Nonlinear Characteristics Analysis on 3-Channel Arterial Pulse Waveform for Fast Heart Rate Algorithm

BO YEON KIM  
Medical Research Center  
Seoul National University  
Yongun-dong, Chono-gu, Seoul  
KOREA

YUN SEOK CHANG  
Department of Computer Engineering  
Daejin University  
Sundan-dong, Pocheon  
KOREA

Abstract: - Arterial pulse waveform has useful information that can be adapted on finding fast heart rate algorithm through its nonlinear characteristics and the waveforms from multi channel can give faster and more accurate heart rate algorithm. In this work, we tried to find the relation between the arterial pulse waveform and heart rate through nonlinear characteristics analysis. We collected 3-channel arterial pulse waveforms as continuous signal inputs with our own arterial pulse inspector, analyzed the waveforms using nonlinear characteristics and tries to find the heart rate algorithm. Over 40 people’s arterial pulse data, we show that nonlinear characteristics in the 3-channel arterial pulse waveform can help to find the heart rate sufficiently and easily be used on the heart rate analyzer.

Key-Words: - Nonlinear Characteristics, Arterial Pulse, Pulse Waveform, Heart Rate, 3-channel, Return Map

1 Introduction

Arterial pulse signal is defined as an analog signal generated on the wrist artery by the continuous beating of a human’s heart and arterial pulse waveform is a series of the arterial pulse signals. The arterial pulse waveform is a very important in the medical area and can give us useful biomedical information such as heart rate, arrhythmia, patient’s blood pressure and other important medical factors such as EEG/EKG. In this reason, the arterial pulse signal has been applied on the medical electronic devices and signal analyses.

To get the accurate medical information from the arterial pulse waveform, pulse signal has to be detected and measured from human’s artery as carefully as we can. Most popular devices such as a tonometer catch pulse signals just for measuring blood pressure. Such kind of devices uses the single channel pulse signal for specific biomedical information and has no analysis for any other purpose. But these days, we need more delicate device capturing stable bio signals for multi-purpose qualitative and quantitative analysis and the nonlinear approach is another perspective way for biomedical information because the bio signal has kinds of nonlinear characteristics.

The nonlinear characteristics can be meaningful with signals for analysis as many as we can. So, single channel device should be modified into multi-channel signal capturing capability for analysis[1]. Therefore, bio signal device need at least three channel inputs on a signal waveform and arterial pulse waveform as well.

To get some useful nonlinear characteristics from the 3-channel arterial pulse waveform, we need very special type of computational algorithm to analyze the waveforms in quantitative way to get more accurate medical information such as heart rate. To satisfying the needs, we developed new arterial pulse inspector that can collect the continuous 3-channel arterial pulse waveform in digital and nonlinear analysis algorithm that can perform intensive waveform analysis such as spectrum analysis and nonlinear characteristics analysis including return map. In this work, we applied the arterial pulse waveform analysis on finding heart rate and showed the nonlinear characteristics of the arterial pulse waveform can give us a very useful fast heart rate algorithm.

The rest of this paper consists as follows; section 2 gives the basic requirements of the arterial pulse inspector hardware and nonlinear analysis algorithm for arterial pulse waveform in mathematical method. Section 3 shows system environment including arterial pulse inspector hardware and software implementation for signal capturing, signal converting and nonlinear analysis. Section 4 shows the experiments and analyses procedure for finding fast heart rate algorithm. The final section gives the conclusion and application areas that this work makes sense.
2 Methodologies

The nonlinear analysis algorithm for arterial pulse waveform has to be implemented into software package called arterial pulse analysis software and connected with the arterial pulse inspector hardware. The system architecture of the inspector mainly includes hardware component parts and firmware for hardware control. Arterial pulse analysis software includes the nonlinear analysis algorithm for nonlinear characteristics analysis with intensive mathematical computation, communication routine with the arterial pulse inspector and user interface program. The system requirements for arterial pulse inspector and nonlinear characteristics analysis algorithm of the arterial pulse analysis software details are as follows.

2.1 System Requirements

The arterial pulse inspector has to be designed to collect 3-channel arterial pulse signals simultaneously and convert them into the waveform in digital way and send them into the analysis software operating on the PC. To meet these conditions, the inspector requires several hardware components as follows:

- 3-channel sensor composed three piezoe elements located in consecutive positions.
- A/D converter for digital signal processing includes signal amplifying, band pass filtering and PCM digital quantizing.
- Over 8 bit Microprocessor and logics for controlling A/D converter, communication and air pressure unit with firmware.
- Wire and wireless digital data communication to send the arterial pulse waveforms to analysis software operating on the PC
- Mounting system for circuit and sensor unit such as hard case or sash.
- Air pressure supplier and air band for attaching 3-channel sensor on the wrist with uniform pressure.
- Firmware for microprocessor and A/D converter control.

2.2 Nonlinear Analysis Algorithm

Arterial pulse analysis software performs the spectrum analysis and mutual comparison among the waveforms based on the nonlinear characteristics analysis. In this work, the analysis algorithm includes the spectrum analysis routine and nonlinear characteristic analysis routine. All waveforms are parcelled into same length and generate power spectrum density, fractal dimension, return map, central tendency for each channel. Fractal dimension method was used to measure the degree of self-similarity of raster signal as shown Equation 1 [2, 3, 4, 7].

\[
D = \lim_{{\varepsilon \to 0}} \frac{\ln M(\varepsilon)}{\ln(1/\varepsilon)}
\]  

Here, \( D \) means fractal dimension, \( M \) means the minimum number of boxes to cover the signal and \( \varepsilon \) represents the length of the two dimensional box.

Central tendency measured the second-order degree of concentration of signal’s variation. Equation 2 shows central tendency measuring equation and Fig. 1 shows the graphical representation of Equation 2.

\[
CT = \left( \sum_{n=1}^{t} \delta(d_{n}) \right) / (t - 2)
\]  

\[
\delta(d_{n}) = \begin{cases} 
1 & \text{if } [(X_{n+2} - X_{n+1})^2 + (X_{n+1} - X_{n})^2]^{1/2} < R \\
0 & \text{otherwise}
\end{cases}
\]

\( CT \) means the central tendency…, \( \delta(d_{n}) \) is the delta function, \( t \) is the number of points in the signal, \( X_{n} \) means the n-th value in the signal and \( R \) represents the radius of the circle in Fig. 1.

![Fig. 1 Central Tendency](image)

We performed the nonlinear characteristic analysis and the heart rate analysis simultaneously by using return map as follows:

i) Calculate the center of mass of return.
ii) Calculate the distance from the center of mass to each point.
iii) Finding peak sections that are points over the variance.
iv) Heart rate is the number of peak sections with maximum value.

3 Analysis Environments
3.1 3-channel Pulse Acquisition System

The arterial pulse inspector hardware has self calibrated triple piezzo elements for 3-channel signal capturing mounted on the air band, RS-232-C serial and RF wireless data communication module, LCD display for user interface, air pressure control unit and 8-bit microprocessor including 24-bit resolution A/D converter with firmware. Fig. 2 shows the functional block diagram of the arterial pulse inspector hardware.

![Functional Block Diagram of Arterial Pulse Inspector](image)

Fig. 3 Functional Block Diagram of Arterial Pulse Inspector

Three piezzo elements make 3-channel sensor unit aligned on the air band and air pressure control module applies air into the air band like a common tonometer. Fig. 3 shows the diagram of the 3-channel sensor module.

![Diagram of the 3-channel Sensor Module](image)

Fig. 3 Diagram of the 3-channel Sensor Module

Arterial pulse signals are collected from the 3-channel sensor in analog and transferred into the main module. The MPU in main module digitizes the analog signal into the arterial pulse waveforms through the built-in A/D converter and sends them to the arterial pulse analysis software working on the Windows XP through serial or wireless communication link. The MPU also amplifies the input signals and filters noises if it needs. It can manage the input signal from 20mV to 2.5V range and eliminate 60Hz and common electronic noises.

3.2 Arterial Pulse Analysis Software

The arterial pulse analysis software can shows the shapes of the 3-channel arterial pulse waveform, waveform conversion and the results of the nonlinear analysis directly in a multiple framed windows application on the PC screen. The software is implemented with the Visual C++ under Microsoft Visual .NET environment and gives a very simple and easy way to get the signal processing and numerical analyses through the Microsoft Windows XP GUI.

All analysis procedures are implemented the arterial pulse analysis software as a windows functional module. Each module executes its own function such as communication with arterial pulse wave inspector, signal management, spectrum and nonlinear analysis and software environment setting through the unified control menu.

![3-channel Arterial Pulse Waveforms Collected](image)

Fig. 4 3-channel Arterial Pulse Waveforms Collected

Fig. 4 shows an example of the 3-channel arterial pulse waveform transmitted from the arterial pulse inspector. It shows a kind of differential signal because the piezzo element has the differential characteristics for the pressure and generates voltage level in proportion to the difference between every two pressure gap. Therefore, the transmitted signal has to convert into the integral signal in proportion to the real pressure of the arterial pulse. Fig. 5 shows the converted integral arterial pulse waveform.
4. Experiments and Analysis Results

4.1 Experiment Environment
The arterial pulse analysis software can give various analysis results including spectrum analysis, nonlinear analysis. In this work, we tried to find the fast heart rate algorithm through the nonlinear characteristics analysis algorithm as a typical example. To make the fine analysis result, we collected and analyzed arterial pulse waveforms under the same configuration factors as shown on Table 1.

Over 40 volunteers are participated on this experiment. Total data account includes all 3-channel arterial pulse wave data collected through three sensors simultaneously. Each trials performed 1-day interval during 11 days per person. Every waveform is parceled into the same length for analysis.

Table 1 Configuration factors for the experiment. For each signal factor, only single values are selected for the identical collection of the arterial pulse wave signals.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Value(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/D resolution in MPU</td>
<td>24bits / data</td>
</tr>
<tr>
<td>Data rate</td>
<td>9600bps</td>
</tr>
<tr>
<td>Data accounts (per trial)</td>
<td>1,500 / channel</td>
</tr>
<tr>
<td>Trials per person</td>
<td>10</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>105Hz</td>
</tr>
</tbody>
</table>

4.2 Analysis Results
The arterial pulse analysis software gets all waveforms as input in turn. At the end of each experiment, the arterial pulse analysis software shows the analysis results on screen. Fig. 6 shows an example of the power density of arterial pulse waveform as a result of spectrum analysis [5]. The power density can show the main frequency of the signal and select the minor signal part for nonlinear analysis. Fig. 7 also shows the nonlinear characteristics analysis in 3-way: return map [6], fractal dimension and central tendency.

4.3 Finding Heart Rate by using Nonlinear Characteristics
Fig. 8 shows $t$-variant return maps. The $t$ value means the number of points in the signal and the return maps are used to have various shapes according to $t$ value. The return maps have little difference shapes among the waveforms at the same $t$-value. In this work, we tried to find the shape-invariant $t$ value by changing...
the $t$-value in sequence and finally got the $t$ value as 36 through programmed experimental trials.

\begin{center}
\includegraphics[width=0.4\textwidth]{Fig_8.png}
\end{center}

**Fig. 8 $t$-variant Return Map**

Fig. 9 shows the procedures to find the heart rate from the return map. First, find the return map with $t = 36$ ( ). From the return map, calculate the distance from the center of mass ( ) and get the distance graph for each channel ( ). Then we can check and find the peak section of the center of mass graph as heart rate ( ).

\begin{center}
\includegraphics[width=0.4\textwidth]{Fig_9.png}
\end{center}

**Fig. 9 Heart Rate from Return Map**

Once we found the $t$-variant return map that has little difference among the patients by adjusting the $t$ value, we can easily find the peak sections from the pulse waveform. These peak sections represent the exact heart rate characteristics what we want to find. On the 3-channel arterial pulse inspector, all these procedures can be processed very simple and easy way including arterial pulse waveform collection, spectrum analysis, nonlinear characteristics analysis, finding $t$-variant return map and heart rate determination. Therefore, we can use it as an alternative fast heart rate analysis algorithm works along with the nonlinear characteristics analysis at the same time.

\section{Conclusion}
In this work, we proposed new algorithm for finding fast heart rate algorithm using nonlinear characteristic analysis on the 3-channel arterial pulse waveforms, which can easily be used on the heart rate analyzer. The arterial pulse inspector we developed for this work collects 3-channel arterial pulse waveforms. The analysis software performs spectrum analysis and nonlinear characteristics analysis and shows the analysis result as a procedure of finding fast heart rate algorithm by simultaneous digital signal processing and nonlinear characteristics analyses.

The 3-channel arterial pulse waveform has three simultaneous channels of arterial pulses and can reflect the characteristics of the heart rate more detail than single channel waveform such as existing medical heart rate analyzer. The nonlinear characteristics analysis results show that we can easily find the return map which has little difference among the waveforms, can detect peak sections and can obtain heart rate with arterial pulse waveforms.

As a result of this work, the arterial pulse waveform analysis algorithm can help to make the fast and effective heart rate analyzing device and can be useful to determine biomedical information through the nonlinear characteristics of the multi channels bio signals.

\section*{Acknowledgement:}
This work is the result of research activities of Advanced Biometric Research Center (ABRC) and the international cooperative research program supported by KOSEF.

\begin{thebibliography}{99}


\bibitem{2} Gleik, J., Chaos: Making a New Science. Viking Penguin Inc. 1987
\end{thebibliography}


