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On the Chaotic Nature of Biological Signals Using Nonlinear Data Analysis Methodology

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***Abstract*- In this study, we analyze the characteristic of biological signals using nonlinear data analysis methodology. Biological signals are not linear so to get a more accurate portrait of nonlinear signals, we must analyze them with nonlinear analysis methods. The nonlinear analysis method is emerging as relatively new and rapidly growing in biomedical field. One of the most useful techniques in nonlinear data analysis is the concept of Lyapunov exponent. As we may know, Lyapunov exponent is often used to define whether a dynamical system is chaotic or not. If the system exhibits at least one positive Lyapunov exponent and is purely deterministic, then it is chaotic. In this work, we measure the finger pulse signal for twenty minutes in two different situations. Then, we analyze the finger pulse signal using nonlinear data analysis method. We extract and evaluate Lyapunov exponent parameters from the finger pulse signal. We finally find the positive value of Lyapunov exponent and confirm the existence of chaotic nature in biological systems.**

I. INTRODUCTION

The analysis of chaotic behavior in biological signals has attracted great interest in recent years due to its important demands for clinical and biomedical application. Biological signals can be defined as a collective electrical signal acquired from any organ in human body that represents a physical variable of interest. The example of biological signals are EEG signal which measures the electrical activity of a brain, EMG signal represents the electrical activity generated from muscle fibers and also finger pulse signal measures the blood flow in our body. Biological signals are decidedly nonlinear [1] and usually exhibit complex behavior with nonlinear dynamic properties. Regarding this matter, the nonlinear dynamic theory may be a better approach than conventional linear methods in characterizing the complex nature of biological signals. The study of nonlinear dynamic and chaos theory can give the opportunities to develop new approaches that are needed to understand and control the complex system in biology and medicine. The literature study on the application of the nonlinear dynamics theory to analyze physiological signals shows that nonlinear methods were used for analysis of heart rate, nerve activity, arterial pressure, EEG and respiratory signals [2, 3].

In this study, the finger pulse signal is measured for a certain time in different situations. In the beginning of experiment, the finger pulse is measured in relax condition while in the end of experiment, the finger pulse is measured in concentrate situation which the subject must solve some mathematical calculation. Then, the time series of this signal is evaluated and analyzed using nonlinear method. We also make a comparison with the traditional linear method in term of characterizing the complex nature of biological signals. We choose the Lyapunov Exponent technique as nonlinear analysis method and Fast Fourier Transform as linear method.

II. EXPERIMENTAL SETUP

The finger pulse signal is measured by using pulse oximetry. Pulse oximetry is a non-invasive method, which measures the arterial oxygen saturation (SaO_2) and allows monitoring of the oxygenating of a subject's hemoglobin. This method involves placing a sensor on a thin part of the subject's anatomy such as fingertip or earlobe. A light containing both red and infrared wavelengths is passed from one side to the other. These light waveforms are transmitted by a semiconductor light emitting diode and detected by a photo detector. Pulse oximetry determines SaO_2 by analyzing two wavelengths of light that are absorbed differently by specific hemoglobin structures in the blood. The relative absorption of these wavelengths reflects the ratio of oxygenated to total hemoglobin and this ratio is expressed as a percentage. A SaO_2 of 97% to 99% is considered normal for a healthy human adult [4].

In this study, the finger pulse signal of one healthy person is measured by using pulse oximetry for duration of twenty minutes. The pulse rate signal is first recorded for the subject under resting normal condition (relax). In second state, the pulse rate signal is measured with subject solving some mathematical calculation. This state requires subject to be in concentrate condition because it will involve the thinking process on how to solve that mathematical calculation. Then the data is digitally filtered and analyzed using linear and nonlinear analysis methods.

Fig. 1. Pulse oximetry

III. ANALYSIS METHODS

A. Fast Fourier Transform (FFT)

Fast Fourier Transform (FFT) is an efficient algorithm to compute the discrete Fourier transform and its inverse [5]. FFT has a great importance to wide variety of applications, from digital signal processing and solving partial differential equations to algorithms for quickly multiplying large integers. In biomedical engineering application, FFT are also widely used for biological signal processing especially EEG signals. PCs with FFT implemented already in EEG-data acquisition software were quickly accepted in clinical environment because FFT gives physicians what they have been using and fast computational time. The only weakness of FFT is that, this method is a linear method and it can only describe the spectral characteristic of biological signals. The linear method may be not appropriate to model and analyze living systems or biological signals because the living systems itself are complex, nonlinear and operate far from equilibrium.

B. Lyapunov Exponent

The algorithm calculating Lyapunov Exponent λ from time series was originally proposed by Wolf et al [6]. Lyapunov Exponent provide a direct measure of the sensitive dependence on the initial conditions by quantifying the exponential rates at which neighboring orbits on an attractor diverge as the system evolves in time. The existence of a positive value of exponent for almost all initial conditions in a bounded dynamical system is used to define the deterministic chaos. To discriminate between chaotic dynamics and periodic signals, Lyapunov exponent is often used. It is a measure of the rate at which the trajectories separate one from other. Lyapunoc exponent can characterize the average rate of divergence of these neighboring trajectories. A negative exponent implies that the orbits approach a common fixed point. A zero exponent means the orbit are on a stable attractor and finally, a positive exponent implies that the orbits are on a chaotic attractor.

This algorithm proposed by Wolf is used to measure the Largest Lyapunov exponent from a time series. For given time series $x(t)$ for m dimensional phase space with delay coordinate t, a point on the attractor is given by

$$x(t),\ x(t+t),\ \ldots,\ x(t+(m-1)t) \qquad (1)$$

Then, the nearest neighbor must be located to initial point

$$x(t0),\ x(t0+t),\ \ldots,\ x(t0+(m-1)t) \qquad (2)$$

And denote the distance between these two points as $L(t0)$. At a later time $t1$, initial length will evolve to length $L_0(t1)$. In implementation of this program, the following set of numerical parameters has to be chosen:

$$P = (m,\ t,\ T,\ S_{max},\ S_{max},\ th_{max}) \qquad (3)$$

where m is the embedding dimension, t is time delay, T is an evaluation time and S_{max}, S_{min} are the maximum and minimum separations of replacement point respectively. Therefore, th_{max} is the maximum orientation error.

IV. SIMULATION RESULTS

Figure 2 shows the time series data of finger pulse signal for one healthy person. This data is measured for twenty minutes in two different situations. In the beginning of experiment, the finger pulse is measured in relax condition while in the end of experiment, the finger pulse is measured in concentrate condition where the subject must solve some mathematical calculation. Time series data for each relax and concentrate condition can be shown as in Figs. 3(a) and (b).

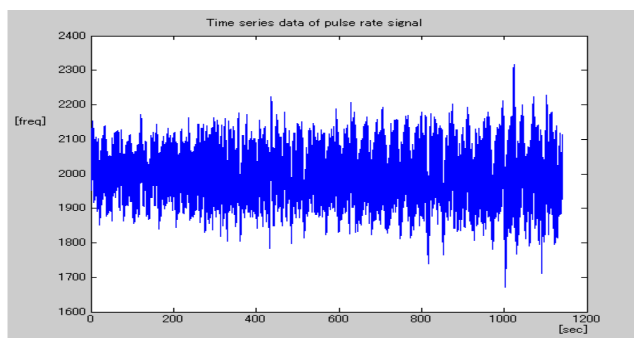
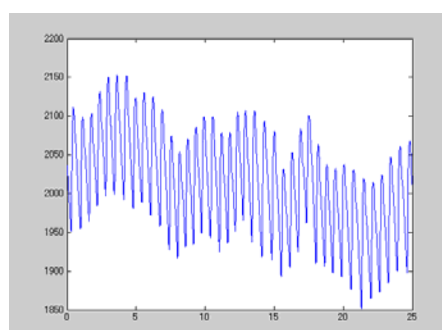
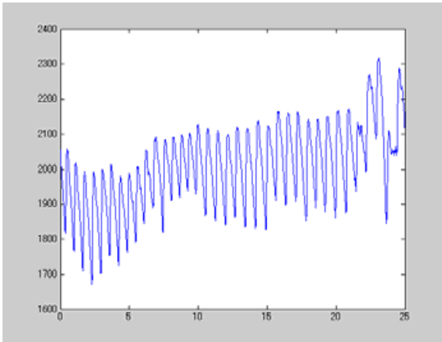


Fig. 2. Time series data of finger pulse signal for one healthy person (twenty minutes).



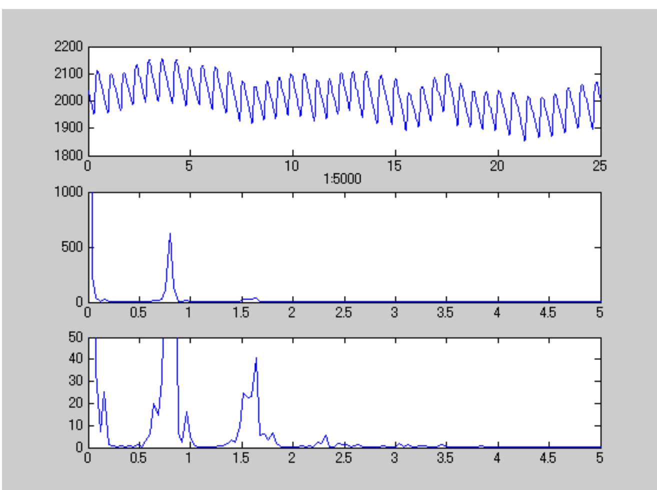
(a)



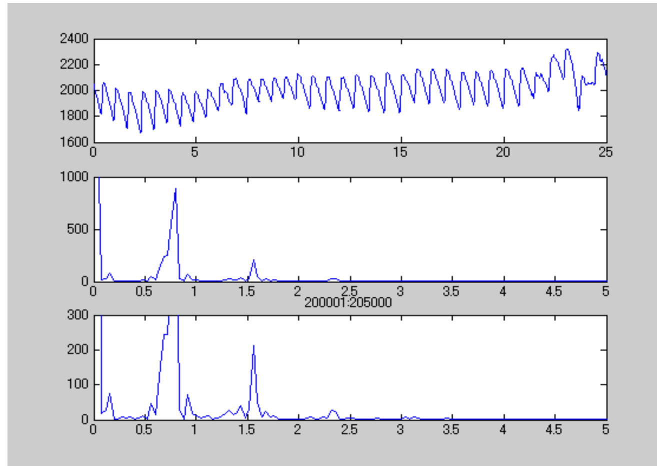
(b)

Fig. 3. Time series data of finger pulse signal. (a) Relax. (b) Concentrate.

After we measure the finger pulse signal, the time series data is filtered and analyzed using linear and nonlinear method. We make a comparison in terms of characterizing the biological signals by using these two different methods. We want to confirm which method is the most appropriate for analyzing and modeling the biological signals. Figure 4 and 5 show the analysis result for FFT method and Lyapunov Exponent method both for relax and concentrate condition respectively.



(a)

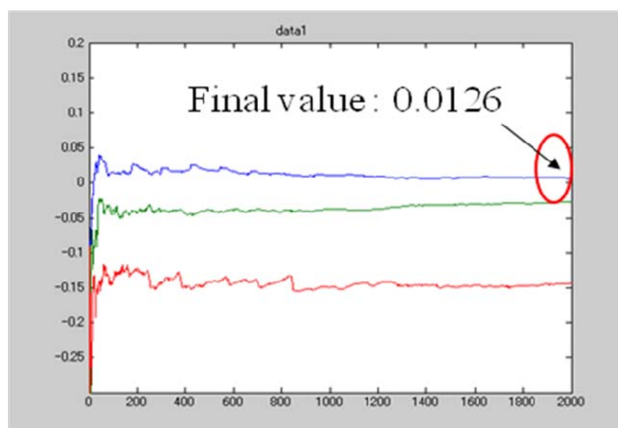


(b)

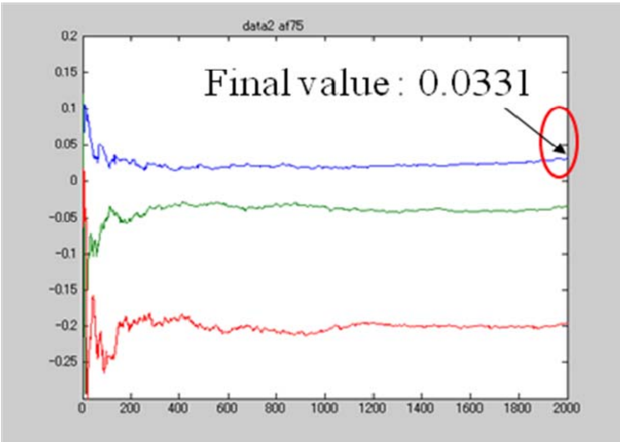
Fig. 4. The analysis result of finger pulse signal using FFT method. (a) Relax. (b) Concentrate.

We find that it is hard to extract the characteristic of finger pulse signal using FFT method. From these signals, according to Nyquist Theorem, one cannot recover Fourier components with frequencies higher that 35 – 40 Hz.

On the other hand, it is easy to find the different characteristic of two different conditions by using Lyapunov Exponent method. As we may know, Lyapunov Exponent is a nonlinear analysis method and widely used to define the deterministic chaos. If a positive λ value exists in a system, it can be said that the system is in a chaotic attractor.



(a)



(b)

Fig. 5. The analysis result of finger pulse signal using Lyapunov Exponent method. (a) Relax. (b) Concentrate.

Figure 5 (a) and (b) show the analysis result of Lyapunov Exponent method using Sunday Chaos Times software [7]. In this analysis, we have chosen an embedding dimension of 3 and the time delay of 1. Table 1 shows the final value of Lyapunov exponent for both relax and concentrate condition. From this table, we can conclude that we finally find the positive exponent of both situations, showing that the existence of chaotic behavior in biological signals. As we can understand from the Lyapunov Exponent theory, the larger the value of λ, the more chaotic the system will be. Hence, it is clear to say that the biological signal become less complex when the person is in relax (normal) condition. On the other hand, the biological signal become more chaotic if a person do difficult tasks such as solving mathematical calculation because it will require more complicated thinking process.

TABLE 1
FINAL VALUE OF LYAPUNOV EXPONENTS

Condition	Relax	Concentrate
Final λ value	0.0126	0.0229

V. CONCLUSIONS

In this study, we make a comparison between linear and nonlinear analysis method for characterizing the biological signals. We have extracted the nonlinear parameter from finger pulse signal and confirm the existence the chaotic nature in biological system by using Lyapunov Exponent method. We also observe that the chaotic nature of biological signals can be reduced if one person is in relaxing condition. From the analysis result, we can conclude that the nonlinear analysis approach is more suitable used in modeling the biological system due that the biological system is already nonlinear. But still nonlinear methods are used only in research and not in everyday clinical practice because these methods are still new in medical field. Moreover, the nonlinear analysis methods are costly and need more computational time compared with the traditional method.

These results show only a little information on the biological systems since it is the first step for developing nonlinear analysis methods. In the future, we will make a further analysis method of other biological signals. We would like to analyze the changes in EEG activity due to different mental physiological state.

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