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Human photoplethysmogram: new insight into chaotic characteristics

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ABSTRACT

The photoplethysmogram is widely used in medical settings and sports equipment to measure biological signals. The photoplethysmogram, which is measured noninvasively, can provide valuable information about cardiovascular system performance. The present study sought to investigate the underlying dynamics of photoplethysmographic signals from healthy young human subjects. In previous studies the photoplethysmogram was claimed to be driven by deterministic chaos [Tsuda 1992, Sumida 2000]; however, the methods applied for chaos detection were noise sensitive and inconclusive. Therefore, to reach a consistent conclusion it is important to employ additional nonlinear time series analysis tools that can test different features of the signal's underlying dynamics. In this paper, methods of nonlinear time series analysis, including time delay embedding, largest Lyapunov exponent, deterministic nonlinear prediction, Poincaré section, the Wayland test and method of surrogate data were applied to photoplethysmogram time series to identify the unique characteristics of the photoplethysmogram as a dynamical system. Results demonstrated that photoplethysmogram dynamics is consistent with the definition of chaotic movement, and its chaotic properties showed some similarity to Rossler's single band chaos with induced dynamical noise. Additionally it was found that deterministic nonlinear prediction, Poincaré section and the Wayland test can reveal important characteristics of photoplethysmographic signals that will be important tools for theoretical and applied studies on the photoplethysmogram.

1. Introduction

Physiological signals derived from the cardiovascular system show an extreme intricacy that arises from the interaction of many processes, structure units and feedback loops in humans. Attempts to improve our understanding of physiological complexity and develop new tools for promising applications for human mental and physical health monitoring have made physiological signals such as electrocardiogram (ECG), electro-encephalogram (EEG), blood pressure, heart rate variability (HRV) and photoplethysmograph (PPG) the subject of recent studies [1–9]. Due to an increase in the successful use of nonlinear time series analysis (NTSA) methods in many scientific disciplines to quantify the complexity of signals [4,9], methods of nonlinear dynamics analysis have become a new and powerful tool for physiological signal investigation. NTSA allows one not only to quantify, but to qualify data.

Many studies have investigated ECG, EEG and HRV signals obtained from healthy human subjects, as well as from

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patients with mental or heart illnesses [1,3–9]. In early studies PPG as well as ECG and HRV were claimed to be chaotic mostly based on results of time-delay reconstructed trajectory, correlation dimension and largest Lyapunov exponent. Later, with the development of methods of nonlinear time series analysis for real world data, evidence for the chaotic nature of many biological signals was questioned [8,9]. Many tools that were previously thought to provide explicit evidence of chaotic motion were discovered to be noise sensitive and could produce misleading results. Thus it is still quite controversial whether these signals' dynamics involve chaotic motion or not [8,9]. Signals like HRV and ECG that were believed to be driven by deterministic chaos have been subjected to detailed reinvestigation [8,9]. Similarly PPG signal was claimed to be chaotic in the early 90s, however nowadays past evidence of chaos was found to be necessary rather than sufficient, especially in biological studies [8,9]. Therefore it is also still not known whether the PPG signal, which is commonly measured by commercially available medical and sport equipment devices to obtain HRV data, oxygen saturation and blood pressure, is chaotic or not. In addition, many of its characteristics are not yet well studied.

The microcirculation of the skin is rather complex dynamic system which is important for skin metabolism and temperature regulation and plays an important role in an organism's defense system. As the skin surface is directly accessible, it has become a valuable organ for many studies. Photoplethysmography (PPG) is one of the widely-used techniques that allows registration of pulsatile changes in the dermal vasculature [10,11].

Photoplethysmography is a simple and low-cost optical technique that can be used to detect blood volume changes in the microvascular bed of tissue. The PPG wave form 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 various lower frequency components attributed to respiration, sympathetic nervous system activity and thermoregulation [10–12]. Even though pulsation in a finger's capillary vessels (i.e. PPG obtained from finger) in normal subjects was claimed to be chaotic [13,14], only classical methods such as time-delay reconstructed trajectory, power spectrum, correlation dimension (CD) and Lyapunov exponent (LE) and surrogation have been applied to characterize PPG time series [5,13,14]. Positive Lyapunov exponent was believed to provide strong evidence of chaotic behavior. However, these tests (CD and LE) are inconclusive since as it was found in recent studies that they may indicate chaos even in systems that are not driven by chaos [9,15]. Therefore, a clear answer regarding the nature of the PPG signal dynamics cannot be obtained by only applying these types of classical measurements, although they may provide useful results for medical applications.

In this study we applied the time delay embedding method, calculated the power spectrum, largest Lyapunov exponent (LLE), deterministic nonlinear prediction's (DNP) correlation coefficient (CC) and relative route mean square error (RRMSE), Poincaré section, Wayland test translation error and applied method of surrogate data to investigate whether

a strange attractor and to study the chaotic motion characteristics of the PPG signal. This expanded toolkit is designed to cover most of the important characteristics of chaotic motion and is expected to help us investigate a wider range of PPG signal characteristics, compared with previous studies, and thus to extract its underlying properties. Additionally, in an effort to analyze the PPG signal not only quantitatively, but qualitatively we conducted a comparative analysis of PPG signal and Rosser's single band chaos.

2. Methods and materials

2.1. Photoplethysmography

PPG can be defined as the continuous recording of the light intensity scattered from a given source by the tissues and collected by a suitable photodetector [10]. Modern PPG sensors usually utilize low cost semiconductor technology with LED and matched photodetector devices working at the near infrared (NIR) wavelengths (NIR band 0.8–1 μm), which allows measurement of deep-tissue blood flow [11,12]. The light from the LED is absorbed by hemoglobin, and the backscattered radiation is then detected and recorded. The backscattered light depends on the amount of hemoglobin in the skin, and the obtained result therefore reflects the cutaneous blood flow [10,11].

The microcirculation of the skin is rather complex and dynamic system which is important for skin metabolism and temperature regulation and is an important part of the organism's defense system against invaders. The cutaneous blood supply is carried out into microcirculatory bed composed of three segments—arterioles, arterial and venous capillaries, and venules; most of this microvasculature is contained in the papillary dermis 1–2 μm below the epidermal surface [10–12]. PPG waveform reflects heartbeat synchronized cutaneous blood flow pulsatile changes in the dermal vasculature. The shape of the waveform is related to anacrotic and catacrotic phases. The anacrotic phase corresponds to the rising edge of the pulse, and the catacrotic phase to the falling edge of the pulse curve. The first one is primarily connected with contraction of the heart and therefore with the systolic phase of cardiac cycle, while the second corresponds to diastolic phase (Fig. 1) and wave reflection from the periphery. A dicrotic notch, connected with wave reflected from the periphery, usually can be seen in the catacrotic phase of subjects with healthy arteries [6,11].

The pulsatile component of the PPG waveform that relates to cardiac pulsation is usually called the 'AC' (alternative current) component and its fundamental frequency depends on the heart rate and typically varies around 1–1.4 Hz. The AC component is superimposed onto a large 'DC' (direct current) component that depends on the structure of the tissue and the average blood volume of both arterial and venous blood. The DC component varies slowly due to respiration, vasomotor activity, vasoconstrictor waves, thermoregulation and other slow circulatory changes [10–12].

Although the origins of the components of the PPG signal are not fully understood, it is generally accepted that PPG can provide valuable clinical information about the cardiovascu-

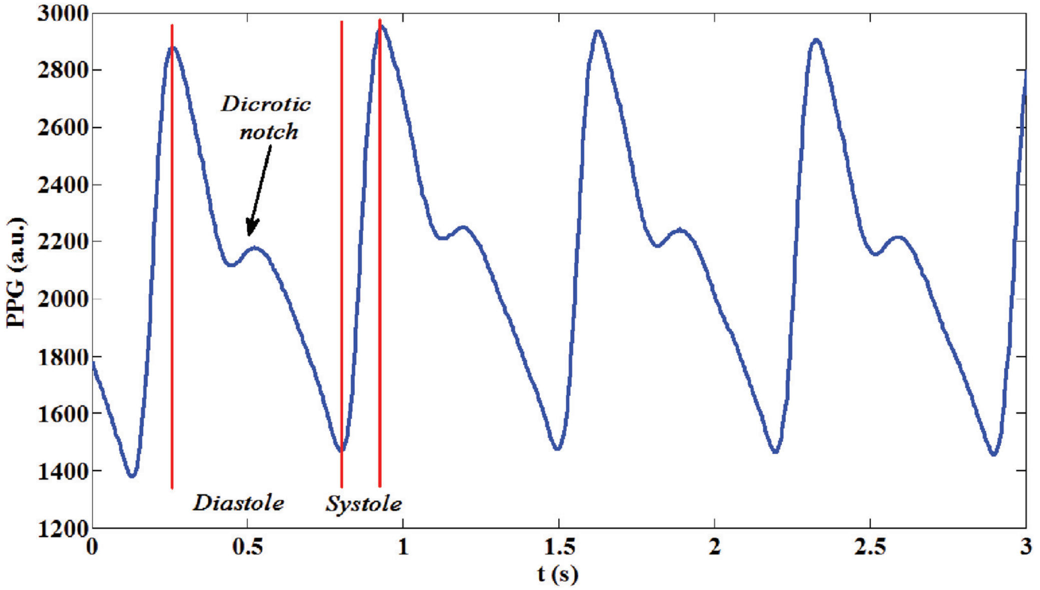

Fig. 1. Components of PPG signal waveform for healthy young subjects.

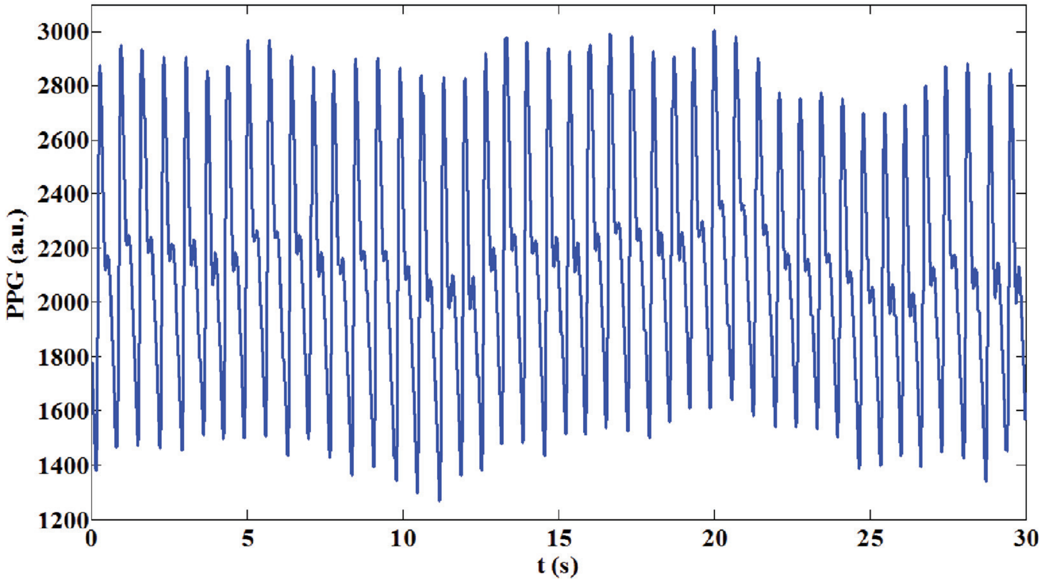

Fig. 2. Example of 30-second long portion of the healthy young subject PPG signal (9th subject's 2nd measurement).

2.2. Data collection

The PPG signal was recorded using a finger PPG recorder by detecting the near infrared light reflected by vascular tissue following illumination with a LED. Data were collected from nine healthy 19–27-year old volunteers among Tokyo University of Agriculture and Technology (TUAT) students. Experimental data collection was approved by TUAT authorities. Written informed consent was obtained from participants prior to the experiment. At the time of the study all subjects were healthy non-smokers, physically active to similar levels, were not taking any medication, and none declared a history of heart disease.

For each subject five measurement repeats were done. The measured period was 5 min with 5 ms sampling steps. For all data collection sessions, a BACS (Computer convenience, Inc.) transmission-mode PPG sensor was located on the right forefinger. Every measurement was preceded by a blood pressure check. Since physical and mental activity, as well as external effects such as temperature, noise etc. can considerably affect cutaneous blood flow [10,11] all measurements were done with the subject in a relaxed sitting position in a room

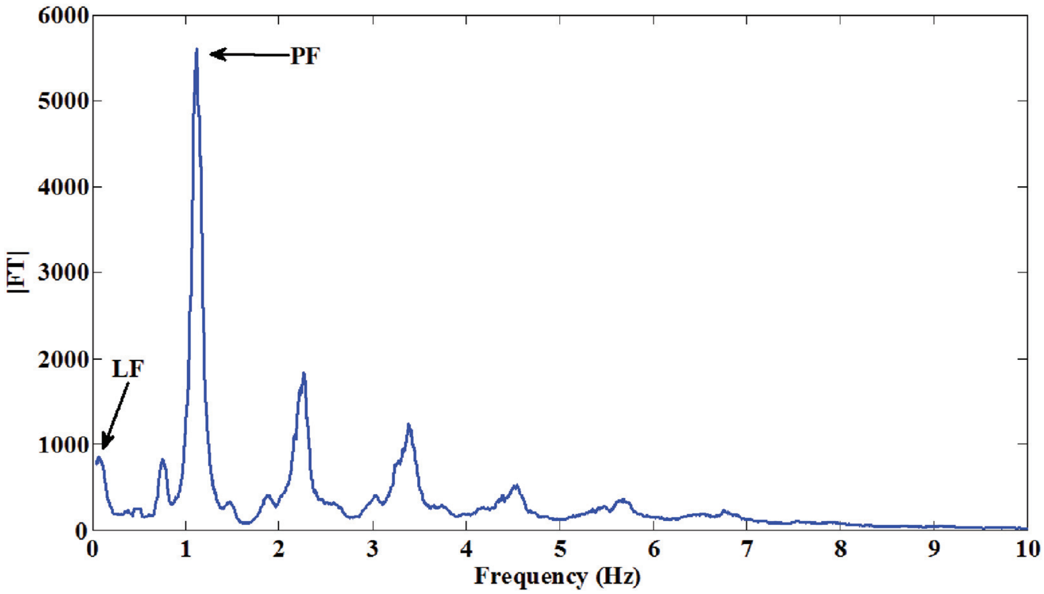

Fig. 3. Example of typical spectra obtained by Fourier analysis, where LF is low frequency and PF is predominant frequency component.

with temperature, noise and vibration control. Each test subject was asked to rest for 5 min under quiet conditions in the laboratory room in a sitting position in which the recordings were obtained, and with the test site uncovered. An example of a 30-second long portion of the obtained PPG signal is shown in Fig. 2.

3. Results

Various definitions of chaos can be found in the literature; Thompson et al. [20] provide quite broad, so called "positive" definition of chaos as "recurrent motion in simple systems or low-dimensional behavior that has some random aspects as well as certain order", which covers wide range of systems that produce chaos and yet have significantly different properties, as for example chaotic Lorenz and Rossler systems.

In this paper to analyze data sets obtained in the experiments described in Section 2.2 and to investigate whether the PPG signal is consistent with the above definition by Thompson et al. and study its chaotic characteristics in details, we applied a complex of nonlinear time series analysis tools. Orbital instability was tested with LLE, determinism with DNP, WTE, recurrence of motion with time-delay embedding and Poincaré section; additionally we applied phase randomized surrogation.

3.1. Spectral analysis

An example of typical plot of the Fourier spectrum in the studied time series is shown in Fig. 3. In Fig. 3, small fluctuations, which indicate environmental noise, can be distinguished around the predominant component (PF) whose period is approximately equal to the heart cycle period. Lower frequency (LF) components correspond to respiration and other effects, such as thermoregulation and nervous system activity. Table 1 shows values of amplitude and frequency corresponding to the predominant component obtained by Fourier transform. As seen from Table 1, all predominant frequencies (PF) are in the range 1.02–1.52 Hz, which is the range of normal heart beat frequencies.

Table 1
Amplitude (|FT|) and frequency (PF) of PPG predominant component obtained by Fourier analysis.

Subject	Repeat									
	1		2		3		4		5	
	|FT|	PF	|FT|	PF	|FT|	PF	|FT|	PF	|FT|	PF
1	5339.0	1.20	5608.5	1.12	5057.4	1.09	4185.4	1.04	1814.5	1.02
2	1877.5	1.24	2063.1	1.21	2906.8	1.21	2276.4	1.12	1839.4	1.22
3	6198.9	1.16	6960.6	1.15	5438.9	1.11	5765.3	1.03	2947.3	1.19
4	1057.7	1.40	3475.7	1.28	2384.0	1.24	4018.1	1.29	3792.7	1.34
5	7843.4	1.07	6379.4	1.09	7048.2	1.05	4945.1	1.03	2784.6	1.05
6	4382.0	1.17	5915.2	1.19	7298.9	1.12	5763.3	1.14	4100.3	1.15
7	7085.3	1.17	6758.1	1.12	5449.0	1.15	4378.1	1.07	4711.1	1.13
8	3028.2	1.09	2557.6	1.10	2451.6	1.11	3563.0	1.12	3006.1	1.06
9	5324.7	1.52	7062.0	1.47	8937.0	1.43	5444.2	1.41	3658.1	1.39

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