼ 60 seconds), and preprocessing steps need to be done first by applying STFT. The STFT is used in the direction of extract the low-frequency components and high-frequency components from the cardiopulmonary. STFT is also used to convert the time domain signal into the frequency domain. Hence, the heart-beat signal is converted to the frequency domain, and then the frequency corresponding to the rate of the heart-beats is extracted by choosing the maximum amplitude between 0.8Hz and 3Hz. Fast Fourier Transform (FFT) is not efficient because the heart-beat changes over time; hence the heart rate variability (HRV) cannot be extracted. To track the heart rate (HR) overtime variation, the STFT is proposed. This technology is established on applying the Fourier transform over servings of the signal, explicitly windows, as an alternative of applying the Fourier transform over the whole signal. This allows analyzing the signal in time and frequency domain with a variable resolution according to the selected length of window. A short window results in high resolution in time, and poor resolution in frequency, while a large window results in poor resolution in time but the high resolution in frequency. Digital filter processing plays the main role in this system. The overall block diagram of the system is shown in Fig. 1.

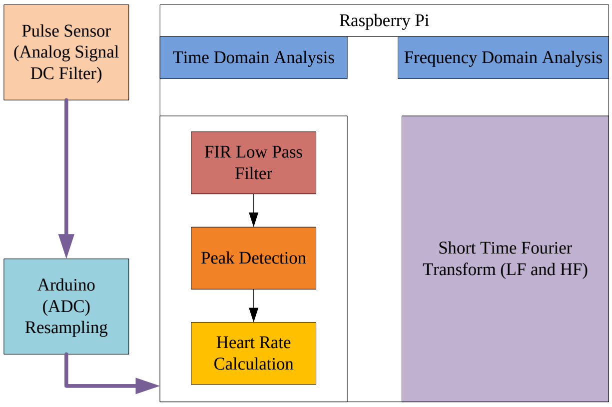

Fig. 1. Overall system block diagram

III. Implementation

A. Finite Impulse Response (FIR) Design

The desired frequency response specification $H_d(\omega)$ and corresponding unit sample response $h_d(n)$ are determined using the following relation.

$$h_d(n) = \frac{1}{2}\int_{-\pi}^{\pi} H_d(\omega)e^{j\omega n}d\omega \tag{1}$$

$$H_d(\omega) = \sum_{n=-\infty}^{\infty} h_d(n)e^{-j\omega n} \tag{2}$$

The impulse response $h_d(n)$ achieved from the directly above relation is infinite period, so it must be curtailed at some point, say $n=M-1$ to yield an FIR filter of length M (i.e., 0 to $M-1$). This truncation of $h_d(n)$ to length $M-1$ is the same as multiplying $h_d(n)$ by the rectangular window defined as

$$\omega(n) = \begin{cases} 1, & 0 \le n \le M-1 \\ 0, & \text{Otherwise} \end{cases} \tag{3}$$

Thus, the unit sample of the response of the FIR filter becomes

$$\begin{aligned} h(n) &= h_d(n)\omega(n) \\ h(n) &= h_d(n), 0 \le n \le M-1 \end{aligned} \tag{4}$$

Now, the multiplication of the window functions the window function $w(n)$ with $h_d(n)$ is equivalent to the convolution of $H_d(\omega)$with $W(\omega)$, where $W(\omega)$ is the frequency domain representation of the window function:

$$W(\omega) = \sum_{n=0}^{M-1} w(n)e^{-j\omega n} \tag{5}$$

Thus, the convolution of $H_d(\omega)$ with $W(\omega)$ yields the frequency response of the truncated FIR filter

$$H(\omega) = \frac{1}{2\pi}\int_{-\pi}^{\pi} H_d(v)W(\omega - v)d\omega \tag{6}$$

A filter is a device or system that removes unwanted components or features from a transmitted signal. This means removing some frequencies and no other to suppress interfering signals and reduce background noise. Filters are categorized according to the functions they perform in terms of ranges of frequencies. Preferably, a filter will not add new frequencies to the input signal, nor will it change that signal component frequencies, but it will change the various frequency components' relative amplitudes and/or phase relationships. In this research work, the Butterworth type is used to eliminate the PPG signal [10].

The Butterworth filter is a variety of signal processing filter designed to have a frequency response as flat as possible (no ripples) in the pass-band and zero roll-off response in the stop-band. Butterworth filters are one of the best ordinarily used digital filters in motion analysis and audio circuits. They are fast and simple to use. Since they are frequency-based, the effect of filtering can be easily understood and predicted. Choosing a cutoff frequency is easier than estimating the error involved in the spline methods' raw data. However, the main disadvantage of Butterworth filter is that it achieves this pass-band flatness at the expense of a wide transition band as the filter changes from the pass-band to the stop-band. It has poor phase characteristics as well. The ideal frequency response is referred to as a "brick wall" filter. The magnitude response of the Butterworth filter decreases with an increase in frequency. Butterworth filters have a wide transition band. Butterworth filters have a better time domain as output is more stable (no peaking) in time domain signal. The higher the Butterworth filter order, the higher the number of cascaded stages within the filter design, and the closer the filter becomes the ideal "brick wall" response.

However, this "ideal" frequency response is unattainable in practice as it produces excessive pass-band ripple. Where the generalized equation representing an "nth" order Butterworth filter, the frequency response is given as:

$$|H(j\omega)| = \frac{1}{\sqrt{1+\varepsilon^2\left(\omega/\omega_p\right)^{2n}}} \tag{7}$$

where n means the filter order, ω is equal to $2\pi f$, and ε is the maximum pass-band gain ($A_{\max}$). If $A_{\max}$ is specified at a frequency equal to the cutoff –3dB corner point (f_c), ε could be equal to one, and so ε^2 will also be one

$$H_1 = \frac{H_0}{\sqrt{1+\varepsilon^2}} \tag{8}$$

The heart-beat information signal is considered to be between 7Hz to 20Hz. So, the cutoff frequency of the system is determined as 20Hz. The continuous frequency response is calculated as an interpolation of the sampled frequency response. The sampling frequency of the system is about 100Hz. The frequency response for the design of low pass FIR filter with cut off frequency, f_c = 20Hz, f_s = 100Hz. The parameters specified for FIR filter in this studies are as follows. The peak pass band ripple (δ_1) is 0.05, the peak stop band ripple (δ_2) is 0.035, the normalized pass band frequency is 0.4π and the normalized stop band frequency is 0.5π. The order for Butterworth FIR filter (N) could be evaluated and the order was observed as 29.5106 and the filter order should be 30. The Kaiser window was utilized. Therefore, the specified parameters were used to design the Butterworth FIR filter in this study.

B. Short-Time Fourier Transform (STFT)

The STFT is a Fourier-related transform accustomed regulate the sinusoidal frequency and phase component of local portions of a signal as it fluctuations over time. In this research work, STFT is used to determine the low-frequency components and high-frequency components of PPG signal.

The spectral density analysis evaluates how the power (variance) is distributed as a function of frequency [3]. The frequency-domain analysis is delimited in three distinct frequency bands, spectral components, independently of the spectral density (Short Time Fourier Transform Techniques). These are:

- High frequency (HF) (0.15Hz to 0.40 Hz)
- Low frequency (LF) (0.04Hz to 0.15 Hz)
- Very low frequency (VLF) (0.01Hz to 0.04 Hz)

The STFT method is used to obtain an approximation of the spectral power of the HRV. In real-world situation, the route for computing STFTs is to divide a longer time signal into shorter fragments of equal length and then compute the Fourier transform disjointedly on each shorter fragment. This exposes the Fourier spectrum on each shorter fragment. One then usually customarily intrigues the changing spectra as a function of time. In the discrete-time case, the transformed data could be broken up into chunks of frames (which typically overlap each other, to condense artifacts at the borderline). Each large piece is Fourier transformed, and the complex outcome is added to a matrix, which archives magnitude and phase for each point in time and frequency. Fig. 2 demonstrates the function of STFT. This can be expressed as:

$$\mathrm{STFT}\left\{x[n]\right\}(m,\omega) = X(m,\omega) = \sum_{n=-\infty}^{\infty} x[n]\omega[\nu-\mu]e^{-j\omega n} \quad (9)$$

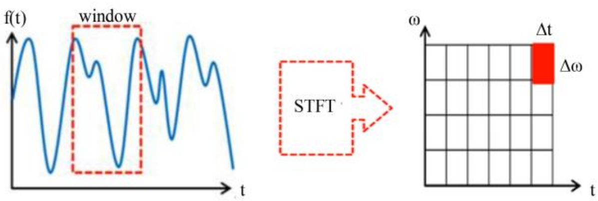

Fig. 2. Short time Fourier transform

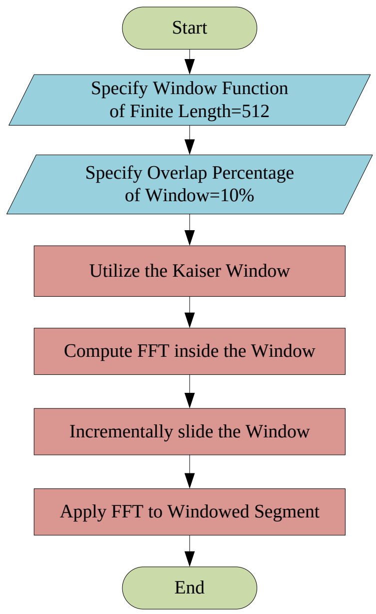

Fig. 3. Flowchart of STFT

Fig. 3 mentions the flowchart of STFT. The STFT design calculation is completed based on the flowchart of STFT. There are six steps to perform STFT algorithm. Step 1 is to choose a Window function of finite length. Step 2 is to place the window on top of the signal at t=0. Step 3 is to truncate the signal using this window. Step 4 is to compute the FT of the truncated signal, and save results. Step 5 is incrementally slide the window to the right and Step 6 is to go to step 3 again, until window reaches the end of the signal.

C. Heart Rate Measurement

Due to the strong influence of cardiac activity on pulsatile nature of arterial blood flow, HR measurements can readily be estimated based on the PPG signal. Individual pulse peaks can also be located by identifying local minima or maxima in the PPG signal. As shown in Fig. 4, each point in the signal is assessed concerning the surrounding points.

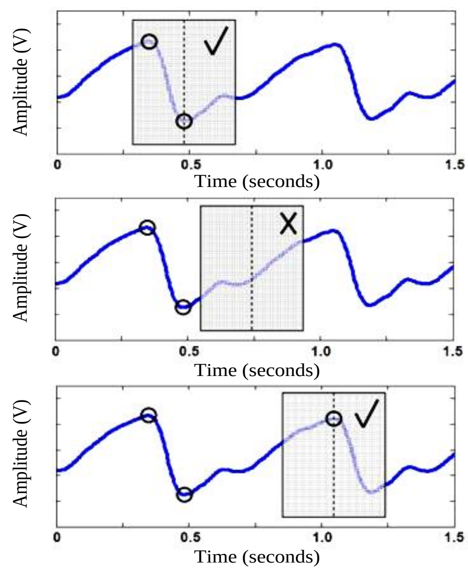

Fig. 4. Identifying local maxima and minima in a PPG using a window

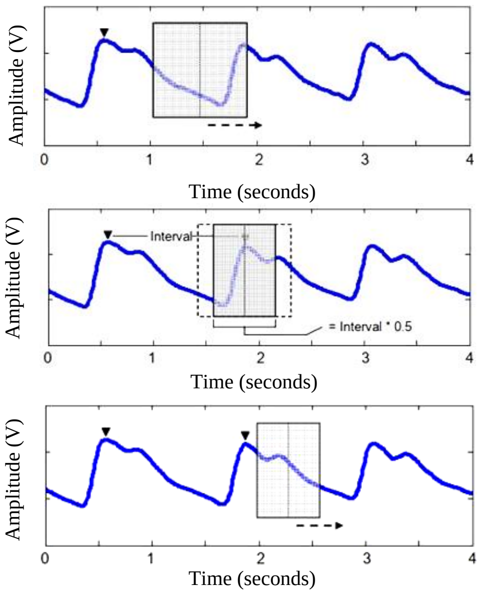

Fig. 5. Using an adaptive window to locate pulse peaks: (a) Searching for a peak, (b) adapting the window width after locating a peak, and (c) searching for next peak using the new window

If the center point is lower or higher than all surrounding points, a local minimum or maximum has been located, possibly indicating a pulse peak. The processing window width determines the peak detection sensitivity, with narrow windows detecting smaller, more subtle peaks that a wide window would overlook. The optimal window width is dependent upon the relative frequency of the peaks that are to be identified.

Curve fitting implementation is used to detect the peak point in each window. A window with a varying width was used to locate individual pulse peaks in the PPG signals. The window scanned a PPG signal by moving one data point at a time. After each move, the maximum value in the window was located. If the maximum value was in the window center, that data point was marked as a peak.

To account for variations in HR, the processing window width was adjusted every time a peak was located. The new window width was set to half the previous beat-to-beat interval length, as demonstrated in Fig. 5. This reduced the chances of a peak being overlooked while maintaining a reduced sensitivity to noise and signal irregularities. The number of identified peaks in each 60-second recording were counted and provided a measure of the average HR in beats-per-minute (BPM).

D. Heart Rate Estimation

The measurement calculation of the frequency domain is a minute trickier. The main reason is to transform the heart rate signal to the frequency domain (doing so would only return a strong frequency equal to BPM/60, the heart-beat expressed in Hz). The heart rate varies over time as the heart speeds up and slows down in response to the changing demands of body [8]-[10]. This variation is expressed in the changing distances between heart-beats over time. The distances between P-P peaks vary over time with their own frequency. To find the heart rate estimation, the following steps are required to perform:

- Create an evenly spaced timeline with the P-P intervals on it
- Interpolate the signal, which serves to both create an evenly spaced time series and increase the resolution
- Transform the signal to the frequency domain
- Integrate the area under the LF and HF portion of the spectrum.

Fig. 6 shows the PP intervals in PPG signal. Fig. 7 illustrates the Original and interpolated signal in PPG signal. The detection of peak portion in the original signal could be utilized based on interpolation technique in this scheme.

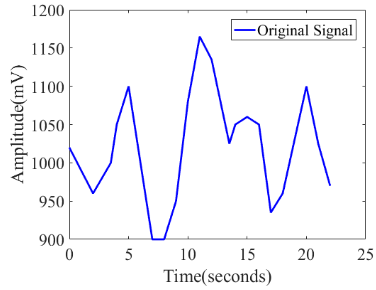

Fig. 6. PP intervals in PPG signal

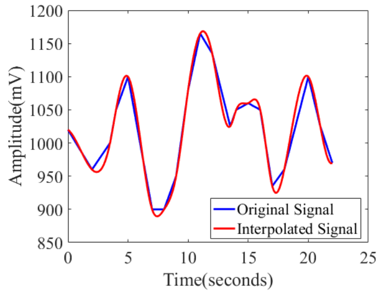

Fig. 7. Original and interpolated signal in PPG signal

E. Clipping Detection and Interpolation

Whenever a measured thing exceeds a sensor sensitivity range or digitalizes an analog signal, clipping can occur. In this case, Clipping means the peaks are flattened off because the signal continues outside the boundaries of the sensor used in this research work. Clipping functions by detecting (very nearly) flat portions of the signal near its maximum, come first and tailed by a steep angle on both ends. The "missing" signal peak is interpolated using a cubic spline, which considers 100ms of data on both ends of the signal clipping portion. Fig. 8 mentions the missing peaks in PPG signal.

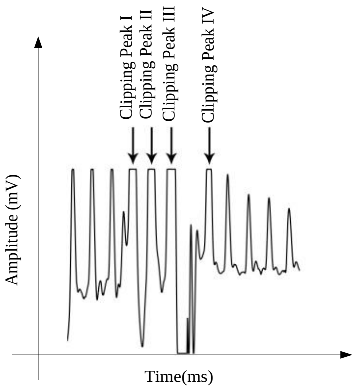

Fig. 8. Missing peaks in PPG signal.

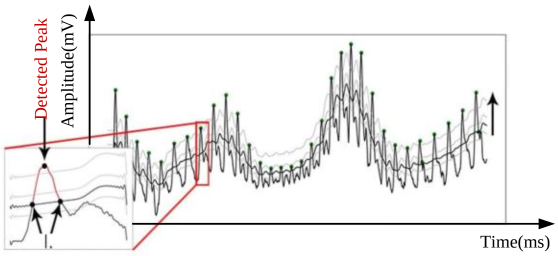

Fig. 9. Peak detection in PPG signal.

F. Peak Detection

The peak detection phase attempts to accommodate the PPG complexes' amplitude variation and morphology changes using an adaptive peak detection threshold, followed by several outlier detections and rejection steps. A moving average is evaluated using a window of 0.75 seconds on both sides of each data point to identify heart-beat. The start and end 0.75 seconds of the signal are inhabited with the mean of signal; no moving average is generated for these sections. Regions of interest (ROI) are marked between two points of intersection where the signal amplitude is larger than that of the signal of the moving average filter, as shown in Fig. 9, which is a standard way of detecting peaks. P-peaks are marked at the maximum of each ROI. During the peak detection phase, the algorithm adjusts the amplitude of the calculated threshold stepwise. The standard deviation between successive differences is minimized to find the best fit, and the signal BPM is checked. This represents a fast approximation of the optimal threshold by exploiting the relative regularity of heart rate signal. Fig. 9 demonstrates the peak detection in PPG signal.

IV. Experimental Results and Discussions

There are two types of PPG signal generation in a heart-beat detection system to give the system input. The sensor signal is used to detect the analog heart-beat information from the bloodstream, and the signal from the Arduino Uno is used to filter the unwanted noise for real-time heart rate detection.

A. Digitalizing the PPG Signal

The test and results of digitalizing PPG may conclude sampling, Analog-to-Digital Conversion, and send digitalized information via the serial port. Fig. 10 shows the digitalized PPG Signal from Serial Port. This step is done by using C programming and Arduino Uno. An analog-to-digital converter (ADC) is a useful feature that converts an analog voltage on a pin to a digital number. On the Arduino board, pins with the label "A" (A0 through A5) can be determined as an analog pin, and these pins can read the analog voltage from the pulse sensor. The ADC under the Arduino is a 10-bit ADC meaning it has the ability to detect 1,024 (2^{10}) discrete analog levels. Equation (10) could be used to check the discrete analog levels.

$$\frac{ADC_{RESOLUTION}}{V_{system}} = \frac{ADC_{READING}}{V_{ANA_{MEASURED}}} \quad (10)$$

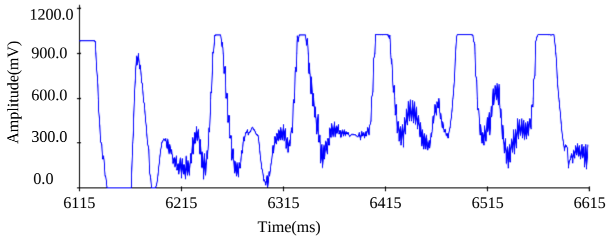

Fig. 10. Signal from serial port to digitalize PPG signal.

There are not many different ways to achieve this feat. Still, one of the best corporate practices utilizes the analog voltage to charge up an internal capacitor and then estimate the time it takes to discharge across an internal resistor. The Arduino microcontroller screens the number of clock cycles that permit in advance the capacitor is discharged. This number of cycles is the quantity that is returned once the ADC is complete. The ADC reports a radiometric value. This means that the ADC assumes 5V is 1023, and anything less than 5V will be a ratio between 5V and 1023.

The analogRead( ) function observes the value from the identified analog pin, and it returns the digital value ranging from 0 to 1023. The serial port is an interface for serial communication over and done with which information allocates in or out one bit at a specific time. The term "serial port" usually identifies hardware more or less compliant to the RS-232 standard. The serial print function is used to drive the data via the serial port. The digitalized PPG information signal is sent to the Raspberry Pi to perform the FIR filtering process. The Raspberry Pi converts the received digitalized PPG signal into .csv format to read from the Python script.

B. Developing Butterworth FIR filter in Raspberry Pi

FIR filter is a digital filter with a finite-duration impulse response. FIR filter can be implemented by using the python scientific library in Raspberry Pi. There are some scientific libraries like numpy, scipy and panda scientific library written in Python programming language. These libraries support filter implementation like moving average, convolution, windowing method, and curve-fitting method.

So the FIR filter implements with the support of these libraries in Raspberry Pi. Some step in implementing the Butterworth type FIR filter are as follow:

- Installing the numpy, scipy, matplot, panda, and math library
- Creating the environment for reading the .csv format
- Define the sampling frequency, order, and cutoff frequency
- Perform convolution and moving average in assigned window size
- Suppressing the frequencies beyond the specified cutoff range
- Save the results into the register to perform STFT.

The coefficient values of the impulse response are the major step for the FIR filter. FIR digital filter scheme consists of a pre-filter or anti-aliasing filter to filter an input signal by using a low pass filter. This is obligatory to restrict the bandwidth of a signal to fulfill the sampling theorem. Table I gives the unquantized Butterworth FIR filter coefficients by evaluation of FIR filter design. The resulting filter coefficients are symmetric. Fig. 11 shows the designed Butterworth FIR filter. In this design, there are 29 unit delay of z^{-1} in the developed filter design. The specific coefficients are given in Table I.

Fig. 12 presents the magnitude response of Butterworth FIR filter. According to the magnitude response of designed Butterworth FIR filter, the normalized pass band frequency values could be obtained at 0.4π and the normalized stop band frequency value could be achieved at 0.5π. There have been small amount of pass band ripple in the pass band region of the FIR filter design with 30 order. These coefficients as essentially unquantized was considered. The coefficients are quantized to 16 bits (15 fractional plus 1 sign bit) in this study.

TABLE I: UNQUANTIZED BUTTERWORTH FIR FILTER COEFFICIENTS

Order (k)	Filter Coefficient (b_k)	Order (k)	Filter Coefficient (b_k)
0	0.0066	30	0.0066
1	0.0164	29	0.0164
2	-0.0088	28	-0.0088
3	-0.0135	27	-0.0135
4	0.0026	26	0.0026
5	0.0222	25	0.0222
6	0.0040	24	0.0040
7	-0.0301	23	-0.0301
8	-0.0172	22	-0.0172
9	0.0378	21	0.0378
10	0.0412	20	0.0412
11	-0.0443	19	-0.0443
12	-0.0916	18	-0.0916
13	0.0486	17	0.0486
14	0.3133	16	0.3133
15	0.4499	15	0.4499

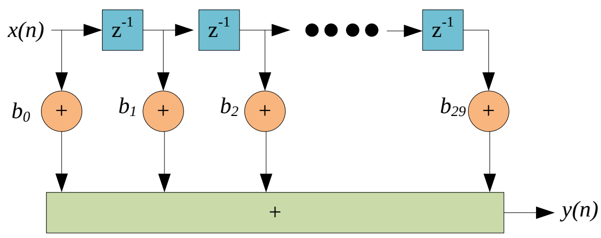

Fig. 11. Designed Butterworth FIR filter

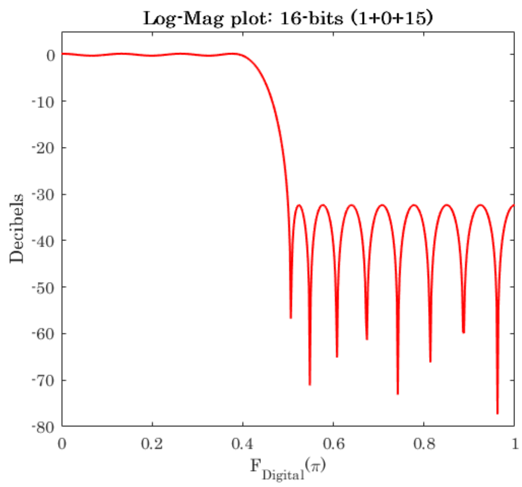

Fig. 12 Magnitude response of Butterworth FIR filter.

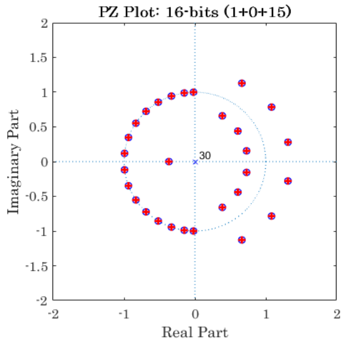

Fig. 13. Pole-zero response of Butterworth FIR filter.

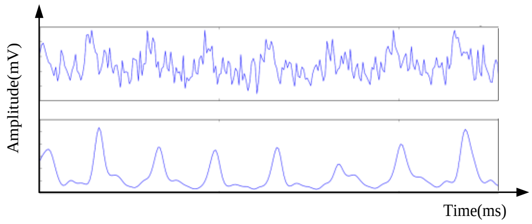

Fig. 14. Signal with unwanted noise and after FIR filtering process.

Fig. 13 illustrates the pole-zero response of Butterworth FIR filter. When 16 bits are utilized, the resulting filter is virtually indistinguishable from the original one. Nevertheless, when 8 bits are utilized, the filter performance is rigorously slanted and the filter does not fulfill the design specifications.

An interface is needed between the analog and the digital filter, and this interface is known as an analog-to-digital converter (ADC). After sampling and converting, a digital signal is ready for further processing using an appropriate digital signal processor.

The window method corresponds to the weight of the impulse response of a filter. The first preprocessing step added to the algorithm was a 30 order Butterworth low pass filter with a cutoff frequency of 20 Hz. The cutoff frequency value was chosen because the PPG signal ranges from 0.4 to 30Hz depending on the sensor accuracy, and the main part of its energy contained between 0.8 and 20 Hz. So, 20 Hz cutoff frequency is reasonable. By changing the cutoff frequency, the output of the filter may slightly reduce in amplitude. Fig. 14 shows the signal with unwanted noise and after FIR filtering process.

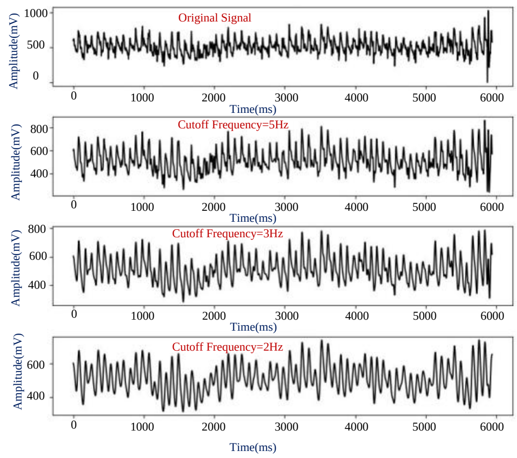

Fig. 15. PPG signal with different cutoff frequency

A signal of 2Hz, on the other hand, will only get through very weakly, if at all. Fig. 15 shows the amplitude changes due to the different cutoff frequencies. PPG signals contain a small amount of energy in the frequency range above the selected cutoff frequency of 20Hz. FIR filter is performed in the Time domain, and heart-beat information can be calculated using the FIR filter output information. Fig. 16 mentions the clean PPG signal after FIR filter.

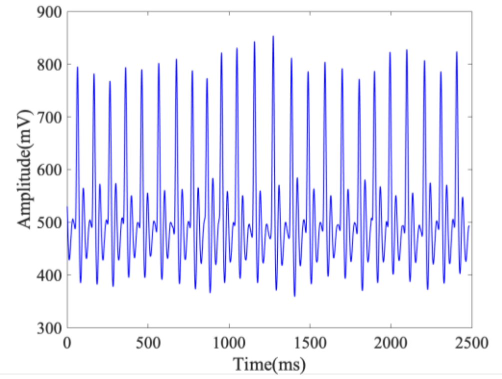

Fig. 16. Clean PPG signal after FIR filter

C. Detecting the First Peak in PPG signal

The first step is to observe the location of all the P-peaks. It needs to determine Regions of Interest (ROI) to find the P-peaks in the signal. After getting the P-peaks, it needs to regulate their maxima. There are a handful approaches to go about doing this:

- Fit a curve on the ROI data points, unravel for the maximum x-position;
- Check the slope between each set of points in ROI, find the set where the slope reverses;
- Mark data points within ROI, find the position of the highest point.

The first provides an exact mathematical solution but is also the most expensive computationally. With the help of .csv dataset, the difference does not matter, but it needs almost half a billion data points to get accurate results, and future datasets seemed only to get larger. High precision with these methods be sure of much more strongly on a high sampling rate than the curve fitting method. After all, the actual maximum of the curve will undoubtedly white lie somewhere between two data points more willingly than on an actual data point; with a higher sampling rate, this error margin will decrease.

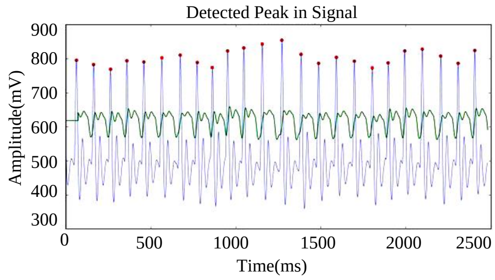

Fig. 17. Detected peak and moving average in PPG signal.

The curve fitting method is used to get a more accurate approximation of the P-peaks, and it also governs the position of the highest point in the ROI as the position of the beat. The amplitude of the less significant secondary peak can also alter independently of the amplitude of the P-peak. Fig. 17 shows the detection of peak and moving average on the clean PPG signal. One approach is to reduce the incorrect peaks by fitting moving average at different heights and determining which fit seems best.

D. Calculating the Heart Rate

The heart rate signal contains much information about the heart and breathing, short-term blood pressure regulation, body temperature regulation, and hormonal blood pressure regulation (long term). It has also (though not always consistently), and not surprisingly so since the brain is a very hungry organ, using up to 25% of total glucose and 20% of oxygen consumption. If its activity increases, the heart needs to work harder to keep it supplied.

The original idea of peak detection method comes from one adaptive threshold method for the peak detection of PPG waveform. Heart Rate can be calculated by finding the time interval between two consecutive P peaks in PPG output. Fig. 18 shows the PPI between two peak points in PPG signal. Then calculate the distance between the peaks, take the average and convert to a per-minute value.

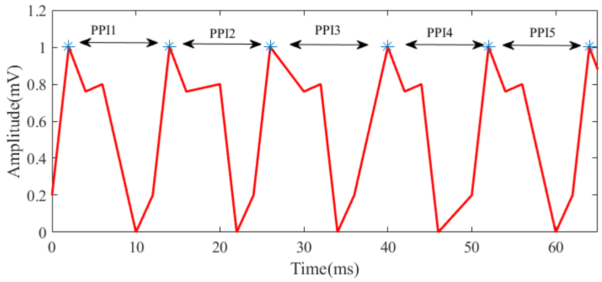

Fig. 18. PPI in PPG signal.

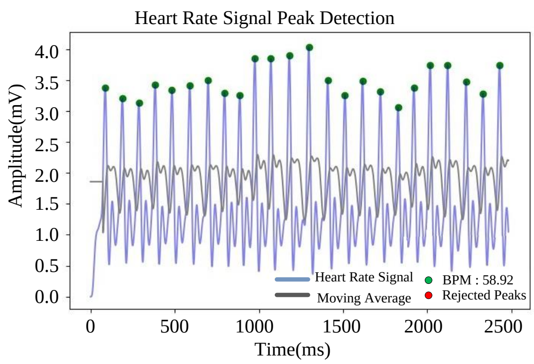

Fig. 19. Heart beat information in PPG signal.

Fig. 19 shows the heart beat-per-minute (BPM) information in PPG signal. The detected signals could be observed at beats-per-minute of 58.92. There is no rejected signal found in that results. The moving average filer could be rejected the unwanted signal from the original heart rate signal and the clear results could be obtained in this analysis.

E. Experimental Results

The experiment results of the heart rate detection system are illustrated in the following figures.

Experimental results show the output result from the Raspberry Pi and the input from the pulse sensor. Fig. 20 shows the output signal of the Arduino (with clip and artifacts).

Fig. 21 illustrates the results of digitalized PPG Signal. In this implementation, the pulse sensor is used to detect the heart-beat information from the blood. The pulse sensor is directly connected to the Arduino Uno analog part to convert the analog heart-beat information signal into digital form. The Raspberry Pi used as the main controller in this research work. The digitalized heart rate information signal is forwarded to the Raspberry Pi to perform the digital filtering process. The digitalized heart rate information is kept as comma separate value (csv) format in Raspberry Pi. The Raspberry Pi is read the csv file to filter the signal through the FIR filter.

The graph of digitalized PPG signal could be observed from the experimental results. Fig. 22 demonstrates the PPG signal with scaled threshold. The Short-Time Fourier Transform (STFT) is used to extract the low-frequency components and high-frequency components from the cardiopulmonary. The Butterworth FIR filtering process is designed with MATLAB programming language and implemented with Python programming language in Raspberry Pi. A PPG signal needs to be split into small segments, and preprocessing steps need to be done first by applying STFT.

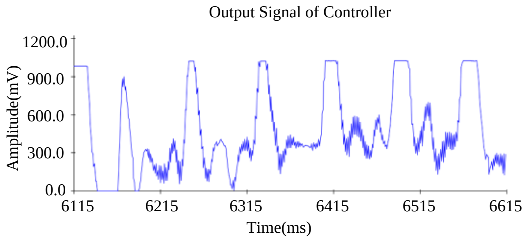

Fig. 20. Output signal of the Arduino (with clip and artifacts)

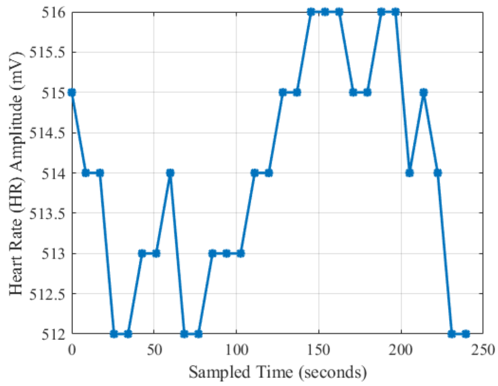

Fig. 21. Digitalized PPG signal

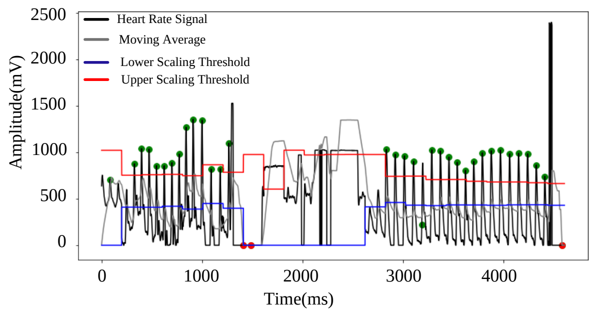

Fig. 22. PPG signal with scaled threshold

Fig. 23 mentions the detection of uncertain points in PPG signal. In this system, the Butterworth low pass FIR filter is used to eliminate the unwanted noise. The Raspberry Pi is the main controller, and the Python programming language is used to implement it. The Butterworth low pass filter removes high frequency, clipping, and motion artifacts. The STFT is used to identify the low and high-frequency components of the PPG signal. There is two analyses in this system, namely time domain analysis and frequency domain analysis. FIR filter is performed in the Time domain to perform the filtering process, and STFT is implemented in the Frequency domain to analyze the frequency components in the PPG signal.

Fig. 24 highlights the heart beat-per-min of 63.48 in PPG signal. The experimental results are the same as the simulation results of this model. From tests and results, this system can exactly detect all PPG signals in real-time. From the modification of the FIR filter, P peak detection becomes more accurate, and other PPG waves can be simply identified.

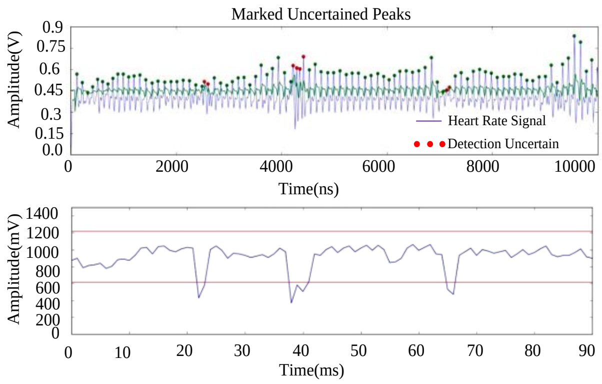

Fig. 23. Detection of uncertain points in PPG signal.

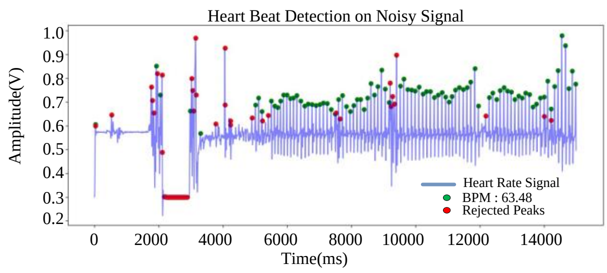

Fig. 24. Heart beat-per-min of 63.48 in PPG signal

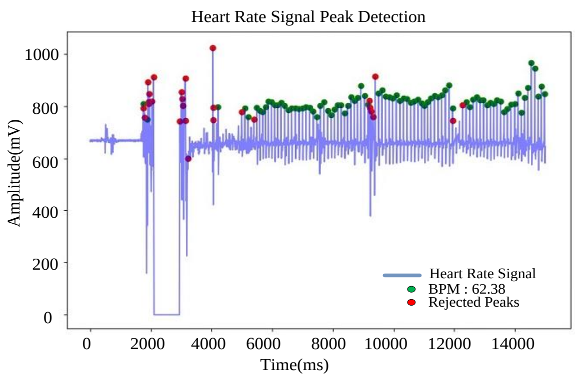

Fig. 25. Heart beat per min 62.38 in PPG signal

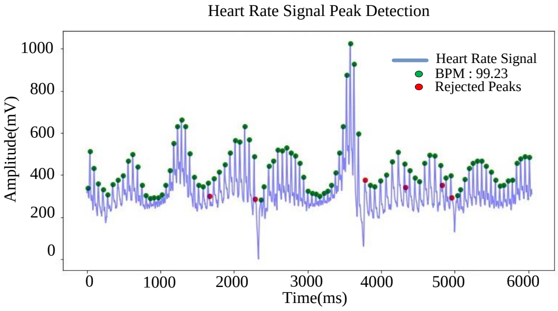

Fig. 26. Heart beat per min 99.23 in PPG signal

The observation of heart beat detection on noisy signal; with different amplitude level. The maximum detection level; is about 1.0V from the original signal. Fig. 25 gives the heart beat-per-min of 62.38 in PPG signal. According to the experimental results, the maximum detected peak level is over 1000 mV of the original heart beat signal. Therefore, this system can provide a less complicated heart rate measurement system.

Fig. 26 offers heart beat-per-min of 99.23 in PPG signal from the experimental tests. This results confirm that the developed filter could detect the unwanted signal over the original heat beat signal in experimental studies.

The measurement of performance accuracy of the developed system could be evaluated by using the following mathematical equation.

$$\text{Accuracy}_{\text{Overall Performance}} = \frac{R_{\text{Accepted}} - R_{\text{Observed}}}{R_{\text{Accepted}}} \times 100\% \quad (11)$$

where $\text{Accuracy}_{\text{Overall Performance}}$, R_{Accepted} and R_{Observed} are percent in overall performance accuracy, accepted value with noise-free signal and observed value with noise-free signal, respectively. From performance evaluation, it can be concluded that the FIR filter performance is approximately 80%, and the performance of the whole system is also approximately 85%.

The statistics table for performance comparison is given in Table II. According to this comparison with [1], the proposed system used 30 dataset which is more than that and the computational time is less than that system. Fig. 27 exports the developed hardware design. The main components of this studies are Arduino controller and Raspberry Pi. The hardware design was successfully constructed under the department laboratory.


Fig. 27. Developed hardware design

TABLE II: STATISTICS TABLE

No	Filtering techniques	Applied dataset	Computational time (in seconds)
1	Ref [1]	22	32.19
2	Proposed Method	30	15.5

V. LIMITATIONS AND RECOMMENDATION OF SYSTEM

The first limitation is that the PPG signal digitalized from pulse sensor is not absolutely the same as the original PPG signal. The digitization of PPG image as in original signal may help to have more accurate detection. The classification of the heart murmur and clicks needs exact feature extraction or neural network to determine the defect of the heart. From the test and results, wrong detection of PPG signal can cause when the PPG signal is very noisy and abnormal. This is the final limitation of this system.

There are some recommendations for developed system in this research. Firstly, the system shall be designed to be able to classify all heart conditions with feature extraction. Secondly, the algorithm shall be modified to be adjustable even when the PPG signal is too much noise affected. Finally, the sensor section shall be designed with accurate operational amplifier.

VI. CONCLUSION

The FIR filter performance is determined by the accuracy of the estimated instantaneous heart rate, and the appropriate value of the filter coefficient depends on the accuracy of the PPG signal. The estimated heart rate performance is compared with that of the PPG signal, where both the time domain and frequency domain parameters are extracted and evaluated. The evaluated results showed that all other parameters are good enough, except time-domain parameters compared to that calculated from the PPG signal. It should also be noticed that PPI and estimated heart rate give similar to the standard deviation of normal to normal RR intervals (SDNN) while that of the PPI is different, making SDNN a less reliable parameter to compare the performance of PPI. The digital filters are digital systems with linear time invariant, used to modify the distribution of frequency components of signal according to given specification. Method of digital filter used is based on the modification of the PPG signal, heart sounds (S_1 and S_2) are considered low frequency. Murmurs and clicks are considered as high frequencies. But even though FIR filer has some restriction in classification of the heart sound signal, the performance accuracy of the proposed system is 85% and it is higher than other system with less computational time of 15.5 seconds.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Hla Myo Tun initiated the study and prepared the review conception/design; he prepared the literature and wrote the manuscript; revised the manuscript critically before submission; he revised the manuscript according to reviewers' comments and prepared it for final submission; the author had approved the final version to be published.

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