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IJK complex detection within BCG signal based on multi-core fiber sensors

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Abstract: BCG signal is detected based on proposed multi-core fiber sensors and IJK complex is extracted and explored for biomedical applications.

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1. Introduction

Vital signs have been drawing attention in both research and industrial area due to its significance for human health condition assessment. Heartbeat signal plays an important role among various human vital signs since it represents the activity of the key organ. There are many kinds of heartbeat signals describing heart activities, such as Electrocardiogram (ECG) and Impedance Cardiogram (ICG) and they generally require skin contact, which may discomfort the patients [1]. To realize contactless heartbeat monitoring, Ballistocardiogram (BCG) signal becomes preferred since it is based on the recoil force caused by the blood pumped into the aorta during every heartbeat [2]. The BCG waves are commonly separated into three groups: pre-systolic, systolic and diastolic. In detailed BCG waves, I and J waves are referred as ejection waves, F and G waves represent pre-systolic phase. The systolic phase contains H, I, J, and K waves, and the diastolic phase contains L, M, and N waves [3]. Current research mainly focuses on I, J and K waves, or IJK complex since it directly reflects ventricular ejection and aortic flow, which is significant in some clinical usage. For example, for blood pressure measurement, when monitoring diastolic blood pressure, the I-J interval is comparable to the pulse transit time and pulse arrival time while the J-K amplitude can show a significant effect when monitoring systolic blood pressure [4]. In addition, cardiac output, which is the amount of blood pumped by the heart per minute, can be used to assess the myocardial contractility. In clinical settings, it has been demonstrated that I-J amplitude has a positive correlation with cardiac output [5]. Moreover, accurate J-J interval obtained from IJK complex can be used for heart rate variability analysis to evaluate the activation of the sympathetic and parasympathetic rhythm of the body while J-amplitude can be used for premature atrial contractions (PACs) and premature ventricular contractions (PVCs) prediction [6]. Thus, BCG signal is promising for heart condition assessment and IJK complex within it is essential for specific heart related parameters measurement.

For BCG signal monitoring, there are many schemes based on different principles, such as radar-based BCG signal collection system, weight-scale and static charge sensitive bed BCG systems. Although they can realize the BCG detection, the sensitivity is not high enough for IJK extraction and the systems are usually bulky and high-cost. To realize detailed BCG signal detection with additional advantages of compact and cost-effective, our group proposed to use optical fiber sensors and also has demonstrated many structures, such as traditional Mach-Zehnder interferometers and few-mode fiber based in-line interferometers [7]. In recent work, we attempt to design and draw specialty optical fibers and fabricate corresponding sensors for BCG detection. In this paper, multi-core fiber sensors for BCG detection are proposed. The sensors are fabricated and then packaged as a smart mattress placed under the bed. The subjects lie on the bed and BCG signal can be detected successfully. Signal processing methods are utilized to extract IJK complex and the preliminary work on biomedical applications is introduced. In conclusion, multi-core fiber sensor can be a desired and promising candidate for BCG signal detection and IJK complex within it will show its capability for heart condition assessment.

2. Multi-core fiber sensor and experimental set-up

The multi-core fiber sensor is based on twin-core fiber (TCF), the cross-section of which is shown in Fig. 1(a). The cladding diameter of TCF is 125 μm. One core is located in the center with diameter of ~6 μm and the other identical off-axis core is positioned ~10 μm away from the center with the same diameter. Due to the small core pitch size, the TCF supports two supermodes, including asymmetric and symmetric mode. To form the mode interference in TCF, core-offset structure is introduced, and two standard single mode fibers are spliced on both ends of TCF.

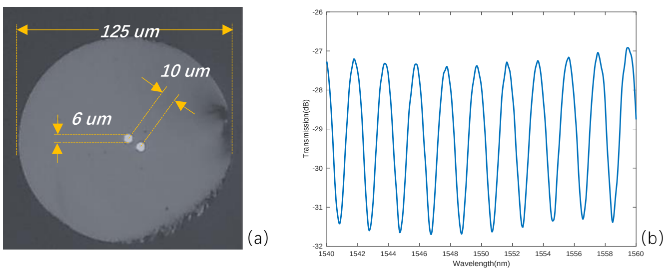

Fig. 1. Cross-section of the TCF (a) and mode interference results in the TCF sensor (b).

Mode excitation results and obtained interference spectrum are shown in Fig. 1(b). The extinction ratio can research 5 dB and spectral period is 0.9 nm. In experiment, the TCF based sensor is packaged as a smart mattress and placed under the bed for BCG signal collection. The experimental set-up is shown as Fig. 2. The laser source is a standard DFB laser working on the wavelength of 1550 nm. A low-speed photodetector converts the optical signal to electrical signal that are collected using a DAQ card. The sampling rate is 1 kHz. To obtain the heart related reference signal, a commercial ECG device (AD8232, Sparkfun) is introduced here. During the experiment, the subject attaches three electrodes on three body positions as shown in Fig. 2(b) then the subject lies on the bed for vital signs signal collection, including respiration, heartbeat and the reference ECG signal.

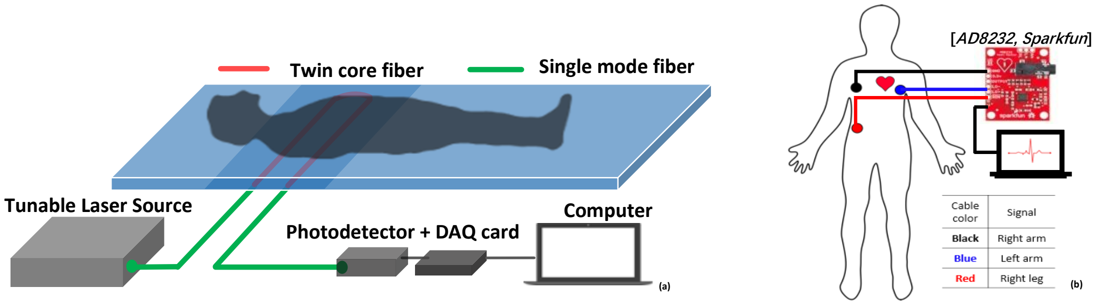

Fig. 2. Vital signs monitoring system (a) and the ECG monitoring device (b).

3. Signal processing and results

The collected raw data is shown in Fig. 3(a). Based on the raw signal, a signal processing method based on the filtering technique is proposed, as shown in Fig. 3(b). Due to the intrinsic frequency difference of respiration and heartbeat, two filters are used for vital signs signal extraction. A high-pass filter with a cut-off frequency of 0.5 Hz is used to extract the respiration signal. Then a low-pass filter with the cut-off frequency of 30 Hz is used to obtain the BCG signal with IJK complex details since it has been investigated that the BCG signal can only be recovered with low-pass cut-off frequency over 25 Hz [8].

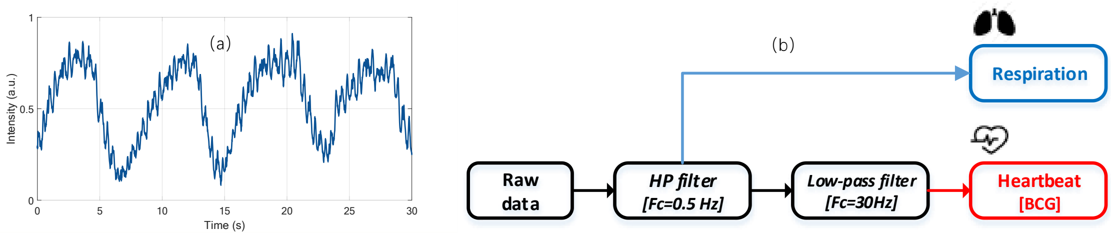

Fig. 3. Raw data obtained (a) and the signal processing method (b).

Based on the proposed signal processing method, both respiration and heartbeat signal can be obtained. The results are shown in Fig. 4(a). It can be seen that the respiration and heartbeat signal are recovered successfully. The respiration rate can be calculated to be 9 beat per minute (bpm). For heartbeat, the BCG signal can be obtained with detailed IJK complex in it. The I, J and K waves are shown in Fig. 4(a). From the interval between two adjacent J waves, we can obtain the heart rate of 90 bpm.

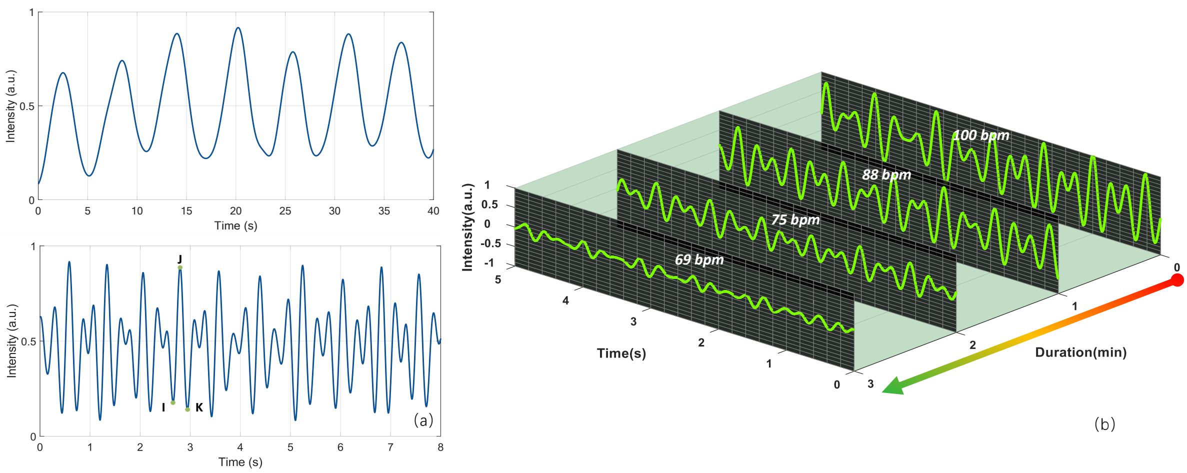

Fig. 4. Recovered respiration and heartbeat waveform (a) and physiological activities characterization using IJK complex in BCG signal (b).

For biomedical applications using IJK complex in BCG, our first attempt is to characterize the heart related physiological activities. The analysis on physiological activities can be used to assess the autonomic nervous function, which is significant for early detection and prevention of various disorders [9]. In clinical settings, the most common method to modulate the heart rate is the static exercise and then corresponding device is introduced to monitor the heart parameters such as heart rate. In our work, the subject is told to perform static exercise and then lie on the bed and the BCG signal is collected for further heart rate analysis. Based on the aforementioned signal processing method, the post-exercise heart rate results are shown as Fig. 4(b). It can be seen that both the heart rate and amplitude decrease within four minutes. This first attempt demonstrates the feasibility of IJK complex in BCG signal on specific biomedical applications.

4. Conclusion

In our work, the BCG signal is introduced and IJK complex is reviewed with significance on many biomedical applications. To detect BCG signals, we proposed multi-core fiber sensors with desired interference performance for vital signs monitoring in a contactless way. The experiment is conducted, and the signal processing method based on the filtering technique is proposed to extract respiration and heartbeat. For BCG signal, IJK complex can be obtained successfully. For preliminary biomedical applications based on IJK complex, post-exercise physiological activities are characterized and the results demonstrate the potential of IJK complex on future biomedical applications. In conclusion, multi-core fiber sensor can be a desirable candidate for BCG signal detection and IJK complex within BCG signal is promising in biomedical applications in the future.

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