New algorithm for automatic determination of systolic and diastolic blood pressures in oscillometric measurements

Vojko Jazbinšek
Institute of Mathematics, Physics and Mechanics, Ljubljana, Slovenia
Email: vojko.jazbinsek@imfm.si

***Abstract*—Most automated non-invasive blood pressure measuring devices are based on some empirically derived criteria applied to the oscillometric index, which is defined as a certain characteristic physical property of pressure pulses measured by an inflated cuff wrapped around the upper arm during cuff pressure deflation. In this study, different algorithms for automatic determination of the systolic and diastolic pressures are compared. In addition to the measured pressure pulses, which are one of a typical physical property used for the oscillometric index, some other properties are applied such as a time derivative and a powered short time variance of the pressure data, as well as the audible part of the data measured by a microphone implanted in the cuff (Korotkoff sounds). Beside known empirical algorithms based on characteristic ratios of the oscillometric pulse amplitude, and the maximum and minimum slope of the oscillometric envelope, a new algorithm is introduced based on the presence and absence of oscillometric activity. This algorithm can be applied either to the powered short time variance of the pressure changes in the cuff or to the Korotkoff sounds.**

I. INTRODUCTION

Almost all automated non-invasive blood pressure (NIBP) measuring devices use the oscillometric technique [1], [2], which is based on arterial pressure pulses, called oscillometric pulses, that are generated by the arterial blood pressure (BP) pulsation in the cuff that occludes the artery during cuff pressure deflation [3]. Algorithms for automatic determination of the systolic (SP) and diastolic (DP) pressure values are based on some empirically derived criteria applied to the so-called oscillometric index [2], which is defined as a certain characteristic physical property plotted against the baseline cuff pressure. Empirically based algorithms include those based on characteristic ratios of the oscillometric pulse amplitude, and the maximum and minimum slope of the oscillometric envelope [2]. However, the algorithms used for detecting SP and DP are different from one device to another and are not revealed by the manufacturers [1].

The aim of this work was to find a possibly better method of oscillometric data analysis in NIBP measuring devices. A new presentation of an enhanced oscillometric index obtained by a powered short time variance (STV) of the oscillometric data is introduced. This presentation shows significant activity only below SP and above DP values, which simplifies the criteria for the automatic determination of blood pressure values, as in the case of the auscultatory technique where only the presence and absence of pulses has to be detected. A new algorithm for automatic detection of SP and DP based on the presence and absence of activity using the proposed STV oscillometric index is introduced and compared with known algorithms applied to oscillometric index based on peak-to-peak pressure pulses presented in the related study [4].

II. METHODS

A. Measurements

Measurements were performed on healthy volunteers with the cuff mounted on the upper arm using the same device (LODE, Groningen, Netherlands) described in the related paper [4]. Briefly, the device has a transducer for recording pressure changes in the cuff and a microphone implanted in the cuff for recording Korotkoff sounds. We used two modes of gradual cuff deflation, linear and exponential, both with an averaged deflation rate of 3 mm Hg/s. For each volunteer we recorded BP at least twice for both deflation modes. Simultaneously, we always measured the BP with a commercial OSZ4 device (Welch Allyn) and the electrocardiogram (ECG) with the HP 78353A device (Hewlett Packard).

For the evaluation of different algorithms we used the same database as in [4] consisted of 92 recordings. The average heart rate was 69$\pm$9 (range from 56 to 94) beats per minute and the average measured SP and DP values were 113$\pm$10 (89 to 139) and 73$\pm$8 (55 to 97) mm Hg, respectively. Measurements were performed on 23 volunteers of age from 20 to 66 (32$\pm$ 15), 12 males of age from 22 to 66 (39$\pm$17) and 11 females of age from 20 to 42 (25$\pm$6). For 3 males (all older than 55) we found specific ECG signals (arrhythmia, extra systoles). The remaining 9 males were from 22 to 55 years old (mean age 31$\pm$11).

B. Oscillometric index

The oscillometric index is in general defined as an envelope of a certain characteristic physical property of data obtained with the NIBP measuring device. In the previous studies [4], [5], we performed an extensive study of the signals, i.e. pressure changes in the cuff and responses of a microphone implanted in the cuff, which can be recorded during NIBP measurements. We applied several methods, including segmentation into heart beats, fitting, Fourier digital filtering, and a combination of numerical derivative and anti-derivative procedures, to separate the cuff deflation from the arterial pressure pulses. Using

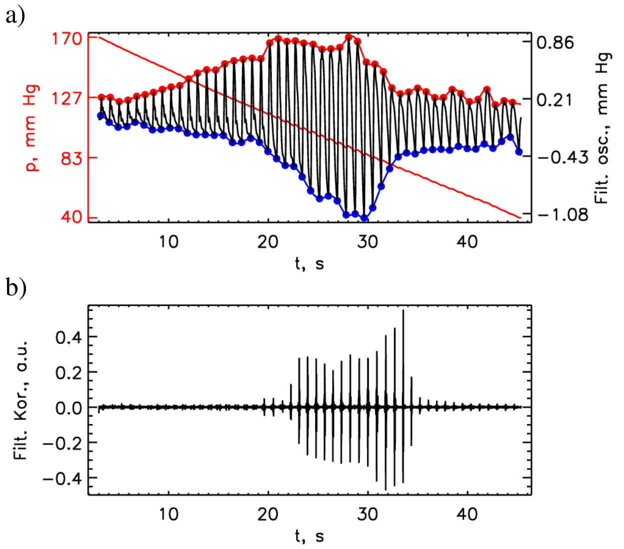

Fig. 1. a) Measured pressure data (left scale) and the arterial pressure oscillations obtained by digital filtering (right scale). Envelopes are defined with maximal (MAX) and minimal (MIN) pressure values for each pulse and are denoted by red and blue bullets, respectively. b) High frequency - audible part of microphone data.

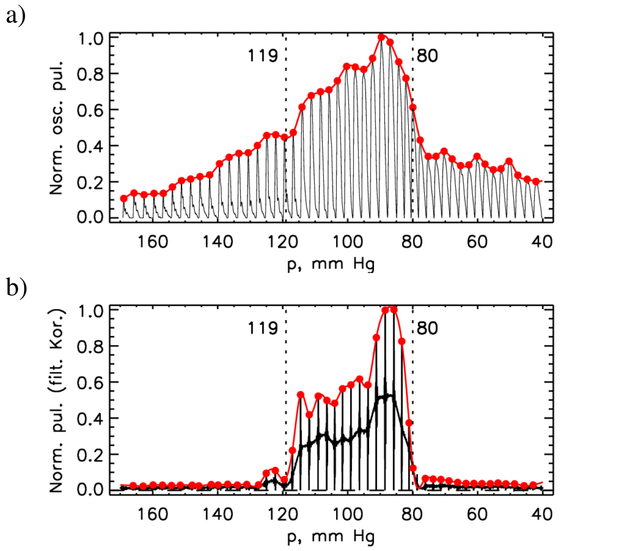

Fig. 2. Normalized oscillometric index obtained from a) the arterial pressure oscillations (Fig. 1a), and b) $E_{\rm kp}$ – the audible part of microphone data (Fig. 1b). Envelope of peak-to-peak oscillation values, obtained by subtraction of MIN envelope from MAX envelope, are displayed as a function of cuff pressure (deflation) level. Vertical dashed lines denote SP (119 mmHg) and DP (119 mmHg) values measured with OS4 device.

digital filtering we separated the microphone data into an audible part (Korotkoff sounds) and a low frequency part, which we found to exhibit a similar property as the time derivative of pressure pulses. We derived several presentations of the oscillometric index using measured signals in our NIBP device.

Using digital filtering, we separated deflation and arterial pressure pulses from the measured pressure data (Fig. 1a) and we extracted a high frequency audible part of the measured microphone data (Fig. 1b), which can be related to the Korotkoff sounds observed in an auscultatory BP measurements [6]. Figs. 2a,b show two types of the oscillometric index defined as envelopes of peak-to-peak oscillation amplitudes from Figs. 1a,b plotted vs. the pressure level in the cuff (deflation).

In this study, another method to represent oscillometric activity is proposed: power enhanced short time variance (STV) defined as the powered normalized variance of the measured data $p(t)$ (see, Fig. 1a) at time subintervals of length Δt

$$V^{\alpha}(t_i) = V_i^{\alpha} = \left\| \sum_k [p(t_k) - \bar{p}_i]^2 \right\|^{\alpha}, \qquad (1)$$

$$t_k \in [t_i - \Delta t/2, t_i + \Delta t/2], \quad \bar{p}_i = \frac{1}{N} \sum_k p(t_k),$$

where N is he number of time points in Δt ($N = \Delta t \cdot f_{\rm s}$, $f_{\rm s}$ is sampling frequency), t_k is a time point in the i-th Δt and $\bar{p}_i$ is a mean value of measured pressure in that Δt. Fig. 3 shows the influence of the two parameters, Δt and the power α, on the shape of the oscillometric index obtained from (1) ($E_{\rm vp}$ – envelope of normalized peak-to-peak values of V_i^{α}). In the limit case ($\Delta t \to 1/f_{\rm s}$, $\alpha = 1/2$), V_i^{α} is equivalent to the absolute value of the time derivative of the measured data. For larger Δt, STV gives a measure of the rate of arterial pulse changes in a given time interval Δt, or in other words, how much energy is transferred in Δt between the arterial pulsation in the limb and the cuff wrapped around the limb. Using the heuristic method, we chose one half of an average heartbeat duration ($t_{\rm hb}$) as the most appropriate value of parameter Δt. The curves in Fig. 3a show that i) above SP and below DP not much power is transferred, ii) that a rapid change of transferred power is observed around SP and DP, and iii) that most of the power is transferred between SP and DP. Using power parameter α one could enhance the oscillometric index. As is demonstrated on Fig. 3b, significant activity is observed only in the interval between SP and DP for $\alpha \geq 4$.

C. Algorithms

Two general types of criteria are known in the literature [2]: one is based on the amplitude reading and the other on the derivative reading. They are called the height-based (HB) and the slope-based (SB) method.

In the HB method, the SP and DP values are determined as a certain height of the normalized index when the pressure level in the cuff is equal to SP and DP. These values are different for each type of oscillometric index [4]. In our data base of 92 recordings, where the reference SP and DP were measured with OSZ4 device, we obtained for the oscillometric index constructed from the arterial pressure pulses averaged height ratios of 0.45±0.07 and 0.70±0.10 for the SP and DP values, respectively. Using these height ratios, we obtained for the case shown in Fig. 1a (121/81) mmHg for (SP/DP) values.

In the SB method, we first found the cuff pressure p_m where E_{xy} reached its maximum height. SP and DP were then defined as the maximum slope of the envelope in the increasing and decreasing part of the envelope. The slope is defined by a derivative of the oscillometric index. However, the oscillometric index represents a non-monotonic

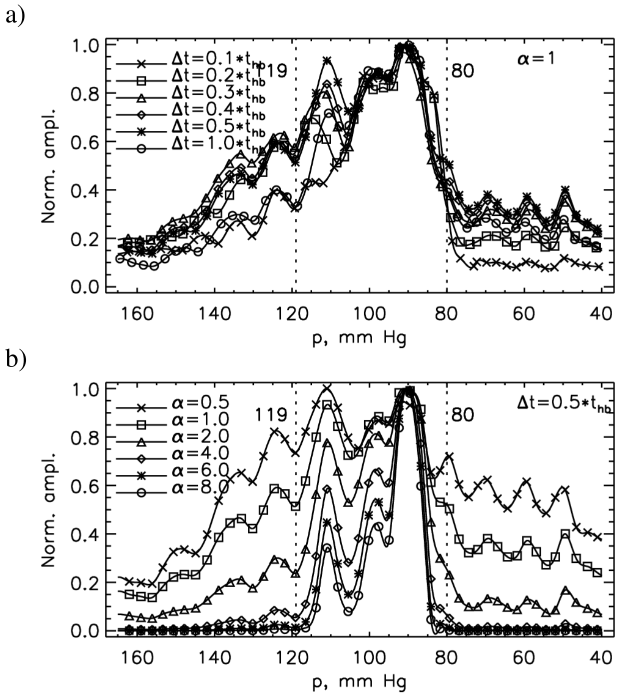

Fig. 3. Influence of a) Δt and b) α on power enhanced STV index E_{vp}) defined as envelope of V^{α} in (1). Vertical dashed lines denote measured SP and DP values in mmHg.

function due to the beat-to-beat variability of the pulse amplitude, artefacts, etc. Therefore the derivative can have many local extrema. To improve the prognostic value of the SB method, we introduced in [4] some constraints for estimation of SP and DP. Using SB method, we obtained for the case shown in Fig. 1a (114/80) mmHg for (SP/DP) values.

For the power enhanced STV oscillometric index defined (E_{vp}) defined as an envelope of V^{α} (1), we introduced a new algorithm based on the presence and absence of signal activity. We called it a presence/absence (PA) algorithm. It consisted of two steps. In the first step, threshold values T_{s} and T_{d} for SP and DP were determined from average background activities A_{s} above SP and A_{d} below DP as

$$T_{\mathrm{s}} = (\alpha+1)\cdot A_{\mathrm{s}} \text{ and } T_{\mathrm{d}} = (\alpha+1)\cdot A_{\mathrm{d}}\,, \qquad (2)$$

where α denotes a power in the enhanced normalized index V^{α} (1). Average activities A_{s} and A_{d} were defined as the mean value of E_{vp} for the first N_{b} heartbeats and the last N_{b} heartbeats, respectively. N_{b} was usually set to 3. From T_{s} an onset pressure P_{on} was found as the deflation level at which the envelope reaches T_{s}, and from T_{d} an offset pressure P_{off} was found as the deflation level at which the envelope falls to T_{d}. P_{on} and P_{off} were the first estimates of SP and DP. In the second step, we found maximum slopes S_{s} and S_{d} of the envelope just after P_{on} and just before P_{off}, respectively. A final estimate of SP was defined as the first pressure $p(t)$ level in the cuff below P_{on} that fulfills the following condition:

$$E_{\mathrm{vp}}(t+t_{\mathrm{hb}}) - E_{\mathrm{vp}}(t) > S_{\mathrm{s}}/3\,. \qquad (3)$$

Similarly, DP was determined as the first pressure $p(t)$ above P_{off} that fulfill:

$$E_{\mathrm{vp}}(t) - E_{\mathrm{vp}}(t+t_{\mathrm{hb}}) > S_{\mathrm{d}}/3\,. \qquad (4)$$

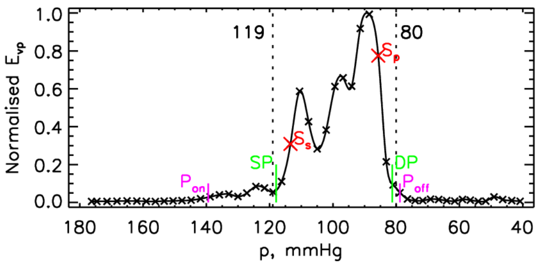

Fig. 4. Demonstration of PA method on E_{vp} envelope. Dashed vertical lines represent measured (PS/PD) values (119/80) mm Hg, vertical magenta lines denote $P_{\mathrm{on}}/P_{\mathrm{off}}$ (139.4/78.8) mm Hg, red $\times$ mark maximum slopes S_{s} and S_{d}, and green vertical lines denote (PS/PD) values (118,81) mm Hg obtained by PA method.

Demonstration of PA method applied to the E_{vp} ($\alpha = 4$, $\Delta t = 0.5\cdot t_{\mathrm{hb}}$) is displayed on Fig. 4. With this method we obtained (118/81) and (120/78) mmHg for the E_{vp} shown in Fig. 3b and for the E_{kp} constructed from Korotkoff sounds in Fig. 2b, respectively.

D. Evaluation protocol

Two standard protocols for evaluating the accuracy of NIBP devices have been widely used. One was published by the British Hypertension Society (BHS) [7] and the other by the American Association for the Advancement of Medical Instrumentation (AAMI) [8]. The criteria for fulfilling the BHS protocol are that devices must achieve at least grade B (50% of readings falling within 5 mm Hg, 75% within 10 mm Hg and 90% within 15 mm Hg of the mercury standard). The criteria for fulfilling the AAMI protocol are that the test device must not differ from the mercury standard by a mean absolute difference ($|\Delta p|$) $>$ 5 mm Hg or a standard deviation (SD) $>$ 8 mm Hg. The mercury standard refers to SP and DP values obtained by the auscultatory method performed by a trained person using a stethoscope for listening to the Korotkoff sounds and a mercury sphygmomanometer to measure the pressure level in the cuff.

Like in the related paper [4], we used a modified combination of BHS [7] and AAMI [8] protocols for the evaluation of different methods for automatic determination of the SP and DP values. For the oscillometric index E_{pp} based on the arterial pressure pulses (Fig. 2a), we applied the HB and SB algorithms to estimate SP and DP values. For the power enhanced STV oscillometric index E_{vp} ($\alpha = 4$, $\Delta t = 0.5\cdot t_{\mathrm{hb}}$), see Fig. 3b), and for the Korotkoff envelopes (see Fig. 2b), we applied PA algorithm to estimate SP and DP values. As in the BHS protocol we used grading criteria, but instead of using a certain percentage of readings falling within 5, 10 and 15 mmHg of the reference values, we found the total number of cases falling within 1, 3, 5, 7 and 10 mmHg of the reference values. Results were classified into 6 grades according to the rule given in Table I. For all estimations of SP and DP, the classification values $\mathrm{V_{SP}}$ and $\mathrm{V_{DP}}$ were found and a combined classification value $\mathrm{V_{SP+DP}}$ was calculated using the following formula biased to the worse of the two classification values:

$$\mathrm{V_{SP+DP}} = \mathrm{round}\left(\frac{\min(\mathrm{V_{SP}},\mathrm{V_{DP}}) + 4\max(\mathrm{V_{SP}},\mathrm{V_{DP}})}{5}\right). \qquad (5)$$

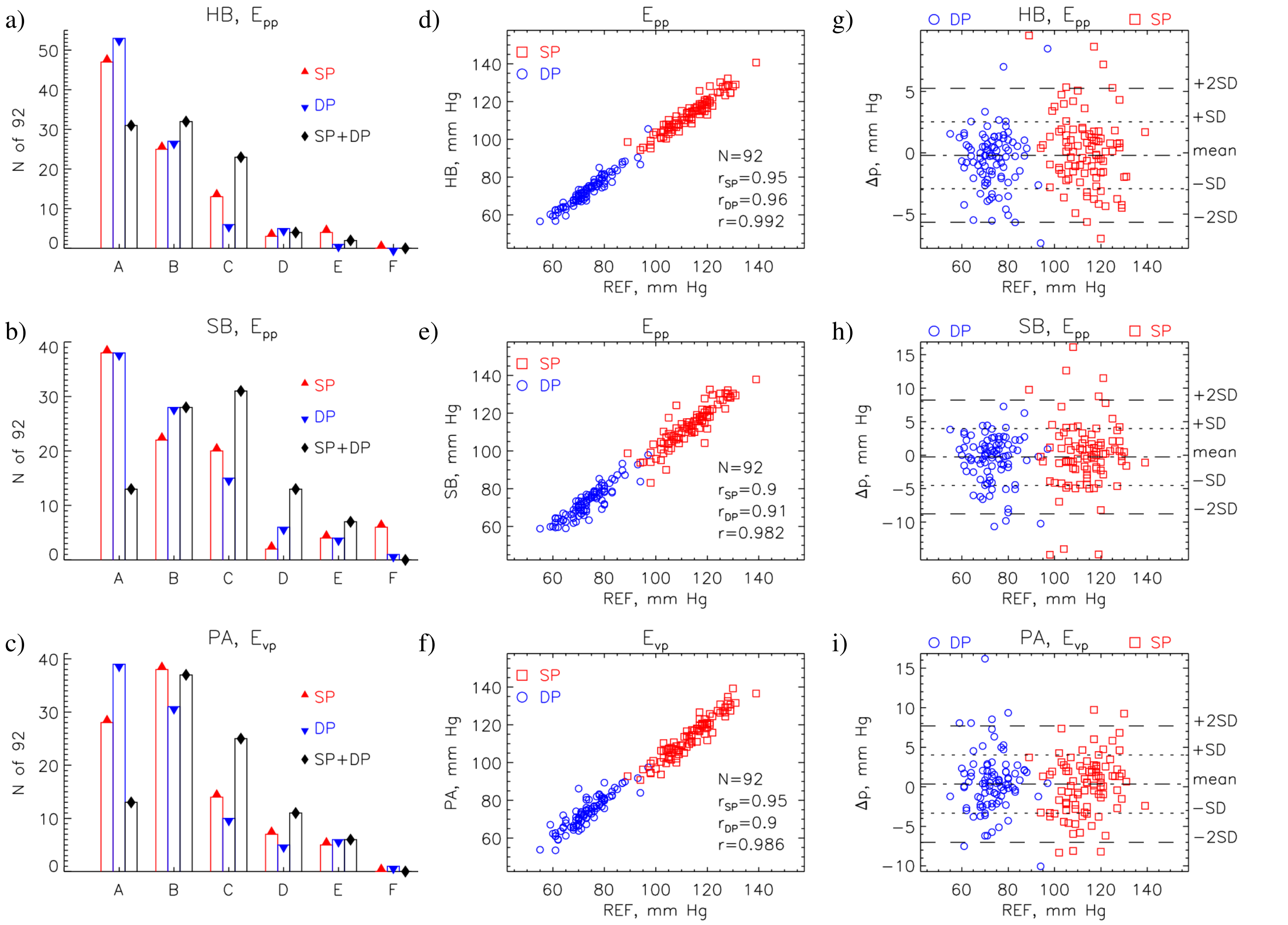

Fig. 5. Bar charts of classification results for the a) HB and b) SB methods applied to E_{pp}, and c) PA method applied to $E_{vp}(\alpha = 4)$. Each bar in the plot corresponds to the total number of cases classified in a given group (A, B, ..., F) defined in Table I. Results for the SP, DP and combined SP+DP are denoted by an red upward triangle, blue downward triangle and black diamond, respectively. Comparison between the SP (labeled by red squares) and the DP (labeled by blue circles) values measured with the OSZ4 device and corresponding SP and DP values obtained by different methods. Scatter plots for d) HB, e) SB, and f) PA methods are displayed, respectively. Linear regression correlation coefficient is denoted by r_{SP}, r_{DP} and r for the SD, DP and combination of both SP and DP. Bland-Altman plots for g) HB, h) SB, and i) PA methods are displayed, respectively. Dash-dotted, dotted and dashed line styles denote mean, mean $\pm$ SD and mean $\pm$ 2SD values for the combination of both SP and DP (see, Table II for values of shown quantities).

TABLE I. CLASSIFICATION OF RESULTS

Grade	Value	description	absolute difference
A	1	excellent	0 or 1 mm Hg
B	2	very good	2 or 3 mm Hg
C	3	good	4 to 5 mm Hg
D	4	approximate	6 to 7 mm Hg
E	5	bad	8 to 10 mm Hg
F	6	fail	more than 10 mm Hg

As in the AAMI protocol, we calculated $\Delta p \pm SD$ but we also included a calculation of the mean pressure difference Δp, which gives the average shift of the estimation regarding the measured reference. In addition, we performed a linear regression fit of estimated vs. measured pressure values, which gives the linear correlation (r).

III. Results and Discussion

Figs. 5a-c shows bar charts of classification results obtained by the HB and SB methods applied to E_{pp} envelopes and by the PA method applied to E_{vp}. Table II displays some quantitative evaluation parameters for the cases shown in Fig. 5, such as C - the total number of cases classified as good (up to 5 mmHg difference between the estimated and the measured SP and DP), F - the number of failed cases (a difference above 10 mmHg), a – offset, b – slope and r – correlation of the linear regression, Δp±SD – the mean difference and its standard deviation in mmHg, $|\Delta p|$±SD – the mean absolute difference and its SD in mmHg, and Δp_m – the maximum difference in mmHg. Figs. 5d-i show comparisons between the SP and the DP values measured with the OSZ4 device and the corresponding SP and DP values obtained by the HB, SB and PA methods. Scatter plots (Figs.5d-f) show that for all these methods we obtained a high correlation ($r > 0.9$) with the measured SP and DP obtained by the OSZ4 device. Bland-Altman plots [9] (Figs.5g-i-f) show that the mean difference Δp between the measured and the estimated SP and DP is below 1 mm Hg for all these methods and most of the results are within ±SD values, which were (see Table II) 2.7, 4.3 and 3.7 mm Hg for the HB, SB and PA methods, respectively. The mean absolute differences were all below 3 mm Hg, i.e. 2.0 ± 1.8, 3.0 ± 3.1 and 2.7 ± 2.5 mm Hg for the HB, SB and PA methods, respectively.

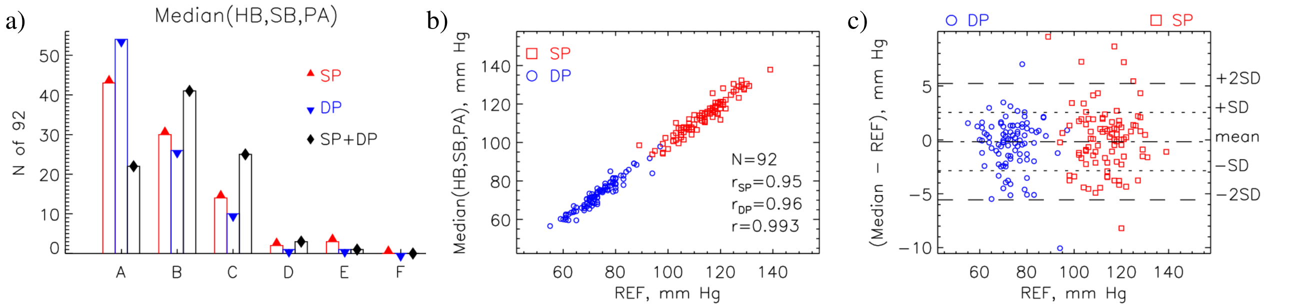

Fig. 6. a) bar chart, b) scatter and c) Bland-Altman plots for median evaluation results, where median values of SP and DP obtained by the HB, SB and PA are compared with corresponding measured SP and DP. See Fig.5 for an explanation of graphs and Table II for values of shown quantities.

TABLE II. SUMMARY OF CLASSIFICATION RESULTS

Method	BP	C	F	a	b	r	Δp±SD	$\|\Delta p\|$±SD	Δp_m
HB	SP	87	0	7.4	0.94	0.952	0.13±3.0	2.2±1.9	10
applied to	DP	87	0	-0.7	1	0.955	-0.54±2.5	1.8±1.7	8
E_{pp}	SP+DP	86	0	-1	1	0.992	-0.21±2.7	2.0±1.8	10
SB	SP	80	6	-2.5	1	0.9	-0.02±4.8	3.3±3.6	16
applied to	DP	81	1	2.6	0.96	0.91	-0.55±3.6	2.6±2.4	-11
E_{pp}	SP+DP	72	0	-1.3	1	0.982	-0.28±4.3	3.0±3.1	16
PA	SP	80	0	-8.9	1.1	0.95	0.18±3.6	2.9±2.2	10
applied to	DP	80	1	1.6	0.98	0.9	0.50±3.8	2.6±2.7	16
E_{vp}	SP+DP	75	0	0.3	1	0.986	0.34±3.7	2.7±2.5	16
median	SP	87	0	2	0.98	0.954	0.05±3.0	2.2±2.0	10
values of	DP	90	0	1.8	0.97	0.955	-0.38±2.4	1.7±1.7	-10
HB,SB,PA	SP+DP	88	0	-0.7	1	0.993	-0.17±2.7	2.0±1.9	-10

C – sum of cases with grades A, B and C, F – number of cases with grade F
a, b, r – offset, slope and correlation of the linear regression, respectively

Results show that all methods fulfill criteria for the BHS protocol [7] (at least 50% of readings falling within 5, 75% within 10 and 90% within 15 mmHg of the reference), as well as for the AAMI protocol [8] (tested device must not differ from the reference by a mean absolute difference ($|\Delta p|$) $>$ 5 mmHg or a standard deviation (SD) $>$ 8 mmHg).

Finally, the median values of SP and DP values obtained by all three methods were calculated. Results displayed in Fig. 6 and bottom part of Table II show that the median values of SP and DP obtained by the HB, SP and PA methods give a best match with the corresponding measured SP and DP. However, the median classification results are only slightly better than the results of the HB method applied to E_{pp} (Fig. 5 and Table II). Detailed statistics of the median values show that in total 39, 34 and 19 cases for SP, and 51, 26, 15 cases for DP were selected from the results obtained by the HB, SB and PA methods, respectively. The algorithm used in the OS4 device is not known to us, but the above results suggest that it is most likely that the HB algorithm is used in this device.

IV. CONCLUSION

We proposed a new presentation of the oscillometric index based on power enhanced STV of measured pressure data, which like in the case of Korotkoff sound in conventional auscultatory method showed significant signal activity only in the region below SP and above DP values. We developed the PA algorithm for automatic determination of SP and DP values. Evaluation study on 92 recordings measured on 23 healthy volunteers showed that the proposed PA algorithm applied to power enhanced STV envelopes gave results comparable to the two known algorithms, HB and SB applied to pressure pulses envelopes. For the evaluation we used a modified protocol which is a combination of the standard AAMI and BHS protocols adapted to our measurements where the measured SP and DP values obtained by the OSZ4 device were used as a reference. Median values of SP and DP estimated by the HB, SB and PA methods gave the best match with the corresponding measured SP and DP.

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