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Cuffless and Noninvasive Measurement of Systolic Blood Pressure, Diastolic Blood Pressure, Mean Arterial Pressure and Pulse Pressure using Radial Artery Tonometry Pressure Sensor with Concept of Korean Traditional Medicine

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***Abstract*—parameters for noninvasive diagnosis and monitoring of cardiovascular disease. We developed a new method to measure blood pressure (BP) noninvasively without cuff. In Korean traditional medicine, the degree of the pulse depth is one of the important criteria to diagnosis. We combined this concept with pulse wave analysis. With clinical data obtained from 163 subjects, we selected APm (applied pressure which has a maximum value of pulse wave), elasticity of wrist tissue, depth of blood vessel, cardiac output and h1 as parameters to estimate blood pressure. And with the parameters, we induced multi regression equation of systolic blood pressure (SBP), diastolic blood pressure (DBP), mean arterial pressure (MAP) and pulse pressure (PP). And the probabilities of these parameters to explain SBP, DBP, and MAP were 89.5%, 91.1% and 94.6%, respectively. To estimate PP, we added h1 to the parameters to explain PP was 97.5%. We compared the estimated SBP, DBP, MAP and PP through the multiple regression equations to the actual measured SBP, DBP, MAP and PP through the wrist type BP meter. Differences were (± SD) 0.38 ± 9.95, -1.0 ± 8.2, 0.02 ± 6.9 and 0.05 ± 5.9mmHg for SBP, DBP, MAP and PP, respectively. According to the American National Standard for Electronic or Automated Sphygmomanometers, the mean difference (MD) should be ± 5mmHg or less with a standard deviation (SD) of ± 8mmHg or less. Hence, the results of MAP and PP were within the limits for the AAMI SP 10 criteria and the results of SBP and DBP were not within the limits for the AAMI SP 10 criteria. The preliminary results indicate the results are quite reliable and promising.**

I. Introduction

Blood Pressure (BP) is powerful and independent risk factor for cardiovascular disease (CVD) [1]. The risk of CVD rises as BP increases. Nearly one billion people from all over the world suffer from hypertension [2]. Continuous and non-invasive BP monitoring is important to prevent CVD [3]. However, most of the prevalent BP devices are cuff-based which can measure BP intermittently because of cuff inflation and deflation [4].

Recently, cuffless BP measurement techniques based on pulse transit time (PTT) [5], [6], [7] and wavelet transform [8] have been studied. PTT refers to the duration for a pressure pulse to travel between two measuring sites in the arterial system. However, to predict BP, these techniques have to measure multi-points of the body and therefore patients may feel uncomfortable. Also, they need both the electrocardiogram (ECG) and the photoplethysmography (PPG) inducing problems in accuracy. Therefore and improved technique which needs only one point of the body and one device is necessary. Recently, a new parameter, APm, defined as the applied pressure which has the maximum pulse pressure, was proposed as an alternative to PTT for predicting BP, especially mean arterial pressure (MAP) without cuff [9], [10], [11], [12]. The previous results showed that the APm-approach was in good agreement with the BP measurement. Nonetheless, the number subjects recruited in the experiments wasn't gratify the number of subjects for the national standard. And the study induced MAP not systolic BP (SBP), diastolic BP (DBP) and pulse pressure (PP). In this project, the BP estimation based on the APm-apporoach including physiological characteristics of subjects was examined on 163 subjects. And we newly used values of estimated cardiac output and the maximum value of pulse pressure (h1) in this study.

Fig 1 illustrates the definitions of APm and h1. Namely, h1 is the maximum value of pulse pressure and APm means the applied pressure at h1 respectively.

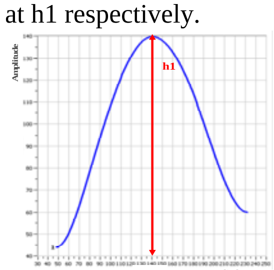

Fig 1. h1 means the maximum value of pulse pressure and APm means the applied pressure at h1

II. Methods

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A. Experiment for data collection

163 volunteers participated in this study. The study was carried out at public health center at Busan in Korea. All volunteers sat comfortably and took a rest for five minutes or more before BP measurement. Data on all subjects are summarized in Table 1.

Table 1 Clinical features of the 163 subjects in the study

BMI (kg/m^2)	20	20~24	24~30	30
	14	85	61	3

AGE (years)	20	20~30	30~40	40~50	50~60	60
	1	4	25	58	50	25

SEX	male	female
	17	146

BP	normal	Pre-hypertension	Stage 1 hypertension	Stage 2 hypertension
	96	54	12	1

*BP indicates blood pressure; normal, SBP <120mmHg, DBP<80 mmHg; prehypertension, SBP 120-139mmHg, DBP 80-89mmHg; stage 1 hypertension, SBP 140-159mmHg, DBP 90-99mmHg; Stage 2 hypertension, SBP>160mmHg, DBP>100mmHg [1]

Similar equipment and methodology were used as in the previous study including wrist type BP meter and 3-D MAC [8]. SBP and DBP were recorded on the left radial artery at heart level by commercial wrist type BP meter (OMRON R6, OMRON Corp.) with cuff. BP data, SBP and DBP, were measured five times for each volunteer and we averaged the data. With the averaged data, we calculated MAP with equation (1)

$$MAP = DBP + \frac{SBP - DBP}{3} \quad (1)$$

The obtained BP data were summarized in Table 2

Table 2 Maximum, Minimum, Mean values of SBP, DBP and MAP

	Max	Mean	Min
SBP(mmHg)	260	121.74	80
DBP(mmHg)	110	78.17	56
MAP(mmHg)	126.67	92.69	66.67

Secondly, we applied pressure on the left radial artery and recorded the pulse wave with 3-D MAC (DAEYOMEDI, Co., LTD., Ansan in Korea). We applied five different pressures on the same spot of left radial artery. With the data we obtained through five steps, we draw tendency graph to get the APm and h1. And we estimated relative values of the elasticity of wrist tissue, depth of blood vessel and cardiac output.

B. Data Handling and Analysis

Radial pressure recordings were digitized at 256 per second and stored in a computer for subsequent offline analysis.

Statistical analysis was performed using MINITAB 14 (MINITAB Corp., Pennsylvania, USA.). Multiple linear regression analysis was performed using a forward stepwise procedure (p=0.05). And results reported as partial regression coefficients of predictor variables. And to compare the actual measured BP with the estimated BP, we used the Bland-Altman plot.

III. RESULT

From 163 data we got regression equations of SBP, DBP, MAP and PP using MINITAB 14. To estimate SBP, DBP and MAP, we used APm, the elasticity of wrist tissue, the depth of blood vessel and cardiac output as parameters [13]. As mentioned above, the values of elasticity of the wrist tissue, depth of blood vessel and the cardiac output were the estimated and relative values. And the probabilities of these parameters to explain SBP, DBP, and MAP were 89.5%, 91.1% and 94.6%, respectively. To estimate PP, we added h1 to the parameters to estimate SBP, DBP and MAP because h1 has considerably high correlation with PP. And the probability of the parameters to explain PP was 97.5%.

We compared the estimated SBP, DBP, MAP and PP through the multiple regression equations to the actual measured SBP, DBP, MAP and PP through the wrist type BP meter. Table 3 shows the comparison between the SBP, DBP, MAP and PP measured by commercial wrist type cuff BP meter and the SBP, DBP, MAP and PP estimated by the regression equation.

Table 3 Comparison between estimated and measured SBP, DBP, MAP and PP

	Mean Difference (mmHg)	Standard Deviation (mmHg)
SBP	0.38	9.95,
DBP	-1.0	8.2
MAP	0.02	6.9
PP	0.05	5.9

Differences were (± SD) 0.38 ± 9.95, -1.0 ± 8.2, 0.02 ± 6.9 and 0.05 ± 5.9mmHg for SBP, DBP, MAP and PP, respectively. According to the American National Standard for Electronic or Automated Sphygmomanometers, the mean difference (MD) should be ± 5mmHg or less with a standard deviation (SD) of ± 8mmHg or less [14]. Hence, the results of the MD and SD shown in table indicate that the results of MAP and PP were within the limits for the AAMI SP 10 criteria and the results of SBP and DBP were not within the limits for the AAMI SP 10 criteria.

Figure 2 shows Bland-Altman comparisons of estimated and measured SBP, DBP, MAP and PP.

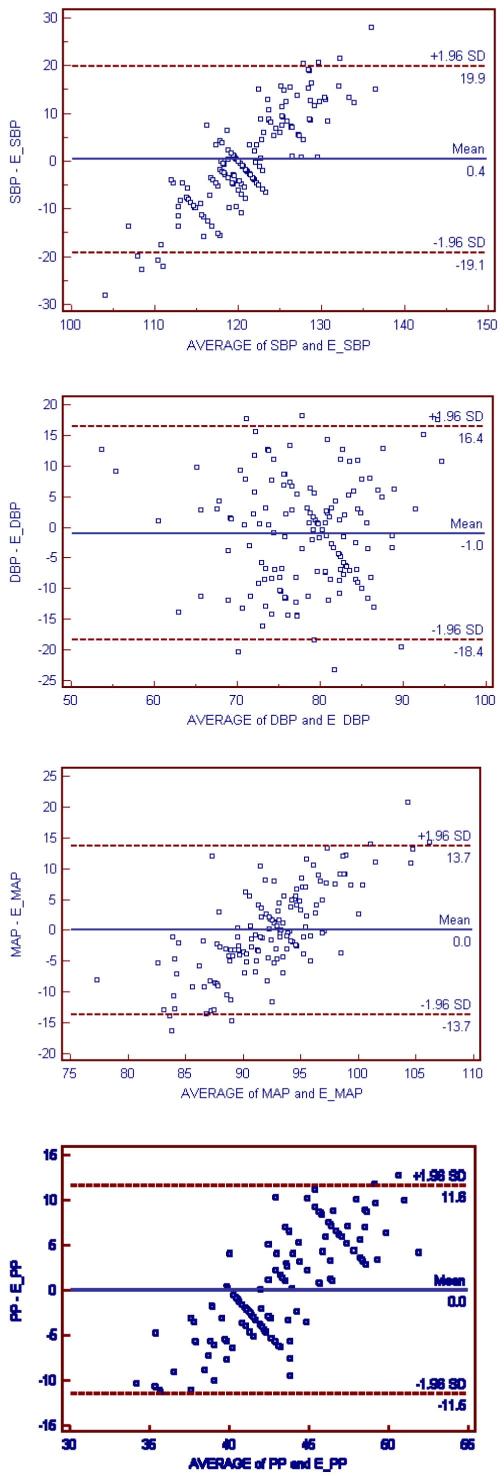

Fig 2. Bland-Altman plots for estimated and measured SBP, DBP, MAP and PP. SBP, DBP, MAP, PP are the measured values and E_SBP, E_DBP, E_MAP, E_PP are the estimated values.

We did Bland-Altman comparisons of estimated SBP, DBP, MAP and PP according to measured BP of subjects.

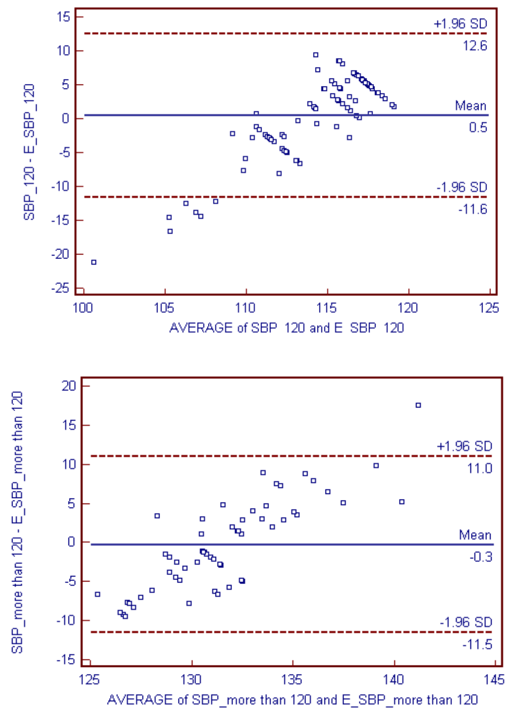

Fig 3. Bland-Altman plots for estimated and measured SBP, DBP, MAP and PP according to SBP of subjects. SBP_120 means SBP of subjects whose SBP is less than 120 (normal). SBP_more than 120 means SBP of subjects whose SBP is more than 120 (hypertension).

Bland-Altman comparisons of estimated SBP, DBP, MAP and PP according to the BP also show an upward tendency. And with this division according to BP, we could reduce mean difference and standard deviation from 0.38 ± 9.95 to 0.49 ± 6.16 for normal subjects and -0.272 ± 5.749 for hypertension subject which were within the limits for the AAMI SP 10 criteria

IV. Discussion

In Korean Traditional Medicine, the depth of the pulse on radial artery is very important factor to determine patients' health condition. The degree of the pulse depth is one of the important criteria to diagnosis. Figure 4 shows one of the diagnostic techniques of Korean Traditional Medicine. We combined the concept with pulse wave analysis.

Fig 4. One of the diagnostic techniques of Korean Traditional Medicine named the six positional pulse diagnosis.

Therefore APm were used to estimate SBP, DBP, MAP and

PP in this study. We also used the elasticity of the wrist tissue, depth of blood vessel, cardiac output and h1 as important parameters to estimate BP. We observed that the difference between estimated and measured SBP, DBP and PP have a conspicuous upward tendency as the averages of BP and estimated BP become higher. The upward tendency was same for the difference between estimated and measured SBP, DBP and PP according to BP. And with analysis of divided data according to BP, we could reduce mean difference and standard deviation from 0.38 ± 9.95 to 0.49 ± 6.16 for normal subjects and -0.272 ± 5.749 for hypertension subject which were within the limits for the AAMI SP 10 criteria. With inverse method using this fact, we could improve the accuracy of our new method. The accuracy of BP estimation may be improved by a calibration which uses the fact that the difference of measured and estimated BP had an upward tendency and that the accuracy of divided data according to BP was improved. Also this study is meaningful because it measured only one point of the radial artery with using only one device. For further study, we will do experiment with invasive catheter to compare BP with our new method [15] [16].

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