IMPROVED ENSEMBLE AVERAGE APPROACH FOR SYSTOLIC BLOOD PRESSURE ESTIMATION

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ABSTRACT

There are many existing wearable devices which are meant to measure blood pressure and heart rate using the Electrocardiogram (ECG) and Photoplethysmogram (PPG), and can be worn on the wrist or finger. However, the future trend of wearable devices is moving towards head-mounted devices. Pulse wave transit time (PWTT) is used as a non-invasive and cuffless method for blood pressure estimation. Therefore, a question needs to be asked if Systolic Blood Pressure (SBP) can be measured or estimated from ECG and PPG recordings from the head. In this study, ECG signals from the head were first extracted by using improved ensemble averaging approach to compute for the $PWTT_{head}$ with reference to the Photoplethysmogram (PPG) signals from the earlobe. The chest ECG signals (lead II) and fingertip Photoplethysmogram (PPG) signals were simultaneously recorded with the head recordings and earlobe PPG to be used as reference signals to measure the $PWTT_{chest}$ from the chest and to verify the performance of the $PWTT_{head}$ measured from the head. The results obtained were analyzed by using regression plots, Bland-Altman plots and hypothesis test. The mean error ±SD (standard deviation) based on $PWTT_{head}$ for the 7 different recorded positions were from -90° Finger position, Sit Rest position, Stand Rest position, 45° head position, Supine position, 45° finger position and 90° head position. The mean error ±SD for -90° Finger position (2.6364 ± 2.5406 mmHg) and Sit Rest position (2.8182 ± 2.6007 mmHg) were within the ANSI.AAMI SP10:2002 standards for non-invasive blood pressure accuracy (±5[mmHg] mean error, 8[mmHg] standard deviations). Overall, this research has contributed a new ensemble based approach to estimate SBP from the head by extracting head ECG using earlobe PPG.

ABSTRAK

Terdapat banyak alat sedia ada yang boleh dipakai dengan tujuan untuk mengukur tekanan darah dan denyutan jantung menggunakan Elektrokardiogram (EKG) dan Photoplethysmogram (PPG), dan dipakai pada pergelangan tangan atau jari. Walau bagaimanapun, trend masa depan alat peranti boleh pakai sedang menuju ke arah pemakaian alat yang dipasang pada kepala. Masa transit gelombang nadi (PWTT) digunakan sebagai kaedah non-invasif dan mudah untuk anggaran tekanan darah. Oleh itu, soalan yang perlu ditanya ialah jika Tekanan Darah Sistolik (SBP) boleh diukur atau dianggarkan daripada rakaman EKG dan PPG dari kepala. Dalam kajian ini, isyarat EKG dari kepala telah diekstrak melalui rangsangan menggunakan pendekatan *ensemble averaging* untuk mengira $PWTT_{head}$ dengan merujuk kepada isyarat Photoplethysmogram (PPG) dari telinga. Isyarat EKG dada (*lead II*) dan isyarat Photoplethysmogram (PPG) hujung jari telah dirakam secara serentak dengan rakaman kepala dan telinga PPG untuk digunakan sebagai isyarat rujukan bagi mengukur $PWTT_{chest}$ dari dada dan untuk mengesahkan prestasi $PWTT_{head}$ yang diukur dari kepala. Hasil yang diperoleh telah dianalisis dengan menggunakan plot regresi, plot Bland-Altman dan ujian hipotesis. Purata ralat ±SD (sisihan piawai) berdasarkan $PWTT_{head}$ untuk 7 kedudukan berbeza yang direkodkan adalah untuk kedudukan jari -90° , kedudukan *Sit Rest*, kedudukan *Stand Rest*, posisi kepala 45°, posisi *Supine*, kedudukan jari 45° dan kedudukan kepala 90°. Purata ralat ±SD untuk kedudukan jari -90° (2.6364 ± 2.5406 mmHg) dan kedudukan *Sit Rest* (2.8182 ± 2.6007 mmHg) berada dalam standard ANSI.AAMI SP10:2002 untuk ketepatan tekanan darah non-invasif (± 5[mmHg] kesilapan min, 8[mmHg] sisihan piawai). Secara keseluruhannya, kajian ini telah menyumbangkan pendekatan baru untuk menganggarkan SBP dari kepala dengan mengekstrak EKG kepala menggunakan PPG telinga..

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LIST OF ABBREVIATIONS

ABR	-	Auditory Brainstem Response
BSS	-	Blind Component Separation
BP	-	Blood Pressure
E-ABR	-	Electrically Evoked Auditory Brainstem Response
ECG	-	Electrocardiogram
EEG	-	Electroencephalogram
EOG	-	Electro -Oculogram
EMG	-	Electromyogram
ERP	-	Event-Related Potentials
HR	-	Heart Rate
HRV	-	Heart Rate Variability
IoT	-	Internet of Things
LED	-	Light-Emitting Diode
LMS	-	Least Mean Squares
NCDS	-	Non-Communicable Diseases
PPG	-	Photoplethysmography
PPI	-	Peak-To-Peak Interval
PTT	-	Pulse Transmit Time
PWTT	-	Pulse Wave Transmit Time
PWV	-	Pulse Wave Velocity
RMSE	-	Root Mean Square
RRI	-	RR Intervals
RMSE	-	Root Mean Square
SAECG	-	Signal-Averaged Electrocardiogram
SIPM	-	Silicon Photo Multiplier
SD	-	Standard Deviation
VEP	-	Visual Evoked Potential
WHO	-	Internet of Things

LIST OF SYMBOLS

L	-	Distance the Pulse Travels
E	-	Elasticity
E_0	-	Zero-Pressure Modulus
ζ	-	Constant
$\triangle P$	-	Changes of Blood Pressure
$\triangle V$	-	Changes in Volume
c	-	Propagation Speed of the Wave
ρ	-	Blood Density
$PWTT_{head}$	-	Pulse Wave Transmit Time Measured from Head ECG and Earlobe PPG
$PWTT_{chest}$	-	Pulse Wave Transmit Time Measured from Chest ECG and Fingertip PPG
Hz	-	Hertz
S_n	-	Signal
σ_n	-	Standard Deviation of Noise
y (t)	-	The Recorded Signal
Y	-	Systolic Blood Pressure
x_t	-	Measured Systolic Blood Pressure
$\hat{x}_t$	-	Estimated Systolic Blood Pressure
S_{raw}	-	The Raw Signal
$\bar{S}_{raw}$	-	Mean of the Raw Signal
S_1	-	Maximum Value of Signal Obtained
S_{norm}	-	Normalized Signal
T_{Rpeak}	-	Occurrence of the R-peak
T_{length}	-	Total Length of the average in time domain and the occurrence time of the Systolic PPG peak

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The blood pressure is an essential parameter for medical diagnostics, prevention and therapy strategies. Blood pressure can used to monitor many illnesses such as stroke, hypertension and various cardiac diseases. With the ubiquity of hypertension, there is huge demand from the medical community to dispose a quality blood pressure monitoring system, targeting improved hypertension diagnostics and blood pressure management (Chan *et al*., 2005). There are mainly two categories to measure blood pressure in recent days, which are the cuff-less blood pressure monitoring and upper arm blood pressure measurement (Bagha *et al*., 2011). For upper arm blood pressure measurement, an indirect and non-continuous blood pressure technique by using an inflatable cuff and stethoscope is used. In the cuff-less blood pressure monitoring, the users can benefit from the continuous blood pressure estimation without using any inflatable cuff.

The continuous blood pressure estimation is usually based on a models related to Pulse Wave Velocity (PWV). PWV is defined as the velocity of the pulse wave propagating inside the blood vessels. The blood pressure is proportional to the PWV. The increase in the blood pressure will cause an increase in the velocity of the pulse wave travelling in the blood vessels. Due to the difference in the length of blood vessels, there is a time interval between the pulse waves measured from heart and body peripheral, which is called Pulse Transit Time (PTT) or Pulse Wave Transmit Time (PWTT). Specifically speaking, what the PWV models depends on is actually PTT.

In recent times, many researches were conducted to perform non-invasive continuous BP monitoring. Using pulse wave transmit time (PWTT) as a variable to estimate Systolic blood pressure (SBP) noninvasively have shown many positive results in numerous studies (Lass *et al.*, 2004; Zakaria *et al.*, 2010; Jeong *et al.*, 2005; Puke *et al.*, 2013). PWTT calculation requires Electrocardiogram (ECG) and Photoplethysmogram (PPG) signal data. PWTT is the time interval between the R peak of ECG and the minimum point of PPG signal (Zhang *et al.*, 2008). The ECG signal which is required for PWTT calculation is usually acquired from various points like chest and limb. However, the ECG wearable devices that are used to acquire ECG from chest and limb are bulky and tend to be unconformable.

1.2 Background of the Problem

There have already been wearable devices which are just meant to measure the heart rate using the ECG, and worn on the wrist or on the chest (Lo and Tsai, 1998). However, the future trend of wearable devices is moving towards head mounted wearable. On June, 2015, Intel has accelerated its entry in head mounted wearable devices by acquiring Recon (Walden, 2015). This acquisition helped Intel in expanding their market for head mounted display products and technologies. Therefore, questions need to be asked if ECG can be recorded across the head or anywhere on the surface area of the head.

In many physiological signal acquisition from the head, ECG signal is treated as artifact (Park *et al.*, 1998) ,(Lu *et al.*, 2009) , (Lv *et al.*, 2010). However, we can put good use to the ECG signal from the head if we are able to filter it from other physiological signals from the head such as electroencephalogram (EEG), EOG (electro-oculogram) and EMG (electromyogram).

ECG signal can also be obtained from the head. Since the PPG signal can be obtained at the earlobe (Jeong *et al.*, 2005), it will be ideal to acquire ECG from the head which will contribute in reducing the hydrostatic pressure to improve the accuracy of SBP estimation via PWTT. Hydrostatic pressure is caused by the presence of joints (the arm, wrist, or neck) between two measurement points (Puke *et al.*, 2013).

1.3 Problem Statement

There are several challenges to be encountered in filtering ECG signal from the head. For example, the frequency range of ECG is between 0.05Hz to 100 Hz (Saritha *et al.*, 2008) and the scalp EEG range is in between 1 to 100 Hz (Bernhardt, 1979) which overlaps the ECG frequency range. Moreover the amplitude of ECG signal is in range of $10mV_{p-p}$ and $30\mu V_{p-p}$, (Da He *et al.*, 2012) at the head may attenuate to the amplitude range of EEG signal which lie between 10 and 100 µV (in adults, more commonly between 10 to 50 µV) (Niedermeyer). One good way to extract ECG from the head is by using a similar method that has been used to filter Event-related potentials (ERP) from the scalp EEG.

ERPs are very small voltages generated in the brain structures in response to specific events or stimuli (Picton *et al.*, 2000). ERP are recorded from the scalp and extracted from ongoing EEG using filtering and signal averaging techniques (Sur and Sinha, 2009). ERP can be obtained from simultaneous recording of EEG and the event stimulus (E.g. is Visual Evoked Potential (VEP) and Auditory Brainstem Response (ABR)). In Electrically evoked auditory brainstem response (E-ABR), in order to retrieve small responses in the magnitude below micro-volts embedded in an EEG signal a 100 times stronger, the signal has to be averaged over a number of measurements. During the averaging, the EEG signal is aligned to the stimulus as a time reference (Bahmer *et al.*, 2008). Therefore in similar manner, an event stimulus can be used to extract ECG signal from the head by aligning the stimulus to the physiological signals recording from the head.

In this study, a PPG signal from the earlobe is proposed to be treated as the event stimulus to extract the ECG signal from the head. This research will propose a head based method using ensemble average approach to extract the QRS complex in the electrocardiogram (ECG) signal from physiological signals recording on the head using PPG signal from earlobe to act like an event stimulus. From this extraction, we will then compute the PWTT using the head ECG and earlobe PPG to estimate SBP.

1.4 Research Questions

The research questions to be answered in this research are as follows:

i. What are the existing techniques to estimate Systolic Blood Pressure?

ii. Can Systolic Blood Pressure be estimated by using Pulse wave transmit time computed from head Electrocardiogram and earlobe Photoplethysmography?

iii. How to validate the performance of the Pulse wave transmit time values computed from head Electrocardiogram and earlobe Photoplethysmography?

1.5 Research Goal and Objectives

To propose a head based method to extract Electrocardiogram signal from the head to estimate Systolic Blood Pressure. To accomplish this goal, the following objectives are proposed for this study:

i. To analyze the feasibility of using head Electrocardiogram and earlobe Photoplethysmography signal to estimate Systolic Blood Pressure.

ii. To propose an ensemble average approach to compute Pulse Wave Transmit Time from head to estimate Systolic Blood Pressure.

iii. To evaluate the performance of the head based Pulse Wave Transmit Time method in estimating Systolic Blood Pressure.

1.6 Motivation of the Study

The main motivation of this study is the future trend of wearable devices which is moving towards the head mounted wearables. The head based method to extract ECG signal from the head to estimate SBP of this study can be potentially integrated into an eyewear device. The R-peak timings of the Head ECG is proven to be similar with the R-peak timing to the ECG obtained from the body such as the ECG (lead I) measured from the arms (Ahn *et al.*, 2019). Since PWTT is the time interval between the R peak of ECG and the minimum point of PPG signal (Zhang et al., 2008), the head ECG signal can be used for PWTT computation in combination with the earlobe PPG to estimate SBP from the head region.

1.7 Scope of the Study

The head ECG signals are first extracted from the physiological signals recording from the head using the proposed method. These extractions are first attempted using the simultaneously recorded earlobe PPG signal as the event stimulus. From this extraction, $PWTT_{head}$ is computed from the head ECG signal and earlobe PPG signal. In this thesis, we refer to this method as $PWTT_{head}$ method. For the signal extraction and analysis, MATLAB 2015a simulation tool are used. The $PWTT_{head}$ and $PWTT_{chest}$ is also computed from the chest ECG signal and fingertip PPG signal to study and compare the performance of the $PWTT_{head}$ in estimating the SBP. The method used to compute the $PWTT_{chest}$ is referred to as $PWTT_{chest}$ method in this thesis. For the result analysis, regression plots, Bland-Altman plot, hypothesis test, difference error, mean error, root-mean-squared error (RMSE) and standard deviation and are used.

1.8 Significance of the Study

The establishment of this research can be potentially integrated with existing eyewear devices and can be also integrated with normal eyewears such as spectacles or sunglasses for continuous blood pressure and health monitoring purpose. Besides this, the future eyewear devices can use the similar points established in this research to record the head ECG signal and also the SBP from head. This research will be an important contribution to the National Internet of Things (IoT) Strategic Roadmap (Ahmad Helmi, A. B.,*et al*., 2014) in utilizing IoT for wearable devices that tracks daily activities and vital signs for healthcare purposes.

1.9 Thesis Organization

The chapter 1 provides the introduction to the research, background of the problem, problem statement, research questions, research goal and objectives, scope of the study and significance of study. Chapter 2 provides literature review of the research. The review will discuss on Electrocardiogram, Photoplethysmography, statistics on cardiovascular diseases, PWTT computation using ECG and PPG to estimate SBP, researches related to chest based PWTT method, physiological signal artifacts from the head region, ensemble averaging approach for noise reduction, noise removal from the head ECG using ensemble averaging approach and research gaps in chest based PWTT methods. Chapter 3 presents the research methodology. It shows the operational framework of the research, research plan and procedure and data sources. Subsequently, the methods used for result analysis and comparison of the research data is explained in detail. Chapter 4 discusses on the head based $PWTT_{head}$ method and the improved ensemble average approach used in the proposed method with great detail. It discusses on the design of the method and discusses the 5

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