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Pulse Arrival Time Measurement with Finger-Based ECG and Trans-nail PPG Circuits for Cuffless Blood Pressure Monitoring

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Abstract

Common oscillometry method of recording blood pressure (BP) is inconvenient, uncomfortable, and unable to provide continuous monitoring results. Recent researches showed that pulse arrival time (PAT), which is measured using electrocardiogram (ECG) and photoplethysmogram (PPG) signals, can be used to estimate BP level thus eliminating the need for pressure cuff in BP monitoring. In this paper, we proposed our circuit design for PAT measurement using finger-based ECG and trans-nail PPG circuits. These circuits were fabricated in 0.18µm CMOS technology with a small recording area of about 2.42mm^2 and 6.25mm^2 respectively. Our ECG circuit has variable amplifier gains between 20~60 dB, wide ranges of cutoff frequencies between 0.1 and 200 Hz for high pass filter (HPF) and between 200 and 10 kHz for low pass filter (LPF) to allow for customization accordingly. PAT was successfully measured from ECG and PPG signals using our circuits and fitted to a linear mathematical model. The good correlation of r = 0.78 between systolic cuff BP and PAT data shows that cuffless BP monitoring is able to be realized with our circuits.

1. Introduction

Since 1890s, BP has become an important physiological indicator in determining the well-being of a person's cardiovascular health [1]. According to the Evidence for Cardiovascular Prevention from Observational Cohorts (EPOCH-JAPAN), mortality rate increased as BP level increased. In Japan, the population-attributable fraction by cause of death was 50% for all cardiovascular disease (CVD) deaths, 59% for coronary artery disease deaths, and 52% for stroke deaths [2]. An early detection of high BP can help in controlling and preventing CVD, thus it is very important to keep BP level monitored at all time. At present, the most popular noninvasive method to obtained BP level is by oscillometry. Nevertheless, this method has several drawbacks. The cuffs are disruptive to be used in ambulatory monitoring situations [3], the pressure on the cuff causes pain and discomfort to patients, and unable to obtain continuous values of BP [1], [4].

In recent studies, it is found out that pulse arrival time (PAT), the travelling time of a pressure pulse from heart to a peripheral site, is a potential parameter to estimate BP. PAT can be measured from ECG and PPG signals without using a cuff [5]. This method is superior to cuff method in the aspect of its convenience, comfortability, and ability to monitor continuous BP level. Here we proposed a cuffless BP monitoring system using PAT measured with both finger-based ECG and trans-nail PPG circuits, as shown in Figure. 1. Our circuits are small and the acquisition of signals is only at finger site hence has great possibility of becoming a wearable BP monitoring device.

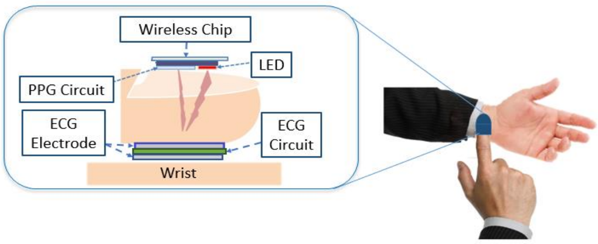

Fig. 1 Conceptual configuration of cuffless BP monitoring system

2. Design of PAT measuring circuit

The design of the circuit is separated into 2 parts, which are the ECG circuit and PPG circuit. Figure. 2 shows the schematics of both circuits.

A. Finger-based ECG circuit

This circuit is designed to capture small amplitude ECG signals using highly programmable gain. Unlike typical ECG recorder, it can obtain ECG signals without the need of grounding the subject, making it safer and able to be used in wearables circuit design. This circuit consists of low noise amplifier (LNA) with variable gains of 20~40 dB, HPF with cutoff frequencies of 0.1~200 Hz, LPF with cutoff frequencies of 200~10 kHz, buffer amplifier (BA) with gains from 0~20 dB, and 12bit SAR type analog to digital converter (ADC).

B. Trans-nail PPG circuit

This circuit is from our previous research work [6]. For LED driver circuit, it includes I-source (current driver for LED), pulse width modulation (PWM) controller to enable wide range of LED duty cycle from 8.26%~99.75%, and a ring oscillator (RING) circuit to generate ultra-low oscillation frequency of 0.17 Hz. Meanwhile, the PPG recording part contains a 600x600 µm^2 photo-diode (PD), LNA with gain levels of 20, 26, 32, and 40 dB, LPF, 2-order differentiator circuit, BA, and a 12 bit SAR type ADC. The PD circuit is separated into AC and DC line, enabling the measurement of peripheral oxygen saturation (SpO_2).

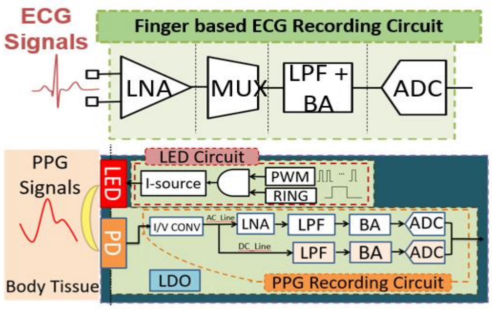

Fig. 2 Schematics of ECG and PPG circuits.

C. Collection of ECG and PPG data

In order to measure PAT, human ECG and PPG signals have to be collected at the same time using the circuits we have designed. In the experiment, subjects were instructed to sit down and relax, followed by the recording of ECG and PPG signals. Within 30s, cuff BP recording was started using OMRON HEM 7511T to obtained cuff BP [1], [3]. This is a very basic protocol to obtain resting BP readings.

3. Results and Data Analysis

As shown in Figure. 3, ECG and PPG circuits were fabricated with 1-Poly 5-Metal 0.18μm CMOS technology and have circuits' areas of about 2.42mm^2 and 6.25mm^2. Both circuits are able to collect the related signals. Figure. 4 shows the signals of ECG and PPG recorded using our circuits the conceptual configuration in Figure. 1.

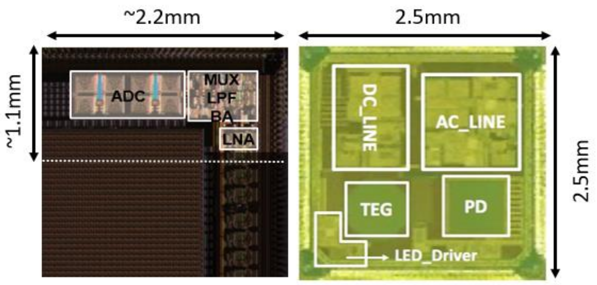

Fig. 3 Microphotographs of the fabricated ECG recording circuit (right) and PPG circuit (left) [6].

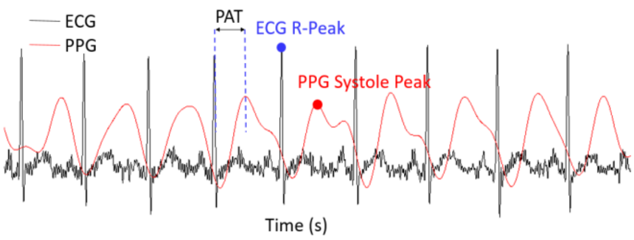

Fig. 4 ECG and PPG signals recorded with finger position as shown in Fig. 1 configuration. PAT duration is determined by time difference between ECG R-peak and PPG systole peak.

PATs calculated from ECG and PPG signals were fitted into equations (1) and (2) linear model [3],[7] to obtained unknown coefficients *a* and *b*;

$$Systolic\ BP\ (SBP) = \frac{a_{sys}}{PAT} + b_{sys} \quad (1)$$

$$Dystolic\ BP\ (DBP) = \frac{a_{dys}}{PAT} + b_{dys} \quad (2)$$

The resulted graphs are shown in Figure. 5. Good correlation of r = 0.78 between cuff SBP and PAT data was obtained. For simple validation, 3 sets of data were substituted into eq. (1) and (2) with known coefficients *a* and *b* to estimate the value of BP. The calculated BPs and percentage of error are tabulated in Table I. The high percentage of error (% of Err.), over 15%, in one of the data set could be due to variations in ECG and PPG recordings.

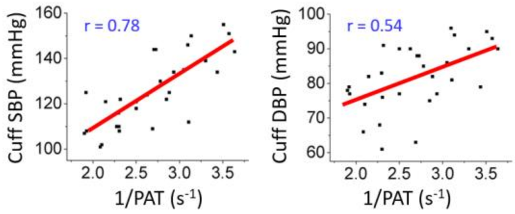

Fig. 5 Graphs of systolic cuff BP vs 1/PAT (right) and diastolic cuff BP vs 1/PAT (left).

Table I Calculation of cuffless BP from PAT

Systole BP			Diastole BP		
Cuff	Cuffless	Err (%)	Cuff	Cuffless	Err (%)
120	124	3.00	77	81	5.19
110	140	27.28	72	88	22.22
123	132	7.32	75	84	12.00

4. Conclusions

The circuits we designed are able to record ECG and PPG signals from fingers and PAT is successfully measured. Cuffless BP were calculated and they showed good agreements with cuff BP. With small area fabricated, our circuits are ready to be used for wearable BP monitoring in the near future. Meanwhile, more data sets with wider BP ranges and better algorithm are required for more accurate BP estimation.

Acknowledgments

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