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On Employing Nonparametric Bootstrap Technique in Oscillometric Blood Pressure Measurement for Confidence Interval Estimation

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ABSTRACT

Blood pressure (BP) is an important vital signal for determining the health of an individual subject. Although estimation of mean arterial blood pressure is possible using oscillometric blood pressure techniques, there are no established techniques in the literature for obtaining confidence interval (CI) for systolic blood pressure (SBP) and diastolic blood pressure (DBP) estimates obtained from such BP measurements. This paper proposes a nonparametric bootstrap technique to obtain CI with a small number of the BP measurements. The proposed algorithm uses pseudo measurements employing nonparametric bootstrap technique to derive the pseudo maximum amplitudes (PMA) and the pseudo envelopes (PE). The SBP and DBP are then derived using the new relationships between PMA and PE and the CIs for such estimates. Application of the proposed method on an experimental dataset of 85 patients with five sets of measurements for each patient has yielded a smaller Cl than the conventional student t-method.

Key words: Blood pressure, confidence interval, nonparametric bootstrap

1. INTRODUCTION

Oscillometric blood pressure measurements have gained popularity and are used in blood pressure (BP) devices [1]. Recently, there is an increasing need to provide health care within the home of the elderly patients. This has led to an increasing demand on home biosignal measurement devices that offer consistent reliable physiological state of the patients. Of the various vital signals that provide information about the physiological state of the patient, blood pressure is a crucial signal; hence, home-based health monitoring devices should have the ability to measure blood pressure. Oscillometric BP devices have become ubiquitous in home-based and personal health care due to its ease of use. However, there is no established standard method for estimating the systolic and diastolic blood pressure from the oscillometric BP measurements. Indeed, these BP devices currently only provide single estimates for both systolic and diastolic blood pressures and do not provide a confidence interval (CI) for these estimates. There has been no study reported in the literature on estimation of CI for blood pressure measurements until recent year [2]. The study in [2] utilizes

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the conventional statistical t-method (T) to obtain the CI of SBP and DBP. Although oscillometric BP methods for blood pressure measurements are noninvasive, faster and simpler than invasive BP measurements, it is not practically feasible to obtain either over 100 measurements for each subject or repeatable conditions for reproducible BP measurements. Thus, one has to content with fewer BP measurements and this rules out the use of the standard method for CI such as the one presented in [2]; hence, there is a need to develop a method for CI that can be applied for oscillometric BP devices.

This paper uses a nonparametric bootstrap (NPB) technique that was originally presented by Efron and Tibshirani [3] to address CI estimate for statistics based on independent identical distribution (iid) random variable from some unknown distribution, $F_{\mu,\sigma}$. The CI using bootstrap method uses limited data set for obtaining accuracy and is used in places where the conventional method such as student-t method for obtaining accuracy are not valid [4]. The NPB technique is widely employed for assessing the accuracy of parameters in small data sample situations and for approximating distributions of estimators in many applications. The advantage of the NPB technique is that it does not need any modeling or assumptions on the data [4]. In our study, there are only five BP measurements per subject. The pseudo measurements (PSM) are obtained employing nonparametric bootstrap technique to obtain the CI of systolic (SBP) and diastolic blood pressure (DBP). In this new approach, pseudo maximum amplitude (PMA) and pseudo envelope (PE) are obtained from pseudo measurements (PSM) based on the oscillometric envelope and using the new relationship obtained between the PSM, PE and the mean cuff pressure (MCP), the systolic and diastolic pressures are estimated using heuristically determined systolic and diastolic ratios.

The paper is organized as follows. In the following section, the conventional techniques are introduced. In Section III, the estimation of pseudo maximum amplitude (PMA) and the pseudo envelope (PE) is presented. Experimental results are presented in Section IV. Conclusion is presented in Section V.

2. CONVENTIONAL TECHNIQUES

2.1 maximum amplitude algorithm

Based on the oscillometric envelope, the maximum amplitude algorithm (MAA) [5] is widely used to estimate the SBP and DBP, which uses SBP ratio and DBP ratio (SBPR and DBPR) to find the points which correspond to SBP and DBP [5-6]. The amplitude of the maximum point is multiplied by the fixed SBPR and DBPR obtained experimentally [1, 5-7].

$$\hat{s}(i,j) = m(i,j) \times sr \quad (1)$$

$$\hat{d}(i,j) = m(i,j) \times dr \quad (2)$$

where $\hat{s}(i,j)$ and $\hat{d}(i,j)$ denote the oscillometric amplitudes corresponding to SBP and DBP, $m(i,j)$ denotes the maximum amplitude (MA) based on the oscillometric envelope, sr and dr denote the fixed SBPR and DBPR, and $i=1,\ldots,N$ and $j=1,\ldots,M$; N and M denote the number of subjects and the number of measurements per subject. Thus, oscillometric envelope corresponding to the SBP and DBP are mapped back to the deflation cuff pressure (CP) obtaining the SBP and DBP values in mmHG as shown Fig. 1.

2.2 Nonparametric bootstrap (NPB) technique and CI estimation

In this subsection, we introduce the principle of the NPB, provide a review of basic resampling techniques, and demonstrate the use of bootstrap method to evaluate the distribution of a parameter estimate [8]. The fundamental idea is to provide a large number of independent BP estimates by re-

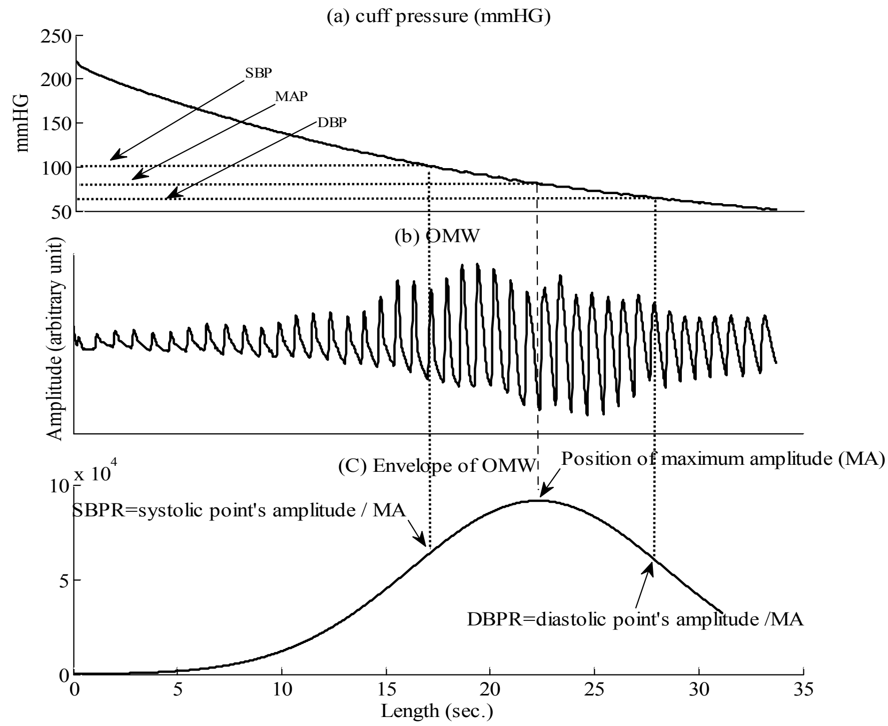

Fig. 1. The basic concept of the maximum amplitude algorithm (MAA) [1]. (a) Cuff pressure (CP); (b) Oscillometric wave (OMW); (c) Envelope of OMW.

sampling the original BP estimates, $X=(x_1,x_2,\ldots,x_n)$ of n measurements at random from a unknown probability distribution F. A bootstrap resamples $X_1^*=(x_1^*,x_2^*,\ldots,x_n^*),\ldots,X_B^*=(x_1^*,x_2^*,\ldots,x_n^*)$ are obtained by sampling n time drawn randomly with replacement from the original sample X with elements occurring zero, once or multiple times, where n is an original sample size and B is a number of resample set.

3. Pseudo maximum amplitude (PMA) and pseudo envelope (PE) using NPB

In many practical situations, it is not easy to obtain lot of measurements due to the cost reasons. Even when cost is not a main concern, the experimental conditions may not produce reproducible measurements. In such cases, one may have to resort to the technique of employing PSM as proposed in this paper. In our study, we have only 5 measurements per subject. Thus, we employ PSM to find the CI using the NPB technique [3]. As the beginning, we need to obtain the maximum amplitudes and the length of occurrence of the maxima from all the five measurements per subject, respectively.

3.1 PMA

In this section, we briefly describe the method to determine the upper and lower bounds on the CI for MA and the length position of the MA on the oscillometric envelope. The NPB method is used to determine the mean of the CI and the range for the SBP and DBP [9]. As a first step, we obtain the MAs and the length of occurrence of the MAs from all the five measurements per subject, respectively. These preliminary values of the MAs are used to determine the final PMAs using the NPB method [9].

Let $X=(x_1,x_2,\ldots,x_M)$ denote the set of five length position of the MAs and $Y=(y_1,y_2,\ldots,y_M)$ denote the set of corresponding five MAs. Employing the NPB on these two sets, we create B of resamples,

$X_j^* = (x_{1j}^*, ..., x_{Mj}^*)$, $Y_j^* = (y_{1j}^*, ..., y_{Mj}^*)$, $j = 1, ..., B$, respectively. We then compute the mean of all measurements in X_j^* and Y_j^* to obtain $\mu_{X(j)}^*$ and $\mu_{Y(j)}^*$ given by

$$\mu_{X(j)}^* = \frac{1}{M}\sum_{k=1}^{M} x_{kj}^* \quad (3)$$

$$\mu_{Y(j)}^* = \frac{1}{M}\sum_{k=1}^{M} y_{kj}^* \quad (4)$$

where M denotes the number of measurements per subject. The distributions of the bootstrap estimates $\mu_{X(j)}^*$ and $\mu_{Y(j)}^*$ are shown in Fig. 2 (a) and (b) which represent the length of occurrence of the maxima and PMA from all the five measurements per subject, respectively. We then sort the bootstrap estimates, $\mu_{X(j)}^*$ and $\mu_{Y(j)}^*$ in ascending order. Thus, the sorted PMAs are given by $\mu_{Y(1)}^* \le \mu_{Y(2)}^* \le, ..., \le \mu_{Y(B)}^*$ and the length locations of the PMAs are given by $\mu_{X(1)}^* \le \mu_{X(2)}^* \le, ..., \le \mu_{X(B)}^*$. The desired $100 \times (1-\alpha)\%$ nonparametric CI for position of PMA and the PMA are respectively given by, $(\mu_{X(Q1)}^*, \mu_{X(Q2)}^*)$ and $(\mu_{Y(Q1)}^*, \mu_{Y(Q2)}^*)$, where $Q1$ is the quotient of $B \times (\alpha/2)$, $Q2 = B - Q1 + 1$, and $Q3 = \frac{B}{2}$. For $\alpha = 0.05$ and $B = 1000$, we get $Q1 = 25$ $Q2 = 976$ and $Q3 = 500$. Thus, we obtain the three positions of the PMA that will be used by the algorithm to estimate CIs of the SBP and DBP, respectively.

3.2 PE

In order to obtain the PEs for estimating the CI of the SBP and DBP using NPB, we construct a BP measurement matrix E as in Eq. (5) consisting of envelopes for five measurements for the systolic and diastolic part of each subject such that [9]

$$E = \begin{bmatrix} e_{11} & e_{12} \cdots & e_{1N} \\ e_{21} & \cdot\cdot & \cdot\cdot \\ \cdot\cdot & \cdot\cdot & \cdot\cdot \\ e_{L1} & \cdot\cdot & e_{LN} \end{bmatrix} \quad (5)$$

where L denotes the length of PE and $N(=5)$ denotes the number of envelopes, respectively. Each column denotes an envelope of the oscillometric BP measurement. Particularly, all measurements are forced to be of length L, by either extrapolating to length L if the measurement is shorter, or by truncating the length to L if the measurement is longer. From the BP envelope matrix $\mathbf{E}$, employing NPB method, we acquire B resample envelope matrices

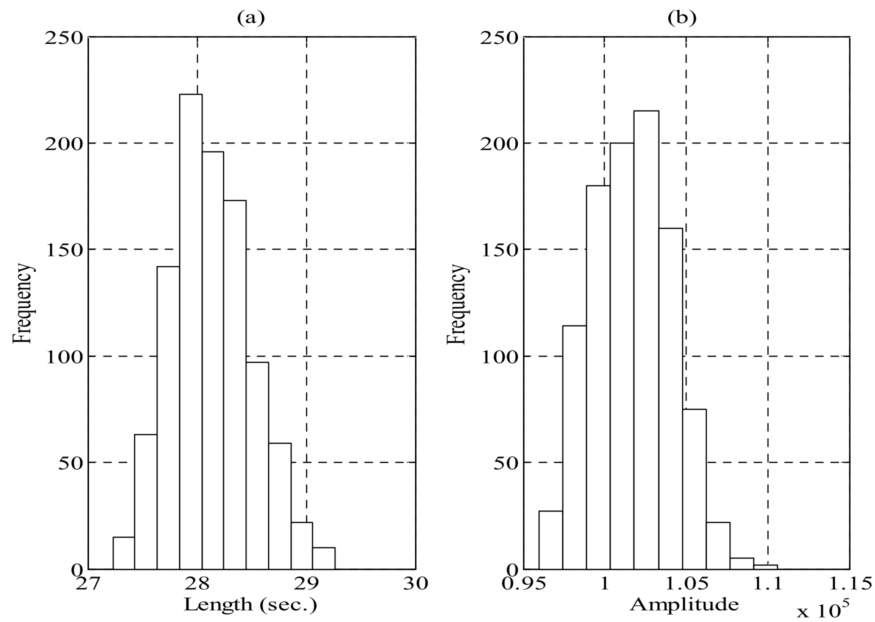

Fig. 2. The distribution of the NPB estimates (a) $\mu_{X(j)}^*$ and (b) $\mu_{Y(j)}^*$.

$E_1^*,...,E_B^*$. The envelopes in the jth resample envelope matrix E_j^* is given by

$$E_j^* = \begin{bmatrix} e_{11}^* \, e_{12}^* \cdots e_{1N}^* \\ e_{21}^* \quad .. \quad .. \\ .. \quad .. \quad .. \\ e_{L1}^* \quad .. \quad e_{LN}^* \end{bmatrix} \tag{6}$$

where $j = 1,...,B(=1000)$. The SBP and DBP parts of the envelope are identified utilizing the peak of the envelope. From the beginning to the peak of the BP envelope (corresponding to the decreasing cuff pressure) represents the SBP part and from the peak to the end of the BP envelope represents the DBP part. We then reoreder resampled BP envelope matrices (for systolic and diastolic part of the envelopes) using the ascending and descending sort techniques (for SBP and DBP part of the envelopes respectively). It is noted that each of the sorted matrices has five columns, each corresponding to a BP measurement of length L. We then obtain a single BP envelope per subject using Eq. (7) to Eq. (9) as the last step of the PE process, where the desired $100 \times (1-\alpha)\%$ NPB CI′s are given by (PE_{Q1}, PE_{Q2})[9]. Here, $Q1$ is the quotient of $B \times (\alpha/2)$, $Q2 = B - Q1 + 1$, and $Q3 = \frac{B}{2}$.

$$PE_{Q1} = \frac{1}{N}\sum_{i=1}^{N} E_{Q1}^*(:,i) \tag{7}$$

$$PE_{Q2} = \frac{1}{N}\sum_{i=1}^{N} E_{Q2}^*(:,i) \tag{8}$$

$$PE_{Q3} = \frac{1}{N}\sum_{i=1}^{N} E_{Q3}^*(:,i) \tag{9}$$

where $E_{Qk}^*(:,i)$ denotes the ith column of matrix E_{Qk}^* and $i = 1,...,N$. Thus, we obtain upper, lower and middle PEs that may be used to estimate the CI for SBP and DBP utilizing the systolic and diastolic BP envelope matrices respectively [9]. In the previous subsection, we obtain the value of the PMA utilizing the NPB approach.

As the PMA estimates may not connect with the end (start) point of the systolic (diastolic) PEs and also in the amplitudes, it may be needful to use signal processing (padding and clipping) to ensure that the location values (both in amplitude and length) of the TSPMA are based on the PEs. In the final step, we need to obtain the MCP to find the CI estimates of SBP and DBP. In order to estimate the SBP and DBP, systolic and diastolic ratios must be determined. The systolic and diastolic ratios used in our algorithm are 0.70 and 0.45, respectively, which were experimentally decided [5-6]. Using these ratios, the SBP and DBP points are identified on the PMAE, and they are mapped back to the MCP in the SBP and DBP values in mmHG.

4. RESULTS

The local research ethics committee approved the research, and all subjects provided informed consent prior to the measurement according to the protocol of the institutional research ethics board. The oscillometric measurements were provided by Biosign Technologies Inc., Toronto, Ontario, Canada for this study. The experimental data set was acquired from 85 healthy subjects aged from 12 to 80, out of which thirty seven were females and forty eight were males. No recruited subject had any history of cardiovascular disease. Five sets of oscillometric BP measurements were obtained from each volunteer ($425 = 5 \times 85$ total measurements) duration range to record a single measurement: 31-95 sec., duration median: 55 sec.) using a wrist worn UFIT TEN-10 blood pressure device (Biosign Technologies Inc., Toronto, Ontario, Canada) at a sampling rate of 100 Hz in accordance with the recommendations of the ANSI/AAMI SP 10 standard [10]. Specifically, the two nurse readings are averaged to provide one SBP and one DBP reading as the reference. The data set provided contains relatively stable nurse readings, in that the maximum difference between the two nurses is no more than 2 mmHG. This again satisfies the recommendations of the ANSI/AAMI SP 10 standard, which requires the mean difference to be no more than 5 mmHG. Nurse reading of SBP ranged from 78 to 147 mmHG and DBP ranged from 42 to 99 mmHG across all subjects. Specifically, our procedure of our BP measurements consists of an oscillometric blood pressure recoding, followed by readings of SBP and DBP with help of two trained nurse after a one minute pause. This is then followed by another one minute pause. The procedure is repeated again four more time to make the recoding of five measurements. For data collection, each subject sat well and upright posture in a chair where the UFIT monitor's cuff is strapped to the left wrist of the subject, which is raised to heart level. Another cuff, which is the component of the auscultatory, is placed on the upper left arm also at heart level.

In order to verify the performance of BP estimation, the mean absolute error (MAE) and the standard deviation (SD) between the estimated BP and the auscultatory nurse measurements were calculated [10]. The MAE of the proposed PMAE algorithm with the bootstrap method in SBP and DBP was compared to that of the MAA [11] algorithm as in Table 1. In addition, the standard deviation (SD) was used to describe a measure of error variability between the auscultatory nurse measurements and the estimates obtained using the proposed method. The range of the CI (mean) of the proposed PMAE with the bootstrap is smaller than that of the PMAE with bootstrap for both SBP and DBP, most likely because of the decrease in the standard deviation through the increase in the pseudo measurements using the bootstrap method for each subject as shown in Table 2.

The degree of error variability between the readings obtained with the proposed method and those obtained with the ausculatory nurse method as the reference (Table 1) was investigated. The MAE of the SBP and DBP obtained through the PMAE is similar to that obtained with the MAA. The proposed PMAE method has a MAE about 5-6 mmHG with respect to the auscultatory nurse measurements. Although the proposed approach in this paper does not focus on providing robust blood pressure estimates, the result of the MAE does not fall within the 5 mm Hg recommendations of the AAMI SP 10 but the result of the SD is satisfied

Table 1. Summary (averaging 85 subjects with five measurements) of the MAE and SD between the auscultatory nurse measurements of MAA, and PMAE

BP (mmHG)	MAE (Nurse vs. MAA)	MAE (Nurse vs. PMAE)	SD (Nurse vs. MAA)	SD (Nurse vs. PMAE)
SBP	6.52	6.50	5.95	5.93
DBP	5.64	5.64	5.32	5.33

Table 2. Comparison of average results (85 subjects with five measurements) in CIs 95 % of SBP and DBP using the MAAST, MAAGUM, and PMAE, where σ is a standard deviation, and L and U are lower and upper limit, respectively. MAA with (ST) is MAAST. MAA with the guide to the expression of uncertainty in measurement (GUM) is MAAGUM [11]

BP (mmHG)	MAAST	MAAGUM	PMAE
SBP (σ) CI	13.3 (8.1)	14.0 (7.8)	2.7 (3.2)
DBP (σ) CI	9.3 (5.7)	10.1 (5.3)	1.6 (2.3)
SBP (σ) L	106.9 (14.3)	106.5 (14.3)	112.4 (13.8)
SBP (σ) U	120.2 (16.5)	120.5 (16.4)	115.1 (14.9)
DBP (σ) L	62.4 (10.4)	62.0 (10.4)	66.7 (10.5)
DBP (σ) U	71.7 (11.0)	72.1 (10.9)	68.3 (9.9)

by the AAMI [10]. In addition, we note that the TSPMAE method has also much smaller spread (i.e., small standard deviation) in the CI when compared with the MAAST, MAAGUM, and PMAE based on average results for 85 subjects in Table 2.

5. CONCLUSION

In conclusion, we demonstrated that the CI obtained using the proposed method is narrower and has a narrower standard deviation than CIs obtained using other methods. Note that, this paper does not focus on accuracy directly while the accuracy in the estimates can be obtained through the standard error from the golden reference. If the standard deviation of the estimate is low and if there is no bias, then the estimates may be deemed to be accurate. The decrease of the standard deviation in the CI results is attributed to the increase in the effective number of samples due to resampling using bootstrap principles. The results indicate that the proposed methodology reduces the standard deviation and consequently improved the accuracy. Our results imply that the proposed methodology is the best available to deal with small samples of blood pressure measurements. Our study has established that the proposed method has outperformed the conventional methods in obtaining CI under normal conditions. We have also conducted further studies to use this methodology in the presence of impulsive noise situation and will be presented elsewhere.

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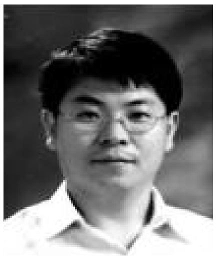

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