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Wavelet-based embedded algorithm for respiratory rate estimation from PPG signal

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ABSTRACT

Photoplethysmography (PPG) is a popular technique utilized in pulse oximeter. Several researches have shown that PPG signal possesses the respiratory-induced intensity variation (RIIV) component, which implies that arterial oxygen saturation, heart rate (HR) and respiratory rate (RR) can be acquired by a single device. The commercial pulse oximeter generally provides the values of arterial oxygen saturation (SpO_2) and HR. To successfully add the function of RR estimation to pulse oximeter, an algorithm requiring fewer resources plays a critical role. This paper presents a wavelet-based algorithm for RR estimation from PPG signal that can be implemented in the micro-controller (MCU) of pulse oximeter. The algorithm has been coded in C language and tested in a 32-bit MCU. The estimation results derived by the algorithm agree well with those from usual spectrum analysis methods. The RR estimations derived by PPG and respiratory signal are analyzed by Bland–Altman method. The RR estimations for long-term trace, breath-holding and paced-breathing experiments are also conducted to verify the performance of the proposed algorithm. The experimental results indicate that the proposed algorithm is highly reliable and is feasible to be incorporated in the commercial pulse oximeter.

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1. Introduction

The level of oxygen saturation in the artery is an important index to evaluate the sufficiency of oxygen supply to peripheral tissue. Monitoring oxygen saturation in the artery is critical for patients under the condition of life support by ventilator or high-flow oxygen therapy and now is a gold standard for patient monitoring in surgery and in intensive care unit (ICU) [1]. Pulse oximeter is the commonly adopted medical device utilized to measure the arterial oxygen saturation (SpO_2) in non-invasive way, in which device an optical measurement technique termed as photoplethysmography (PPG) is employed with at least two light sources of different wavelength [2]. Previous researches have shown that there exists a respiratory-induced intensity variation (RIIV) component in PPG signal which is induced primarily by the tiny variation of venous return resulted from the varying intra-thoracic pressure during respiration [3–5]. The origin for the induced RIIV in PPG is depicted in Fig. 1. The varying volume change of arterial blood in each heartbeat has also been added in the figure. According to Beer-Lambert law, the incident light intensity ($\boldsymbol{I_{in}}$) attenuates exponentially as the light passes through the light media, which are primary hemoglobin (Hb) and oxyhemoglobin (HbO_2) in the blood and partly the tissues such as skin pigmentation and bone in the light traveling path. In addition to the pulsating component resulted from the varying arterial blood volume pumped in each heartbeat, the time-varying intra-thoracic pressure during respiration may also lead to a slight change of venous return in inhaling and exhaling cycle. The tiny difference in the arterial blood volume makes the detected light intensity ($\boldsymbol{I_{out}}$) a slightly different level change ($\boldsymbol{\Delta I}$) between inhaling and exhaling state, and this is primarily the origin of RIIV component in PPG signal. Fig. 2 shows an example for respiratory signal (upper) and PPG signal (lower) measured simultaneously from one subject, in which the dashed line indicates the RIIV component. The demonstrated signals are form the MIMIC database [6] of PhysioNet [7] for the subject numbered 055. As can be seen from Fig. 2, PPG signal is shifted with a short time delay to emphasize the implication of respiratory information

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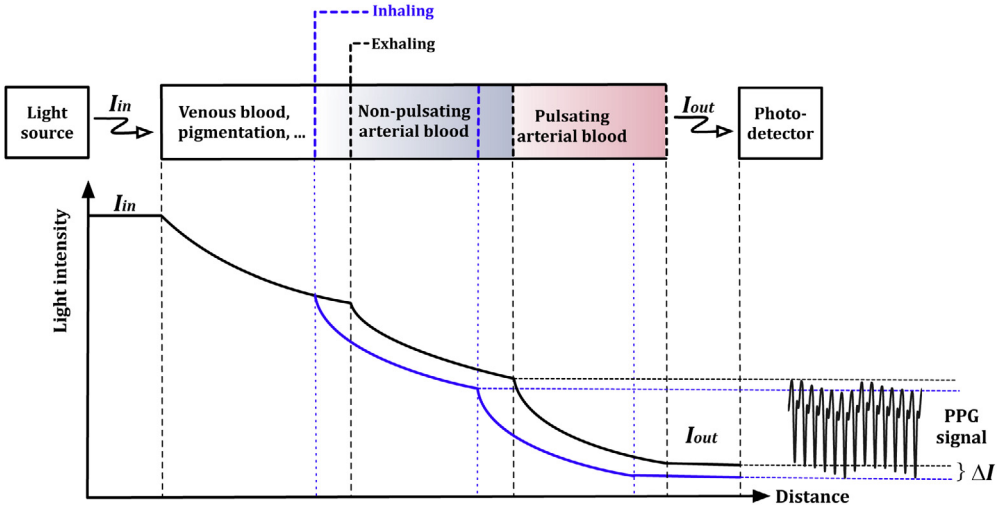

Fig. 1. The effect of respiration on the detected light intensity in PPG resulted from the minor variation of venous return in inhalation and exhalation. The volume change of arterial blood in circulation is also depicted in this figure.

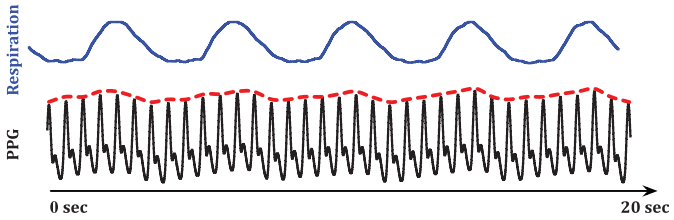

Fig. 2. Respiratory signal and the respiratory induced intensity variation (RIIV) in the PPG.

buried in PPG, which indicates that respiratory rate (RR) can also be detected from PPG signal.

In clinical setting, respiration can be monitored by the transthoracic impedance plethysmography [8], multi-lead electrocardiogram (ECG) [9–12] or the temperature changes induced by the breathing flow [13,14]. In addition to the device for respiration monitoring, pulse oximeter is usually utilized to evaluate the efficacy of oxygen supply to patient's peripheral tissue in the same time. In such case, two different devices are usually employed for SpO_2 and RR monitoring. Most of the commercial pulse oximeters provide the values of SpO_2 and heart rate (HR). As mentioned above, respiration can also be detected from PPG signal. That implies not only SpO_2 and HR but also RR can be obtained by pulse oximeter. In clinical setting, the benefit of integrating the measurement of SpO_2, HR and RR is that the device for monitoring RR can be omitted. The cumbersome accessory leads or conduits for the related devices can be simplified by a single SpO_2 probe. The medical cost can thus be reduced, and the quality of medical care can also be maintained.

Since the operation of commercial pulse oximeter is generally directed by a micro-controller (MCU), the development of embedded algorithm requiring fewer resources and high reliability for RR estimation is the key factor to determine whether it is feasible to incorporate this new function into a pulse oximeter. Fleming and Tarassenko proposed an algorithm based on autoregressive (AR) model to acquire precise RR from PPG signal [15]. AR model has the advantages of shorter data length and higher frequency resolution as compared with Fourier-based methods. However, the basic requirements for AR model include high signal-to-noise ratio (SNR) and proper model order. There are miscellaneous approaches that can be adopted for the optimal order selection of AR model, such as final prediction error (FPE), Akaike information criterion (AIC) and criterion autoregressive transfer function (CAT) [16]. For these approaches, the cost values should be evaluated in various orders and the optimal order is chosen for the one having the smallest cost value. The computation load for AR model with the optimal order selection is too heavy to be used in the MCU of commercial pulse oximeter.

In addition, Chon et al. utilized a time-frequency analysis method termed as variable-frequency complex demodulation (VFCDM) to estimate RR from PPG signal [17]. Compared with short-term Fourier transform (STFT), Wigner-Ville distribution (WVD) and continuous wavelet transform (CWT), VFCDM can provide better frequency resolution and has been verified to be capable of estimating RR from PPG signal reliably [17]. However, VFCDM needs a minimum length of one-minute data and also has a heavy computation load, which make this method infeasible for the MCU of pulse oximeter, too. As the RIIV component in PPG signal possesses the non-stationary and nonlinear properties, the widely adopted empirical mode decomposition (EMD) has also been utilized to serve the purpose of estimating RR from PPG signal [18,19]. EMD needs uncertain number of decomposition process and the interpolation procedure is also needed to derive the intrinsic mode functions (IMF), which make the algorithm too bulky for a MCU-based embedded system. Park and Lee proposed the adaptive lattice notch filter to extract respiratory information from PPG signal [20]. The reference signal for the adaptive filter is extracted from PPG signal by a bandpass filter (BPF, the passband is 0.5–5 Hz), which is primarily composed of heartbeat components. The respiratory signal is then acquired by another BPF (the passband is 0.1–2 Hz) for the residual output of the adaptive filter. As the human respiratory signal may range from 0.17 Hz to 0.73 Hz (depending on patient's age and illness) [21–23], the output for the BPF of 0.5–5 Hz may also contain the respiratory component for some patients, which makes this method not versatile for all subjects. Li et al. proposed a method for the decomposition of PPG signal based on finite Gaussian bases [24]. This method utilizes the feature set composed of the amplitude, mean and standard deviation for each Gaussian basis to reduce data amount. The heart rate and respiratory rate can also be acquired by the decomposition method if the optimal feature set is reached, which can be solved iteratively based on the joint steepest-descent method and modified Gauss-Newton method. However, the processing load for the iterative procedure is also too heavy for the MCU of pulse oximeter.

Due to the limited memory and computational capability for the MCU of commercial pulse oximeter, all of the methods for esti-

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