A NOVEL METHOD FOR THE NONINVASIVE AND CONTINUOUS MONITORING OF ARTERIAL BLOOD PRESSURE ON AN ELECTRONIC STETHOSCOPE

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Abstract: Hypertension is a major risk factor for cardiovascular diseases which are major causes of death and disability in adults. There is an urgent need for a practical and wearable instrument, which allows noninvasive and continuous beat-to-beat measurement of blood pressure (BP) in clinics and for home healthcare. The present study has demonstrated that a close inverse correlation between systolic BP and Tr-s2, which is defined as the time interval between the ECG R-wave and the second heart sound (S2), was reproducible in two experiments. Furthermore, the BP estimated by least-mean-square fitting agreed well with measured BP, suggesting that by using Tr-s2, it is possible to realize noninvasive and continuous monitoring of BP on an electronic stethoscope.

Introduction

Hypertension is a major risk factor for cardiovascular diseases (CVD) which are major causes of death and disability in adults [1]. Hypertension is much more than a "cardiovascular disease" because it affects other organ systems of the body such as kidney, brain, and eye. Approximately 1 billion people around the world are suffering from hypertension. However, the majority of them are not even aware of being hypertensive because it is usually asymptomatic until the damaging effects of hypertension (such as stroke, myocardial infarction, renal dysfunction, etc.) are observed, so it is called “a silent killer”. The monitoring of arterial blood pressure (BP) is vitally important in order to identify and, thereupon, treat the disease at the early stage of its development.

Blood pressure is usually measured by manual or automatic non-invasive measurement. Both methods require, at the very least, an inflatable cuff with a pressure gauge (sphygmomanometer). They can provide only intermittent BP reading. These techniques rely heavily on a constant pulse volume, so in a patient with an irregular heart beat (especially atrial fibrillation) readings can be inaccurate [2]. They are also bulky and make users discomfortable because of the cuff. Therefore, there is an urgent need for a practical and wearable instrument, which allows noninvasive and continuous measurement of blood pressure in clinics and for home healthcare.

The heart and blood vessels work together to circulate the blood around the human body. In this process, many physiological signals can be detected by various biomedical sensors from the body surface. These signals carry the abundant information about the rhythm of the whole system and the interplay between heart and blood vessels. This study is to investigate the inherent relationship among ECG, heart sounds and arterial blood pressure, and to develop a novel BP measurement without the application of inflatable cuff.

The ECG is the electrical manifestation of the contractile activity of the heart, and can be recorded fairly easily with surface electrodes on the limbs or chest. The ECG is one of the most commonly known, recognized, and used biomedical signal. Heart sound results from the interplay of the dynamic events associated with the contraction and relaxation of the atria and ventricles, the valve movements and blood flow [3]. Usually four heart sounds are generated in a cardiac cycle. The first heart sound (S1) and the second heart sound (S2) can be easily heard in a normal heart through a stethoscope placed on a proper area on the chest.

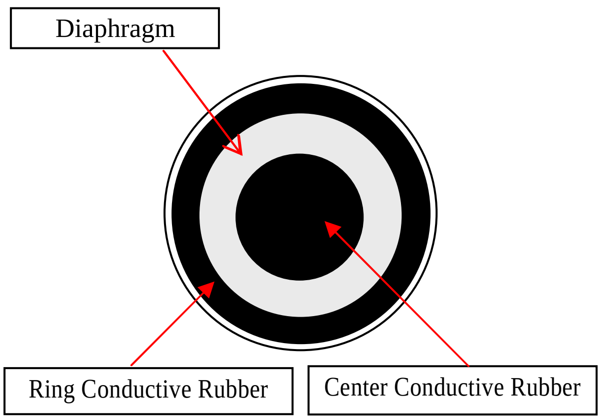

Figure 1: Front-view schematic diagram of a stethoscope’s head.

A novel electronic stethoscope has been reported by our group [4, 5]. As illustrated in Fig. 1, by integrating ECG electrodes into the head of a stethoscope, it is capable of collecting both of biological sounds and ECG signals simultaneously from the chest.

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On the basis of the novel stethoscope, a new method is proposed to estimate the arterial BP from Tr-s2, which is defined as the time interval between R-wave of the ECG and the second heart sound (S2), as illustrated in Fig. 2. This study aims to examine the relationships between Tr-s2 and arterial BP.

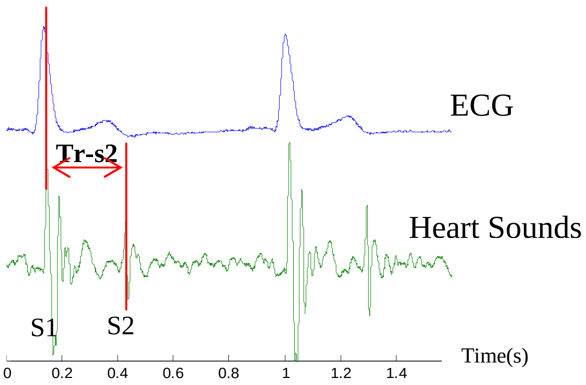

Figure 2: The definition of Tr-s2.

Materials and Methods

Two experiments were carried out to study the correlation between arterial BP and Tr-s2. Dynamic exercises were performed to increase the range of the change in BP. Discrete ECG acquisition device and a commercial electronic stethoscope are used in this experiment.

The first experiment included 16 male subjects aged 22-27. Throughout the signal recording, the subjects were seated in temperature-controlled room (24+/-2℃) and were asked to keep quiet. The experimental session involved three periods: rest, immediately after step-climbing exercise, and recovery from exercise, each with four trials. The phonocardiograms (PCG) and electrocardiograms (ECG) were simultaneously recorded for 20 seconds at a sampling rate of 5 kHz with DATAQ Instrument. Blood pressure was measured immediately after each signal recording by a standard oscillometric BP meter (Model BP-8800, COLIN) at the left upper arm as a reference. During the step-climbing period, the subjects were asked to accomplish 109 step-climbing four times and the data were recorded immediately post-exercise. During the rest and recovery periods, the time interval between any two trials was 3 minutes to avoid too frequent occlusions.

The second experiment served as a reproducibility test, in which 25 subjects, including 14 males and 11 females, were recruited. The experimental recordings included one trial at rest, two trials immediately after treadmill exercises, and two trials at recovery periods. The phonocardiograms (PCG) and electrocardiograms (ECG) were simultaneously recorded for 20 seconds at a sampling rate of 1 kHz with DATAQ Instrument. In the experiments, BP was also measured in each trial by a standard oscillometric BP meter at the left upper arm as a reference.

In both experiments, the signals were processed offline by Matlab® Programming. The average value of Tr-s2 was calculated automatically for each trial.

Results

After dynamic exercise, the substantial changes were shown in the arterial blood pressure, including systolic (SBP) and diastolic blood pressure (DBP), and heart rate (HR). Fig. 3 demonstrates the changes in SBP, DBP and HR under three conditions in the first experiment. In comparison with the rest condition, BP and HR increased significantly immediately after exercise, while BP came to original level quickly and HR is still much higher than the original in the recovery period.

Several meaningful intervals can be measured from ECG and PCG signal. Beside the Trs2, there are Ts1-s2, which is defined as the time from the first heart sound and second heart sound and represent the systolic time, Ts2-s1, which is time from the second heart sound to the following first heart sound and represent the diastolic time, and RRI, which is the interval between adjunct two R peak and represent the time course for a whole cardiac cycle. Fig. 4 gives the changes in these intervals under three conditions in the first experiment. Table 1 gives the changes in percentage of the interval

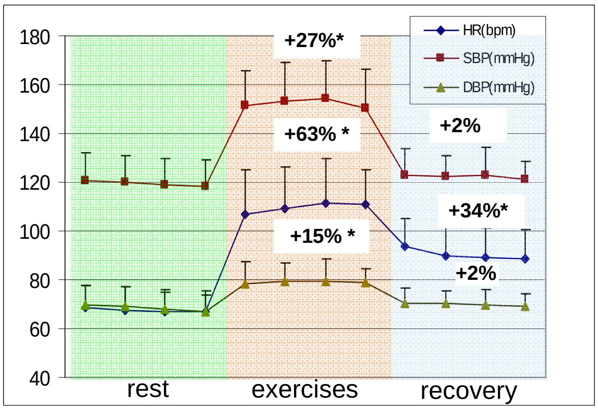

Figure 3: The changes in SBP, DBP and HR under three conditions in the first experiment (*p<0.05 indicating that the change is significant).

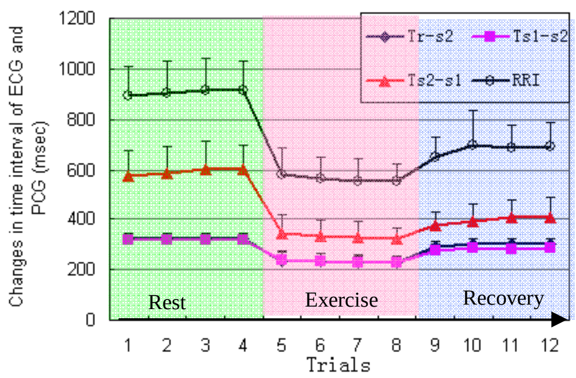

Figure 4: The changes in intervals measured from ECG and PCG signals under the first experiment.

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immediately after exercise and during the recovery in comparison with under the rest conditions. It is shown that the amount of change in percentage in Ts1-s2 is similar to that of the R-R interval. All changes are statistically significant. However, the changes in Tr-s2 and Ts1-s2 were smaller that of R-R interval.

The correlation between Trs2 and arterial blood pressure, including SBP and DBP, has been studied. It is found that there are a high linear correlation between 1/Tr-s2 and systolic BP, and a moderate linear correlation between 1/Tr-s2 and diastolic BP in both experiments. Table 2 gives the mean ± SD of the correlation coefficients between the BP and 1/Tr-s2 for all subjects in two different experiments, which involve different subjects and different experiment protocol. However, the high correlations are reproducible in these experiments.

Table 1: The changes in percentage of the intervals measured from ECG and PCG signal.

	Tr-s2	T_{s1-s2}	T_{s2-s1}	RRI
Exercise	-29% *	-27% *	-44% *	-38% *
Recovery	-8% *	-11% *	-33% *	-25% *

* indicate that the change is statistically significant.

Table 2: The mean ± SD of the correlation coefficients between the BP and 1/Tr-s2 for all subjects (N is the number of subjects)

	Systolic BP	Diastolic BP
Experiment I (N=16)	0.892 ± 0.101^{0}	0.684 ± 0.157^{2}
Experiment II (N=25)	0.879 ± 0.105^{1}	0.647 ± 0.323^{16}

* The superscript represents the number of subject with p>0.05.

Table 3: The mean ± SD of the differences between measured and estimated values.

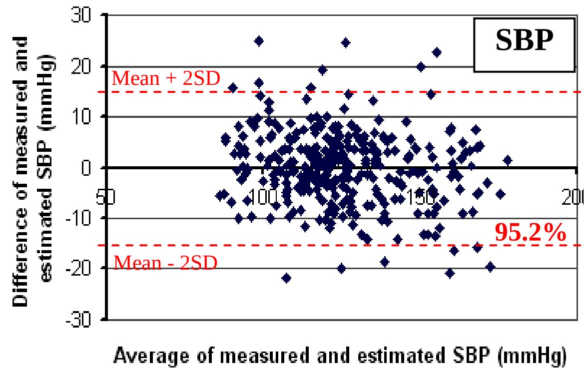
	Systolic BP (mmHg)	Diastolic BP (mmHg)
Experiment I	0±6.674	0±4.418
Experiment II	0±8.032	0±3.579

An optimal linear estimation of BP was obtained in the sense of least-mean-square fitting for each experiment. The mean and standard deviation (SD) of the differences between the measured and estimated values were given in Table 3.

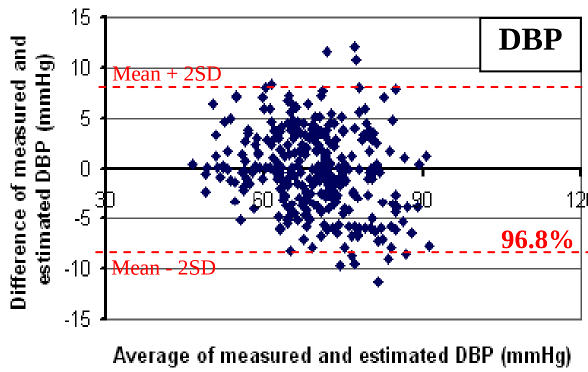
All the estimated and measured values in two experiments were combined and presented in Bland-Altman plots, respectively for systolic and diastolic BP, as shown in Fig. 5. It is found that 95.2% of differences for systolic BP and 96.8% of differences for diastolic BP were in the range of [mean-2SD, mean+2SD], which indicated that the both of estimated SBP and DBP agreed with the measured values reasonably well.

Discussion

The time interval from R wave of ECG to the second heart sound (S2) represent the time of contraction and ejection of blood from the ventricles. This parameter depends on heart rate to some extent. After the dynamic exercise, the heart rate increased dramatically, Tr-s2 become shorter greatly. According the relationship in equation (1), there are close relationship between the changes in heart rate and arterial blood pressure. This partly explains the inverse correlation between BP and Tr-s2. At the same time, because the vessels display dynamic compliance, increasing the rate of ventricular ejection (as occurs with increased ventricular inotropy) will increase the pulse pressure (i.e. the difference between SBP and DBP) compared to the same volume ejected at a lower rate [6].



(a)



(b)

Figure 5: Bland-Altman plot: (a) Systolic BP and (b) Diastolic BP.

$$MAP = SV \times HR \times SVR \qquad (1)$$

Where MAP: mean arterial blood pressure,
SV: stroke volume,
HR: heart rate,
SVR: systemic vascular resistance

There is inter-subject difference in the estimation results, because the cardiovascular parameters are different from subject to subject. Therefore, individual calibration is needed in reality.

Conclusions

The present study demonstrated that a close correlation between 1/Tr-s2 and systolic BP was reproducible in two experiments. Furthermore, the BP estimated by least-mean-square fitting agreed well with measured BP, suggesting that by using 1/Tr-s2, it is possible to realize noninvasive and continuous monitoring of BP on an electronic stethoscope.

Acknowledgement

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