The Circulation Assessment of Daily E-health by Using Instantaneous Pulse Rate Variability during Nonstationary Conditions

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Abstract—**Heart rate variability (HRV) and pulse rate variability (PRV) are used as meaningful indicator of cardiovascular circulation assessment. However, both HRV and PRV are limited by the timescale of the heart beat and pulse wave series. Recently, a novel adaptive method based on Hilbert-Huang transform (HHT), named instantaneous pulse rate variability (iPRV), was proposed. It provides a new indication, called very high frequency band (VHF; 0.4-0.8Hz) for the neural regulatory estimation and peripheral responses. Ten healthy subjects participated this study and photoplethysmography (PPG) signal was recorded in supine baseline and during head-up tilt (HUT) and passive leg raising (PLR). The results showed that the spectral power of VHF decreased during HUT and increased during PLR, which might present the compensated regulation of venous return and fluid responsiveness. This study showed that VHF index has potential to indicate the fluid responsiveness and provides the meaningful information for homecare application, which only requires the simple PPG measurement.**

Keywords-PPG; Hilbert-Huang transform (HHT); instantaneous pulse rate variability (iPRV); passive leg raising (PLR); fluid responsiveness.

I. INTRODUCTION

Autonomic nervous system (ANS) regulates the homeostasis of body system, including heart beat rhythm. Previous studies showed that the variability of heart rate, named heart rate variability (HRV), presents the ANS activities within specific frequency band. Heart rate variability is widely used as a meaningful indicator of cardiovascular circulation assessment in clinic. However, HRV studies are restricted by the feasibility and the reproducibility with inconvenient measurement [1].

A substitute measurement of HRV was proposed, named pulse rate variability (PRV). Gil's study examined that PRV is as a surrogate of HRV during non-stationary conditions [2]. But both HRV and PRV are limited by the timescale of the heart beat and the series of pulse wave time intervals.

Recently, a novel adaptive method, named instantaneous pulse rate variability (iPRV), was proposed [3]. It adopted PRV technique and applied the frequency range extension method based on Hilbert-Huang transform (HHT) [4]. Hilbert-Huang transform is a data-processing technique which can deal with non-stationary and nonlinear data owing to its preprocess, called empirical mode decomposition (EMD). However, the intermittency phenomenon, called mode-mixing problem, is involved in EMD. The mode-mixing problem was eliminated by noise-assisted technique, known as ensemble EMD (EEMD) [5]. It provides a reliable indicator for ANS assessment and, furthermore, breakthroughs the limitation of beat-to-beat series spectral analysis. It provides a new indication, called very high frequency band (VHF; 0.4-0.8Hz) for the neural regulatory estimation and peripheral responses. The literature has examined that iPRV is reliable by using photoplethysmography (PPG) during non-stationary condition, such as head-up tilt (HUT) [6]. But its interpretation of VHF indication still needs further exploration and examination. It had been examined that VHF of HRV is as a novel index of left ventricular function evaluation [7], which further indicates the cardiac function, venous return, and fluid responsiveness. There is a common clinical experiment, named passive leg raising (PLR), which induces the increase of venous return and helps for the quantitative assessment of fluid responsiveness [8].

The aim of this study is to examine the neural regulatory estimation and fluid responsiveness of iPRV on VHF during non-stationary condition, such as HUT and PLR.

The remainder of the paper is structured as follows. The next section presents data collection and introduces the iPRV analysis. Section III illustrates the results of iPRV spectrum. Section IV provides the discussion about mechanism of the VHF indication in iPRV. Conclusion is given in the last section.

II. METHODS

A. *Subjects and data collection*

All measurements were performed in a quiet temperature controlled room and the experiment was approved by institutional review board of the hospital. Ten healthy subjects (male: 5; age: 24±1) participated this study. The PPG signal was recorded by Nonin 8500 (Nonin Medical Inc., Plymouth, MN) with a sampling frequency 200Hz. All recruited subjects performed four trials in whole experiment. First, subjects were rest in supine position with 10-minute recording as baseline. Second, subjects were tilting up passively (HUT) on the automatic tilting table and kept in tilt-up position for 10 minutes. Then, subjects were back to the supine position with 5 minutes for recovering to baseline. Finally, subjects were raising leg passively (PLR) for 10 minutes. This study was approved by institutional review board of Tungs' Taichung Metro Harbor Hospital. Informed consent was obtained from all participants before the experiment.

B. *Ensemble empirical mode decomposition*

EMD extracts components by several steps. First, EMD performs an iteratively detrending operation, named sifting process. The sifting process is based on energy-associated extraction in each timescale, which determined by the local extrema. Local extrema of data $x(t)$ are identified by peak-valley detection. The upper envelope $U(t)$ and lower envelope $L(t)$ are generated by cubic spline interpolation according to the local maxima and local minima. The trend in current timescale is computed by calculating the mean of $U(t)$ and $L(t)$, as $M(t)$.

$$M(t) = (U(t) + L(t))/2 \tag{1}$$

The original data $x(t)$ subtracts the trend, as detrending operation.

$$h_1(t) = x(t) - M(t) \tag{2}$$

After k times iteratively detrending operation, if the trend of $h_k(t)$ satisfies the criterion as the steady constant trend, then the components $h_k(t)$ were extracted from $x(t)$, called intrinsic mode function (IMF). After n sifting process, $x(t)$ was decomposed into n IMFs, $IMF_1(t) \sim IMF_n(t)$, and one residue $r(t)$.

$$x(t) = \sum_{i=1}^{n} IMF_i\,(t) + r(t) \tag{3}$$

The EMD decomposes data into IMFs without information loss or distortion, but it contains mode-mixing problem. Ensemble empirical mode decomposition eliminates this phenomenon by noise-assisted technique [5]. The ensemble IMFs are computed by averaging each corresponding IMF decomposed from different mixtures of added noise and source data. This study used EEMD for the PPG signal decomposition as feature extraction method.

C. *Instantaneous pulse rate variability*

The iPRV analysis contains several steps as follows (Figure 1). First, the blood pulse signal was extracted from PPG signal as one of the IMFs by using EEMD. Second, the instantaneous period of the blood pulse signals were calculated by normalized Hilbert transform (NHT) [9]. Finally, fast Fourier transform was performed as the spectral analysis of instantaneous period. The spectral power of low frequency (LF; 0.04-0.15Hz), high frequency (HF; 0.15-0.4Hz), and VHF (0.4-0.8Hz) were calculated by spectral integration as the clinical indicators. The spectral analysis programs in this study was developed by using commercial software platform (LabVIEW version 2013, National Instruments Corp., Austin, USA).

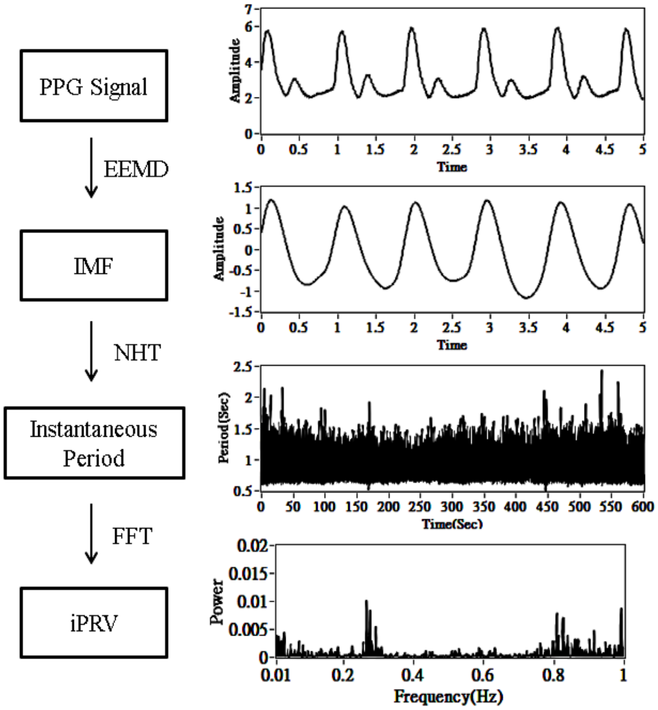

Figure 1. The flow illustration of the algorithm of instantaneous pulse rate variability (iPRV).

III. RESULTS

The results of the iPRV spectrum were summarized in Table I and illustrated in Figure 2 in one of the subjects as an example. The results of all participants' iPRV spectrum were similar with subtle change of the frequency peaks' locations. The power of LF increased both in HUT and PLR. The power of HF decreased during HUT and increase during PLR. The power of VHF decreased in HUT and increased during PLR. The relevant features were observed in the corresponding spectrum in Figure 2. The locations of the major spectral peaks were found around similar locations with those in iPRV spectrum.

TABLE I. THE RESULTS OF IPRV SPECTRUM

	Position		
	Baseline	***Head-up tilt (HUT)***	***Passive leg raising (PLR)***
LF	222.20±185.87	291.20±263.87	287.60±221.97
HF	297.00±212.79	274.20±188.25	417.80±302.50
VHF	366.10±382.74	234.20±179.83	505.40±506.27

The form is (mean ± standard deviation). LF denotes low frequency band (0.04-0.15Hz); HF denotes high frequency band (0.15-0.4Hz); VHF denotes very high frequency band (0.4-0.8Hz).

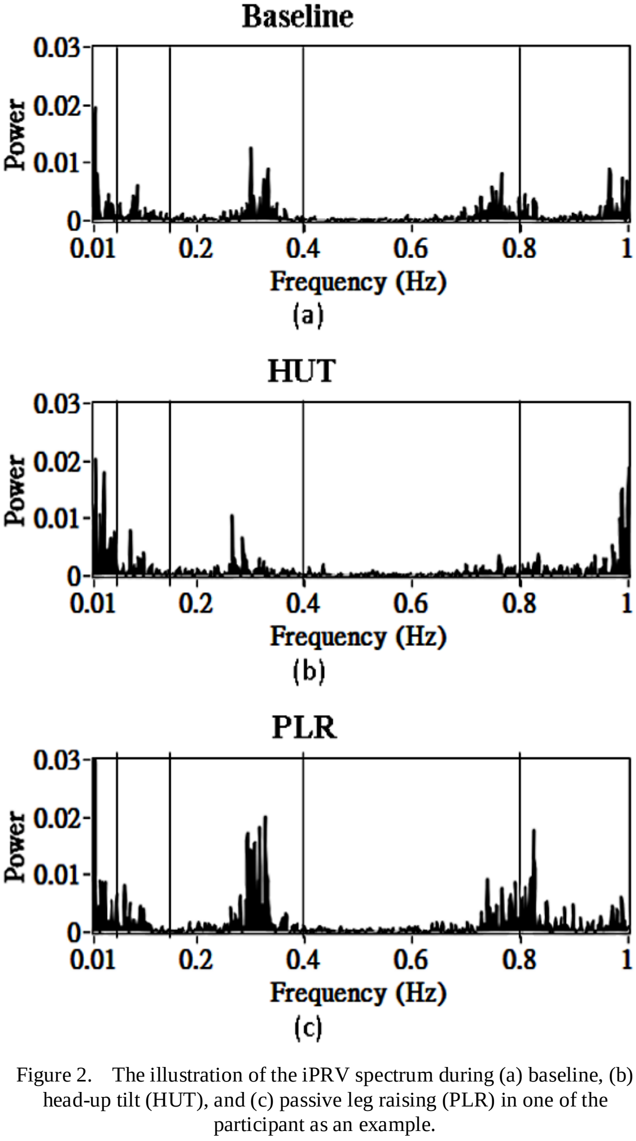

Figure 2. The illustration of the iPRV spectrum during (a) baseline, (b) head-up tilt (HUT), and (c) passive leg raising (PLR) in one of the participant as an example.

IV. DISCUSSION

It had been examined that the reliable iPRV spectrum can be assessed by PPG signal [6] and the new indicator (VHF) can be assessed through iPRV spectrum. Though some literatures investigated that VHF of HRV is a reliable evaluation of left ventricular function [7], VHF of iPRV still needs further examination. It had been examined that VHF contains parasympathetic activities and peripheral responses, which are influenced by venous return and cardiac function. The influences of respiration on VHF were examined by paced respiration study [10]. The mechanism of the VHF indication needs more exploration.

This study performed the clinical experiment, known as HUT and PLR, for the further examination. HUT causes temporarily decrease of blood volume in upper body and then causes the decrease of venous return. These changes induce the auto-regulation for the compensation. The sympathetic activities increased during HUT, and the power of LF also increased, which quantitatively assessed the sympathetic activation. On the other hand, the parasympathetic activities decreased, and so did the power of HF and VHF.

PLR causes the increase of blood volume in upper body and then causes the increase of venous return. The cardiac function was increased temporarily and induces the peripheral fluid responsiveness. These changes induced the regulation mechanism for the compensation. The parasympathetic activities increased during PLR and the power of HF and VHF also increased. The results showed that VHF has potential to indicate the relevant change of venous return and monitor the fluid responsiveness, which can be used in homecare monitoring.

Though VHF provides much more information of auto-regulation and has potential to indicate the parasympathetic activities and fluid responsiveness. It has several limitations as follows. First, the success of iPRV analysis is mainly depends on the waveform integrity of the PPG signal, which is sensitive and easy to be influenced by body movement and unstable measurement. Second, the EEMD of iPRV contains large computational power and causes huge time consumption, which means that it is hard to be applied as real-time application by recent technique. Third, the results in this study depend on ten healthy participants, and the population study needs to be performed for further examination, which is undergoing currently. Furthermore, VHF index should be examined with different group of subjects , such as not healthy people by using iPRV in future.

V. CONCLUSION

This study showed that the iPRV spectrum can be assessed by simple PPG measurement, which is suitable for homecare application, and the reliable VHF can be estimated by iPRV analysis. The power of VHF decreased during HUT and increased during PLR. The results showed the potential usefulness of VHF indication in venous return and fluid responsiveness.

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