

Cuffless Blood Pressure Estimation during Exercise Stress Test

S. Mottaghi, M. H. Moradi, and L. Roohisefat

Abstract—Blood Pressure (BP) measurement without using a cuff is an interesting goal especially during Exercise Stress Test. Conventional methods like Cuff-based blood pressure measurement is not accurate enough due to high motion artifacts. High blood pressure during exercise test will cause pain and discomfort during inflation of cuff as well. Many researches have been conducted and shown Pulse Arrival Time (PAT), can be used in blood pressure estimation. This paper proposes a new calibration method for blood pressure estimation during exercise stress test that increases the quality of estimation. Besides PAT and heart rate, estimated blood pressure of previous stage is added as another input parameter. This technique increases the correlation coefficients between real and estimated blood pressures. We also show that by using Δ PAT, Δ HR instead of PAT and HR quality of estimation improves.

Index Terms—Pulse transit time, pulse arrival time, bruce protocol, exercise stress test, calibration, delta PAT, delta HR.

I. INTRODUCTION

Blood Pressure (BP) is a very important vital sign of body that should be measured accurately and periodically for health care purposes. BP measurement contains systolic blood pressure (SBP) and diastolic blood pressure (DBP) measurement. BP can be measured both invasively and non-invasively; BP cannot be measured invasively during exercise stress test. Auscultatory method measures BP by inflation and deflation of a cuff, however this method is time consuming and has pain and also discomfort [1]. Many studies have been conducted on associating biological signals with BP which have focused on Pulse Arrival Time (PAT) [2]-[4].

Exercise stress test is a physical test that challenges and evaluates the performance of the cardiovascular system by putting the body under the physical pressure. Cardiovascular disease is one of the most common illnesses among people. Physicians usually peruse the cardiovascular performance of the patient by exercise stress test before any invasive operation like angiography. Blood pressure monitoring during exercise stress test is very important. Patients might face chest pain or unusual shortness of breath. If any unusual increase, decrease or no change in BP is seen the test should be stopped immediately.

Some researchers have been conducted on relations

between BP and PAT during exercise test [5]-[8]. Moreover some models have been introduced as well to estimate BP using PAT [10]-[13]. Self-calibration is proposed in almost all of the methods to tune the outputs [9].

Heart rate also used as an important factor in BP estimation beside the PAT. Some studies have empirically observed that for some records in the MIMIC database, BP is highly correlated with instantaneous heart-rate (HR). It has been shown that as heart rate increases, the cardiac output increases as well, and therefore BP increases linearly with HR [9].

II. METHODOLOGY

This test was conducted on 55 healthy subjects including 24 Females and 31 males, aged between 19 years to 60 years old. No disease has been detected in the subjects in the last 3 months. The subjects were asked not to eat heavy meal and drink beverage for at least 2 hours and 30 minutes before the test. PPG and ECG signals were sampled at 1KHz and recorded by AD instrument acquisition system (PowerLab /8SP) during the test. Meanwhile BP and HR were measured simultaneously by Bionet Holter (Model: BM1) that the BP measuring module is from SUNTECH company. Exercise stress test has been conducted according to Bruce Protocol test and a treadmill (Model 870A, Ram, Italy) was used for the test. BP was measured on subject's left arm.

Exercise stress test has 6 stages: Rest, Stage 1, Stage 2, Stage 3, 1-minute Recovery and 5-minute Recovery. Speeds and gradients of the treadmill for three stages are listed in Table I. Initially subjects were asked to rest in sitting position for 5 minutes and at the end of this time, recording ECG, PPG and HR signals was started. After 20 seconds, BP was measured once. Then subject started walking on treadmill in stage 1. Each stage lasted 3 minutes and at the end of the 3rd minute, subject stood on the border of treadmill for 10 seconds of PPG and ECG noiseless recording. Then 15 seconds BP measurement was carried out. Afterwards, the subject went to stage 2 and this procedure went on. After stage 3 subjects sat and 2 recovery stages as is shown in Fig. 1, were conducted. Fig. 1 shows the protocol of the test has been conducted in this research.

The signals were analyzed offline using Matlab to determine the R-peak of ECG, and foot point of PPG. Peak and foot detection algorithm which is introduced in [10] is used in this test. PAT_f is the time interval between the R-wave of ECG and the foot point of PPG signal.

We collected 275 datasets in total over 55 subjects. PTT and HR and BP_{i-1} were selected as inputs. BP of previous stages is selected as a set point in order to calibrate the estimation. Before starting the test, blood pressure of subjects is measured once by automatic cuff-based device.

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TABLE I: SPEEDS AND GRADIENTS OF EACH STAGE IN BRUCE PROTOCOL EXERCISE STRESS TEST.

Stage	Speed (km/hr)	Speed (mph)	Gradient (%)
1	2.74	1.7	10
2	4.02	2.5	12
3	5.47	3.4	14

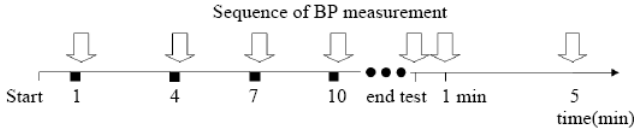


Fig. 1. Time line of the conducted test.

A. Self-Calibration

Pulse arrival time and heart rate are in relation with blood pressure. By Least Squared estimation method, the inputs-output relation is as:

$$BP = A \times (PAT) + B \quad (1)$$

$$BP = A \times (PAT) + B \times HR + C \quad (2)$$

$$BP = A \times (PAT) + B \times HR + C \times BP_{i-1} + D \quad (3)$$

In this relation, PAT is the averaged of PAT s during 10 seconds standing on the borders in each stage, HR is the heart rate measured by the holter in that time and BP is the blood pressure of previous stage. BP can be first time blood pressure measurement or estimated ones in the next stages. By LS algorithm, coefficients A , B , C and D were calculated. Fig. 2 shows the flow chart of this cuff-less blood pressure measurement.

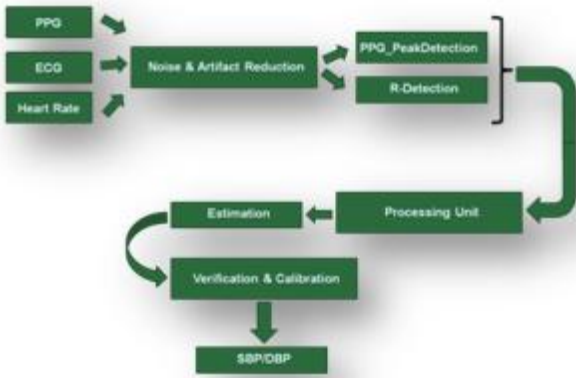


Fig.2. Flowchart of PAT-based blood pressure estimation.

B. Differentiated Inputs with Self-Calibration

Using ΔPAT and ΔHR instead of PAT and HR as inputs, is a method that can be used during exercise stress test. Since the physicians should know the BP every 3 minutes, these differences can be very useful to improve the quality of estimation. LS modeling of blood pressure by using differences are as:

$$BP = A \times (\Delta PAT) + B \times \Delta HR + C \times BP_{i-1} + D \quad (4)$$

$$\Delta PTT = PAT_i - PAT_{i-1} \quad (5)$$

$$\Delta HR = HR_i - HR_{i-1} \quad (6)$$

Delta means differences between the PAT and HR values of current stage and previous stage. Only one previous stage is considered here.

III. RESULTS

Table II compares RMSE of 4 different LS estimators. The first 2 rows are non-calibrated with only PTT and $PTT-HR$ inputs while rows 3 and 4 are calibrated. Fig. 3 shows this comparison better. Calibrated methods have lower errors and delta algorithm has the minimum errors among all algorithms.

TABLE II: ROOT MEAN SQUARED ERROR (RMSE) FOR DIFFERENT ALGORITHMS IN SBP AND DBP.

Algorithm	SBP	DBP
	RMSE	RMSE
PTT	9.23	8.34
HR PTT	8.94	8.02
PTT HR BP	5.671	4.651
dPTT dHR BP	5.21	4.321

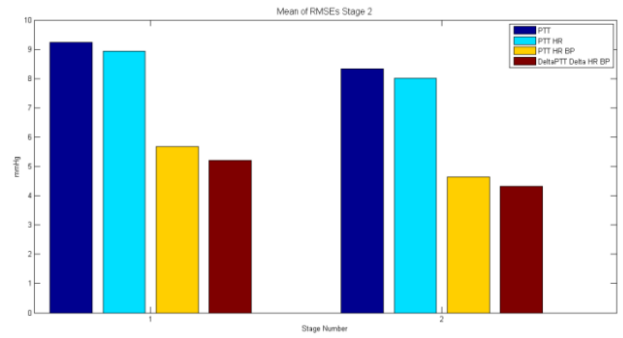


Fig. 3. Bar chart of estimation RMSE for SBP and DBP in Algorithms in Table II.

Table III and Fig. 4 also compare correlation coefficients between real and estimated values of these 4 types of estimators. Correlation coefficients are higher in calibrated algorithm. Delta-calibrated method is the highest.

TABLE III: CORRELATION COEFFICIENT (RMSE) FOR DIFFERENT ALGORITHMS IN SBP AND DBP.

Algorithm	SBP	DBP
	Correlation	Correlation
PTT	0.492	0.485
HR PTT	0.522	0.499
PTT HR BP	0.645	0.512
dPTT dHR BP	0.691	0.578

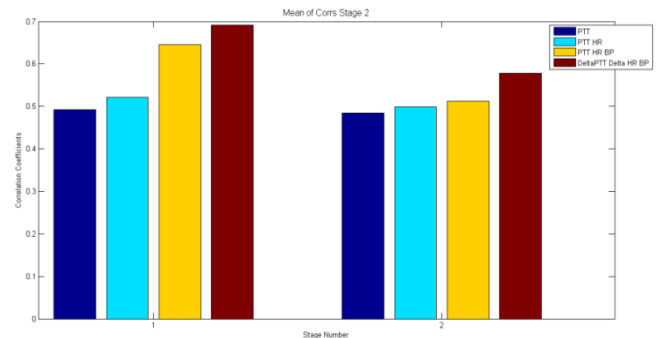


Fig. 4. Bar chart of correlation coefficients. Comparison between real and estimated values for SBP and DBP in algorithms in Table III.

IV. DISCUSSIONS

Our results suggest that this calibration method and using ΔPAT and ΔHR can improve the quality of blood pressure monitoring during exercise stress test. This method increases the correlation and decreases the errors of both systolic and diastolic blood pressure estimation.

Here are two different comparisons of our estimation algorithms and the result of other researches:

- 1) Table IV compares correlation coefficients of estimator described by Equation 4 in this article and the result reported in [3]. Researchers have used the recorded signals of 56 subjects in MIMIC database [3]. This result is comparable to rest stages in our project. The RMSE of our non-delta calibrated algorithm is lower compared to the error in [3].
- 2) In another research conducted in 2007 [9], a fuzzy type II based estimator is used to estimate 10 subjects' Systolic and diastolic blood pressures only using their heart rate. Table V compares the result of this research with system of Eq9 as the best linear estimation system with the RMSE reported in [9]. Delta-calibrated algorithm has lower errors in both systolic and diastolic blood pressure estimation than reported in [9].

TABLE IV: ROOT MEAN SQUARED ERROR (RMSE) REPORTED IN [3], IN COMPARISON WITH ALGORITHM DESCRIBED IN EQUATION 3 IN SBP AND DBP.

	SBP(mmHg)	DBP(mmHg)
Algorithm	RMSE	RMSE
Ref[3]	8.36	5.9
Eq(3)- Stage1	5.24	3.71
Eq(3)-StageR1	7.1415	3.9929

TABLE V: ROOT MEAN SQUARED ERROR (RMSE) REPORTED IN [9], IN COMPARISON WITH ALGORITHM DESCRIBED IN EQUATION 4 IN SBP AND DBP.

	SBP(mmHg)	DBP(mmHg)
Algorithm	RMSE	RMSE
Ref[1 [9]	7.032	5.2555
Eq(4)- Stage1	5.671	4.651
Eq(4)-StageR1	6.5415	3.9929

V. CONCLUSIONS

In this paper we introduced a calibration method for cuffless BP estimation using PAT , HR for the exercise stress test application. Cuff-based BP measurement is not accurate during exercise stress test because of high level of motion artifacts and pain caused by inflation of cuff in high blood pressure. Because of simplicity of the algorithm, BP measurement can be very faster and more accurate during physical activities by using this method of calibration. It would be better if the design of the systems becomes age-grouped. Dividing people into age interval groups might increase the accuracy of the estimation. Delta- PAT and delta- HR used in this paper has higher correlation with BP than PAT and HR and then can be used in wearable devices for athletes as well. Further studies will be done on design of more intelligent algorithms to develop robust, accurate and

reliable devices.

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