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Reliability analysis of an integrated device of ECG, PPG and pressure pulse wave for cardiovascular disease

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ABSTRACT

Cardiovascular diseases (CVD) are the leading cause of death globally and the mortality has been increasing in recent two decades. Most of cardiovascular diseases are preventable by early and long-term monitoring. The common option of physical examinations for CVD includes ECG, photoplethysmography (PPG), pressure pulse wave (PPW). An integrated device was designed and developed by gathering three physiological signals of ECG, PPG, and PPW synchronusly in this research. The tri-modal device was tested for reliability and stability on the synchronism of R-R intervals, distribution of peaks, and noise suppression. The experiment results displayed that the white noise and dark noise was well controlled. In the test of synchronism, PPG and PPW of the P-P intervals show a good linearity in correspondence with the ECG of R-R intervals in cardiac cycle. There is no significant difference in peak distribution of three modal signals from 4 volunteers. Thus, the equipment has excellent properties of anti-electromagnetic interference, removing movement artifacts and light tightness and may be developed to a promising tool for multi-modal diagnosis in CVD.

1. Introduction

Cardiovascular diseases (CVD) are one of the leading causes of death globally and mortality has been increasing in recent two decades. It resulted in 17.3 million deaths (31.5%) in 2013 up from 12.3 million (25.8%) in 1990 [1]. The mortality in China was higher than the global, which accounts for > 40% of deaths from any cause. In 2013, 44.8% of deaths in rural area and 41.9% of deaths in urban area are caused by CVD in China and the incidence of CVD is continuously increasing and will remain an upward trend in the next decade [2, 3]. However, it is estimated that 90% of CVD are preventable [4]. Such tools of electrocardiograph, photoplethysmography [5], sphygmograph [6, 7] were invented and created for indicative diagnosis in CVD. Pulse sensors have received extensive attention because of their noninvasive and convenient in usage. Nowadays, most widely used technologies for pulse measurement are photoplethysmography (PPG) on fingertip for blood oxygen monitoring and pressure pulse wave (PPW) on wrist for radial artery, including a piezoelectric pulse transducer and piezoresistive pulse transducer.

Although current research focused on one of ECG, PPG or PPW, achieved strategically progresses. ECG has long been as an important clinical diagnostic indication for myocardial ischemia [8] and atrial fibrillation [9, 10]. PPG is an important physiological signals representing blood flow and oxygen saturation [11]. Arterial pressure, such as central arterial pressure, was deduced through pulse wave analysis [12]. These parameters will contribute to making use of the information of pulse wave to analyze and auxiliarily diagnose cardiovascular disease in clinic. Nevertheless, the integrated modal with ECG, PPG, PPW are unusual for diagnosis in CVD. In this paper, a non-invasive, low-cost three-mode detection system was designed for monitoring cardiovascular parameter, combining with ECG, photoelectric pulse wave and pressure pulse waves. The study of various parameter measurement and model integration can provide new research ideas for the model of cardiovascular disease. The stability, reliability and noise of the signal on the system are tested to guarantee the accuracy of the physiological information.

2. Materials and methods

2.1. Sensors and placement

Three types of sensors are applied in the device, including photoelectric detector (HKG-07B), ECG detector (cable from HKD-10C, electrode from Heal Force CH50B-20), two pressure transducer (HK-2000). These sensors and accessories were purchased from Hefei Huake Information Technology Co. Ltd., which have been recognized by some

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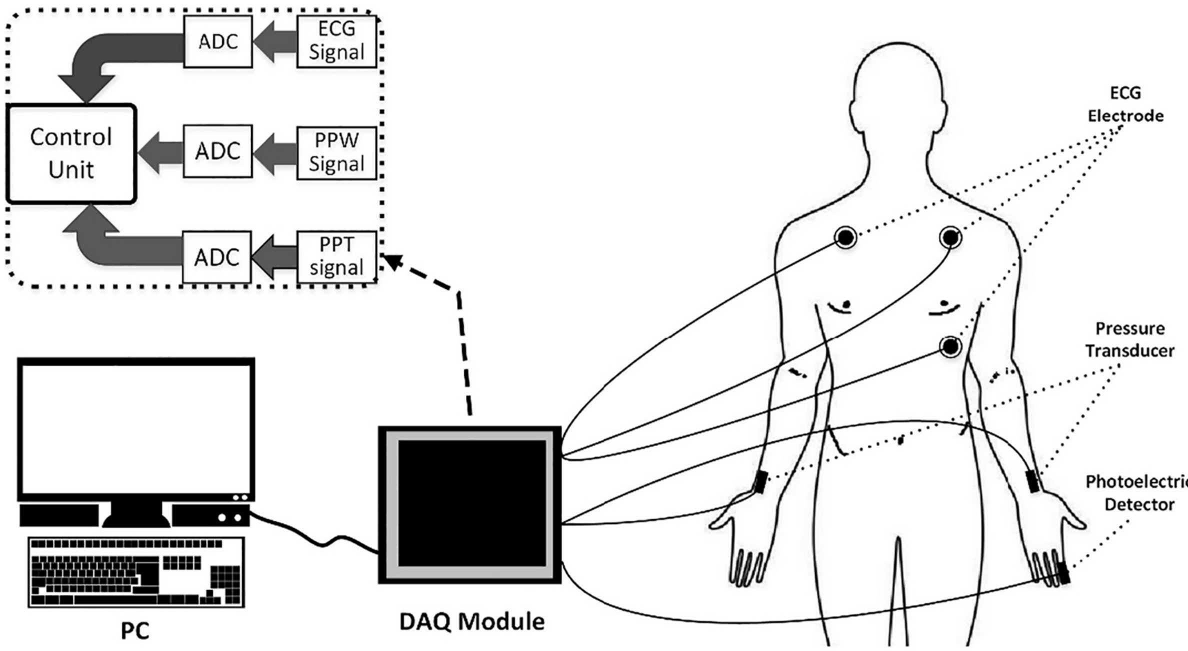

Fig. 1. The schematic diagram of the system and the circuit framework of DAQ module.

research institutions and companies [13, 14]. A simplified electrocardiograms framework of an orthogonal 3-lead ECG from FRANK lead system [15, 16] was adopted in the ECG module, providing sufficient supplementary information for ECG monitoring. With one side connecting to a cable, the three electrodes (RA, LA, LL) stuck on the skin of a person's chest. The white electrode (RA) was placed on the intersection of the first rib and the midline of the clavicle, on the right of the sternum. The black electrode (LA) was placed on the intersection of the first rib and the midline of the clavicle, on the left of the sternum. The red lead was put on the intersection of the horizontal of the xiphoid and the midline of the clavicle on the left of the sternum. The two pressure transducers were put on the wrist of radial artery by elastic wrist straps, on the right and left hand respectively. The third sensor, the photoelectric detector, was utilized with clamping the tip of forefinger.

2.2. Systematic design

Fig. 1 shows the schematic diagram of the system, which was split into three sections: sensors, DAQ module and PC. The signals of ECG, PPT and PPW measured by sensors were transmitted to DAQ module. In order to overcome the power frequency interference and other high frequency noise, a preconditioning circuit including the low-noise preamplifier and filter was introduced in the DAQ module. After the conversion of analog to digital, the signal is transmitted to host PC by the serial port according to serial communication protocol from local researchers.

In view of cost and convenience, the DAQ module was designed including ADC, sampling, smoothing and communicating with host computer. With respect to complex electromagnetic environment in the hospital, the signals were smoothed by filter circuit before analog-digital conversion and by digital filtering in PC Software. The software interface in the host computer is show in Fig. 2.

2.3. Robustness and stability

In the design of the multi-modal device, the robustness and stability affect the reliability of the device. ECG signal belongs to weak signal in the low-frequency so that it is easy to be interfered by all kinds of noise, such as power interference, baseline wander, the myoelectricity interference and so on [17, 18]. The PPW signal is frequently disturbed by motion artifact owing to the special-site, particularly attached on the wrist [19, 20]. The LED module is equipped with a suction cup in the photoelectric detector [21]. It is serious of the interference received by ambient light. Taking these influential factors into account, we performed a number of measurements and tests to substantiate and improve the overall reliability of this device.

We collected data from four healthy volunteers and simultaneously measured the two channels of PPW, PPG of the fingertip, 3-lead ECG. Volunteers were requested to lie down for 2–3 min quietly in a complex electromagnetic environment. The measured data is used to test the stability and reliability of the equipment.

2.4. Accuracy and reliability

Traditionally, R-R interval of ECG is widely perceived as a sign of heartbeats, and was recognized as the reference standard for the accuracy and reliability of pulse sensor in tracking heart rate [14, 22, 23]. The peak R of ECG as shown in Fig. 3a, the peak waves of voltage output (LRA-PPW, RRA-PPW, PPT) are synchronous to corresponding R waves in ECGs. Afterward, the linearity between R–R intervals measured by ECG ($R–R_{ECG}$) and peak intervals measured by the PPG ($P–P_{PPG}$), LRA-PPW ($P–P_{LRA\text{-}PPW}$), RRA-PPW ($P–P_{RRA\text{-}PPW}$), were detected, respectively.

To verify the reliability of signal, the peak of signal was analyzed statistically. Firstly, the peak values in the cardiac cycle were found out by the MATLAB program. The peak distribution of each signal were display from ECG, PPW of the left radial artery (LRA-PPW), PPW of the right radial artery (RRA-PPW). The box-plot, which is an excellent statistical tool reflecting data dispersion, was used through the commercial software Origin8.5. The variability of results and the original signal is under control due to the normal volunteers during resting. Ideally, the variability of the data is small if the device is stable and reliable.

3. Results and discussions

3.1. The analysis of R–R interval

In Fig. 3b–d, the data points ($R–R_n$, $P–P_n$) are shown as points while a linear fit is shown as a solid line. It showed a high linearity in $R–R_{ECG}$

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