Digital IIR Filters For Heart Rate Variability; A Comparison Between Butterworth And Elliptic Filters

Jeom Keun Kim, Jae Mok Ahn

Abstract: Digital infinite impulse response (IIR) filters have been used for heart rate variability (HRV) studies to improve the measurement of normal-to-normal (NN) intervals between two successive heartbeats. HRV is a noninvasive measure for identifying the activity of the autonomic nervous system (ANS) when HRV parameter changes in various environments are evaluated. The accuracy of HRV measures for short-term recordings relies on robust digital IIR filters such as analog models which can obtain NN interval series sufficiently enough to reflect physiological signals. To date, HRV datasets obtained by the implementation of digital IIR filter types have not been compared or analyzed. The purpose of the present study was to investigate the effects of two different digital IIR bandpass filters (BPF) on HRV parameters: Butterworth BPF and Elliptic BPF. There were larger fluctuations in the tachogram for the Elliptic BPF than in that for the Butterworth BPF, but there was no significant difference between the two tachograms overall, which had a correlation coefficient r of 0.8164 with a significance level of p<0.001 (n=326). However, for the comparison between each parameter, major time domain parameters such as the SDNN, RMSSD, and pNN50 demonstrated small differences, but the frequency domain parameters, except for Ln HF, showed no significant differences between the two methods. The results suggest that compared with the Butterworth BPF, the Elliptic BPF with large fluctuations in response to physiological conditions yield more information, and the Butterworth BPF has better performance in determining the NN interval time series, as it is robust to movements during photoplethysmogram (PPG)-based measurements.

Index Terms: Autonomic nervous system, heart rate variability, infinite impulse response, tachogram, Butterworth, Elliptic.

1. INTRODUCTION

Heart rate variability (HRV) is a good measure of the activity of the autonomic nervous system (ANS), which can be used to evaluate a balance in activity of sympathetic and parasympathetic systems and cardiovascular diseases [1, 2, 3, 4]. HRV, in particular, is simply a measure that quantifies the amount of variation in the NN intervals in response to external stimuli produced in one’s heartbeats in short-term HRV recordings [5]. This variation is mostly controlled by the ANS, which comprises parasympathetic and sympathetic nerve branches. However, greatest hindrance to the proper extraction of HRV parameters for the evaluation of ANS activity is that HRV datasets are obtained by an optical technology, which measures HRV based on the intensity of light transmitted through a bed of tissue illuminated by a light source, which has large fluctuations due to various types of movement. Small movement can result in motion artifacts that corrupt the accuracy of the data. Both motion artifacts and respiration cycles can lead to highly inaccurate HRV interpretations, and thus, it is important to implement advanced signal processing methods after or when NN interval time series are obtained by photoplethysmogram (PPG) based measurements [6, 7, 8]. A PPG is a measure of the changes in blood volume over time in a peripheral blood vessel in the index finger [9]. HRV parameters in short-term recordings that are affected by motion artifacts and the respiration rate are distorted in the frequency domain and overlap with the frequency components of very low frequencies (VLF, 0.0033-0.04 Hz), low frequencies (LF, 0.04-0.15 Hz), and high frequencies (HF, 0.15-0.4 Hz) [10]. Therefore, traditional filtering methods including analog and digital filters may not work well unless their characteristics are thoroughly determined according to the specific applications. To identify possible solutions to improve a method of acquiring NN intervals in PPG signals with noise, finite impulse response (FIR) and infinite impulse response (IIR) filters are used. FIR filters have some advantages, including linear phase characteristics that enable stability and easy implementation, but they also have some disadvantages, including a slow response time when a filter order higher than 20 is used to achieve a desired performance. Correspondingly, the delay with an FIR filter is much larger than that with an IIR that performs equally. Therefore, an IIR filter is recommended for the analysis of HRV parameters in the frequency domain and time domain because of its fast response time to PPG signal inputs. In this study, the Butterworth and Elliptic IIR filters were implemented to assess their feasibility in calculating HRV parameters. The order of the digital IIR filters was 2, and 26 HRV parameters were compared to determine the most suitable filter type for this purpose.

2 DIGITAL IIR FILTERS

2.1 IIR Filter Design

A recursive IIR digital filter is a linear time invariant system based on a difference equation, as shown in equation (1).

\[ y[n] = - \sum_{k=1}^{M} a[k] y[n-k] + \sum_{n=0}^{N} b[k] x[n - k] \]

The transfer function is defined by equation (2),

\[ H(z) = \frac{b_0 + b_1 z^{-1} + \ldots + b_M z^{-M}}{1 + a_1 z^{-1} + \ldots + a_M z^{-M}} \]

\[ H(z) = \frac{B(z)}{A(z)} \]

where

\[ B(z) = \sum_{n=0}^{M} b[n] z^{-n} \]

\[ A(z) = 1 + \sum_{n=0}^{M} a[n] z^{-n} \]

The design of an IIR filter is based on the analog prototype transfer function equivalent, which maps the s-plane poles and zeros of the analog filter into the z-plane using bilinear transformation. The bilinear z-transform is a mathematical transformation from the s-domain to the z-domain and is defined by equation (6),

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\[ s = \frac{2 - 1/z^{-1}}{1 + z^{-1}} , \text{ where } T = \text{ sampling period}. \quad (6) \]

In this study, two different IIR filters were used: the Butterworth and Elliptic bandpass filters (BPF). All coefficients for the two digital IIR BPFs were calculated using MATLAB (2014b; MathWorks Inc., Natick, MA, USA), and they are shown in Table 1. The details of the methodology are provided in our previous study [11].

### Table 1. IIR BPF coefficients for the Butterworth and Elliptic BPFs.

<table>
<thead>
<tr>
<th>([b] )</th>
<th>Numerator</th>
<th>([a] )</th>
<th>Denominator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Butterworth</td>
<td>Elliptic</td>
<td>Butterworth</td>
</tr>
<tr>
<td>b0</td>
<td>0.0033489</td>
<td>0.0034419</td>
<td>a0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4</td>
<td>1.00000000</td>
</tr>
<tr>
<td>b1</td>
<td>0.00000000</td>
<td>-</td>
<td>a1</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0.00037360</td>
<td></td>
</tr>
<tr>
<td>b2</td>
<td>0.0066978</td>
<td>-</td>
<td>a2</td>
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<td></td>
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<td>b3</td>
<td>0.00000000</td>
<td>-</td>
<td>a3</td>
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<td>0</td>
<td>0.00037360</td>
<td></td>
</tr>
<tr>
<td>b4</td>
<td>0.0033489</td>
<td>0.0034419</td>
<td>a4</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4</td>
<td>0.8761286</td>
</tr>
</tbody>
</table>

**2.2 Butterworth Bandpass Filter**

The Butterworth filter is one type of signal processing filter design. The Butterworth BPF has a frequency response that is as flat as mathematically possible in the passband. The Butterworth BPF was designed with the following specifications: a dB ripple in the passband (0 dB), dB attenuation in the stopband (80 dB), a passband frequency of 0.8 Hz and stopband frequency of 20 Hz. All coefficients of the Butterworth BPF are provided in Table 1. Fig. 1 shows the frequency and step responses of the Butterworth BPF. Based on the frequency response, a pole-zero plot was obtained. Fig. 2 (left) illustrates a pole-zero plot for the Butterworth BPF. The stability of the Butterworth BPF was confirmed, as all poles are inside the unit circle.

**2.3 Elliptic Bandpass Filter**

An Elliptic BPF also called a Cauer filter or a Zolotarev filter, is a signal processing filter well known for having faster transitions between the passband and stopband compared with the Butterworth BPF. However, the Elliptic BPF has a weakness, which is that the most nonlinear phase response occurs over its passband, but this issue can be solved by designing a filter with an order lower than those of other filters. The Elliptic BPF was designed with the same specifications as the Butterworth BPF except for the dB ripple in the passband (1 dB). Fig. 2 (right) presents the locations of a pole-zero to evaluate the stability within the unit circle on the z-plane. Fig. 3 shows the frequency and step responses of the Elliptic BPF.

**3 MEASUREMENTS**

A digital IIR filter algorithm used to implement the Butterworth BPF and the Elliptic BPF was embedded into a 16-bit microcontroller (MSP430F6638, Texas Instruments, Texas, USA). Two 5-minute HRV recordings were obtained simultaneously using two PPG devices; one was programmed by the Butterworth BPF and the other was programmed by the Elliptic BPF. This digital IIR filter algorithm was implemented into a commercial pulse analyzer with a finger-type sensor for a PPG, TAS9VIEW (CANOPY9 RSA, IEMBIO Co. Ltd., Chuncheon-si, South Korea). While the NN interval time series was measured, the participant was not allowed to move or talk. It was not important in this study to check the participant's
health status because the purpose of our study was to investigate the HRV parameters that can affect types of digital filters.

4 RESULTS
Fig. 4 shows the tachograms measured from the digital IIR filter implemented by the Butterworth and the Elliptic BPFs; one HRV dataset was derived by the Butterworth BPF (top), and the other HRV dataset was derived by the Elliptic BPF (bottom). The fluctuations in the tachogram from the Elliptic BPF were larger than those in the tachogram from the Butterworth BPF with the same maximum (74 bpm) and minimum (57 bpm) heart rate, as shown in Table 2. We investigated the degree of association between the two tachograms by statistical analysis. A correlation coefficient r of 0.8164 was calculated with a significance level of p<0.001 with a sample size of n=326. The result demonstrates that there is no significant difference between the two tachograms as a whole. A graphical comparison between two HRV datasets was conducted by a Youden plot (left) and a Box-and-Whisker plot (right) in Fig. 5. The Youden plot demonstrated that most data were located within the rectangle representing 2 SD on the x-axis and y-axis. In the Box-and-Whisker plot, the central box represents the values from the lower to the upper quartiles (25th to 75th percentile), and the middle line represents the median. A horizontal line could be drawn when two median lines extended from the Butterworth to the Elliptic BPF data. However, there were small differences between the two HRV datasets in terms of the SDNN, RMSSD, pNN50, and SD1. The SDNN values for the Butterworth and the Elliptic BPFs were 43.69 ms, and 50.04 ms, respectively, with a significance level of p=0.7192. The HRV parameters had larger differences in time domain than in the frequency domain. The pNN50 value was 8.28% for the Butterworth BPF, which was very different from that of the Elliptic BPF, which was 31.90%. However, Fig. 6 and Fig. 7 show that there were no significant differences between the HRV parameters calculated in the frequency domain. The red dot indicates that the Ln HF power on the y-axis and the Ln LF power on the x-axis were positioned at the same zone, meaning there was no significant difference between the two powers. The HRV parameters in the frequency domain, including Ln TP, Ln VLF, and Ln LF but not including Ln HF were very similar. The Ln HF values for the Butterworth and Elliptic BPFs were 4.77, and 5.20, respectively, and that of the Butterworth BPF was lower than that of the Elliptic BPF by 8.3%. A Poincare plot, a nonlinear method of calculating the correlation between two consecutive points, is displayed in Fig. 8. SD1 and SD2 of the Butterworth BPF (Elliptic BPF) obtained from the algorithm for calculation of the Poincare indices were 21.79 ms (36.19 ms) and 58.01 ms (61.04 ms), respectively. SD1 was approximately double that of SD2. For the logarithmic value of the area, Ln sArea, which were 8.29 ms² (Butterworth BPF) and 8.84 ms² (Elliptic BPF), there was no significant difference between two HRV datasets.

![Fig. 4. A tachogram measured using two different digital IIR filters; Butterworth BPF (top) and Elliptic BPF (bottom).](image)

### Table 2. All HRV parameters for two HRV datasets obtained by the Butterworth BPF and the Elliptic BPF.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Butterworth BPF</th>
<th>Elliptic BPF</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beat Cnt.</td>
<td>326</td>
<td>326</td>
<td></td>
</tr>
<tr>
<td>Mean HR</td>
<td>65</td>
<td>65</td>
<td>bpm</td>
</tr>
<tr>
<td>Mean NN</td>
<td>921</td>
<td>922</td>
<td>ms</td>
</tr>
<tr>
<td>Max. bpm</td>
<td>74</td>
<td>74</td>
<td>bpm</td>
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Fig. 5. A graphical comparison of a Youden plot (left) and a box-and-Whisker plot (right).

Fig. 6. Frequency domain parameters by the Butterworth BPF.

Fig. 7. Frequency domain parameters by the Elliptic BPF.

Fig. 8. A Poincare plot for Butterworth BPF (top) and Elliptic BPF (bottom).

5 CONCLUSION

The HRV parameters were separately analyzed for two 5-minute HRV datasets using two types of a digital IIR filter; Butterworth and Elliptic BPFs. Our findings indicate that the Elliptic BPF may not a useful method to measure the intervals between successive heartbeats for a traditional HRV analysis of both time domain HRV and nonlinear parameters. The Elliptic BPF showed a faster transition in the step response, which means a faster response to an input signal, than the Butterworth BPF, resulting in a high sensitivity to a PPG signal. However, for frequency domain HRV parameters, a digital IIR filter based on the Elliptic BPF method can help us obtain more information from the high fluctuations in tachogram, which are believed to exist in physiological signals. The SDNN, RMSSD, pNN50, SD1, and SDSD derived by the Butterworth BPF did not have the correlation properties similar to those derived by the Elliptic BPF. Specifically, for the tachogram derived by the Elliptic BPF, the presence of spikes in the NN interval series led to a small difference in the HRV parameters. Therefore, in the future, it is necessary to analyze the complete fluctuation function and consider the possible effect of spike fluctuations to determine the appropriate HRV parameters.

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REFERENCES


[5] V. Vesterinen, K. Hakkinen, T. Laine, E. Hynynen, J. Mikkola, A. Nummel, “Predictors of individual adaptation to high-volume or high-intensity endurance training in...


