Influence of different representations of the oscillometric index on automatic determination of the systolic and diastolic blood pressures

V. Jazbinsek, J. Luznik and Z. Trontelj

Institute of Mathematics, Physics and Mechanics, Ljubljana, Slovenia

Abstract — **The oscillometric technique of non-invasive blood pressure measurement is based on some empirically derived criteria applied to the so-called oscillometric index, defined as a certain characteristic physical property of the arterial pressure pulses. The aim of this study is to evaluate the influence of different representations of the oscillometric index on the known height based and slope based empirical algorithms for automatic determination of systolic and diastolic blood pressures.**

Keywords — **blood pressure, oscillometric technique, height based algorithm, slope based algorithm**

I. INTRODUCTION

Most automated non-invasive blood pressure (NIBP) measuring devices use the oscillometric technique based on some empirically derived criteria applied to the so-called oscillometric index [1,2], defined as a certain characteristic physical property of the arterial pressure pulses.

In addition to the arterial pressure pulses, which is a typical physical property used for the oscillometric index, we also used in this study other properties such as a time derivative and an audible part of data measured by a microphone implanted in the cuff (Korotkoff sounds) [3]. Three different representations of oscillometric index curves can be constructed for each type of physical property. We evaluated these representations on 92 measurements performed on 23 healthy subjects. Estimations of systolic (SP) and diastolic (DP) blood pressures (BP) obtained by the height based (HB) and slope based (SB) algorithms were compared with the reference SP and DP measured with the commercial NIBP device

II. METHODS

A. Measurements

Measurements were accomplished on a device designed by the LODE producer (Groningen, NL) for the EU-project "Simulator for NIBP" [4]. This device has both a compressor for cuff inflation and a transducer for pressure detection built in a personal computer (PC), where also hardware and software for data acquisition was installed. This device also provides recordings of data from an external ECG device and from a piezoceramic microphone implanted inside the cuff (Accoson, UK). We performed measurements on the upper arm of healthy volunteers. In addition, we mounted between the cuff and the computer a commercial automated NIBP device OSZ4 (Welch Allyn, USA).

We included 92 recordings, measured on 23 healthy volunteers, in the evaluation procedure of oscillometric index constructed from pressure part of measured data (pressure pulses and their time derivatives). The quality of the microphone data in our recordings had been often rather poor, so we used a reduced number of 32 recordings for the evaluation of oscillometric index constructed from the audible part of microphone data.

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 a related paper [5] we performed an extensive analysis of signals, i.e. pressure changes in the cuff and responses of a microphone implanted in the cuff, which can be recorded during NIBP measurements. Using different techniques, we separated deflation and arterial pressure pulses from the measured pressure data. Using digital filtering, we also separated the measured microphone data into a low frequency part, which can be compared to a time derivative of the measured pressure pulses, and into a high frequency audible part, which can be related to the Korotkoff sounds observed in an auscultatory BP measurements [3]. Typical results for one of the recordings are shown in Fig. 1. Beside the arterial pressure pulses (Fig. 1a), which are the most common physical property used for the oscillometric index, we have also analyzed in the present paper some other features like the time derivative of the measured pressure data (Fig. 1b) and the audible part of the microphone data (Fig. 1c). Using minimal (MIN), centre of gravity (COG) and maximal (MAX) points for each heartbeat, three different oscillometric index representations can be constructed for each type of physical property as it is shown in Fig. 2 and described in Table 1, where we denote the oscillometric index as E_{xy} and the normalized index as $||E_{xy}||$.

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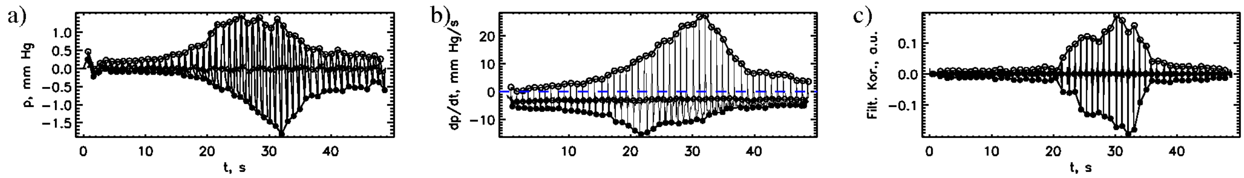

Fig. 1 Data from NIBP device: a) oscillometric pulses obtained by digital filtering [0.3-40 Hz] of measured pressure data, b) time derivative of these data and c) audible part [10-40 Hz] of microphone data. MAX, MIN and COG points of each heartbeat are denoted by circles, bullets and crosses, respectively.

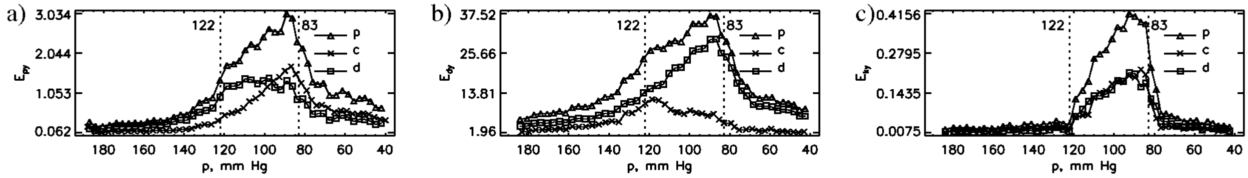

Fig. 2 Different representations of the oscillometric index obtained from data displayed in Fig. 1: a) oscillometric pulses, b) time derivative and c) audible part of microphone data. For each type of data, three different representations of the oscillometric index can be formed (see Table 1).

Table 1 Characterization of oscillometric index E_{xy}

x	Physical property
p	oscillometric pulses or filtered NIBP data
d	derivative of oscillometric pulses
k	Korotkoff sounds (audible part of microphone data)
y	Envelope type
p	pulse amplitude or MIN[a]-to-MAX[b] value
c	centered or MIN-to-COG[c] value
d	difference between p and c or COG-to-MAX value
[a]MIN	minimal value of data for each pulsation
[b]MAX	maximal value of data for each pulsation
[c]COG	center of gravity value for each pulsation

Table 2 Mean RS_{xy} and RD_{xy} and their SD for 92 recordings

E_{xy}	HSxy ± SD	HDxy ± SD
E_{pp}	0.45 ± 0.07	0.70 ± 0.10
E_{pc}	0.24 ± 0.07	0.75 ± 0.10
E_{pd}	0.62 ± 0.10	0.57 ± 0.10
E_{dp}	0.68 ± 0.09	0.82 ± 0.11
E_{dc}	0.82 ± 0.16	0.49 ± 0.14
E_{dd}	0.53 ± 0.08	0.83 ± 0.11
E_{kp}*	0.12 ± 0.12	0.44 ± 0.20
E_{kc}*	0.12 ± 0.12	0.45 ± 0.19
E_{kd}*	0.11 ± 0.12	0.42 ± 0.23

*Reduced data base of 32 recordings

The MIN-to-MAX envelope of the pressure pulses (E_{pp}) displayed as a function deflation (Fig. 2a) is most commonly used representation of the oscillometric index [2]. For the amplitudes of pressure pulses, one would expect monotonic increase until the maximum is reached, for which it is generally accepted that it corresponds to the mean arterial pressure (MP), and monotonic decrease afterwards. However, the results of the real measurements in Fig. 2 represent a non-monotonic function due to the beat-to-beat variability of the pulse amplitude, artifacts, etc. To improve the prognostic value of the SB method, which uses a maximum slope of the oscillometric index curve for estimations of SP and DP, we introduced some constraints. For example, to determine SP, we searched for the maximal slope of E_{pp} at pressure level in the cuff at least 15 mm Hg above MP and values of the normalized index $||E_{pp}||$ less then 0.6, and to determine DP we constrained the search for pressures at least 2 mm Hg below MP and $||E_{pp}||$ less then 0.9. For the automatic estimation of SP in DP values using HB methods, one has to know the characteristic amplitude ratios RS_{xy} and RD_{xy}, which are equal to $||E_{xy}||$ when the BP in the cuff equals to SP in DP. These ratios are different for each type of E_{xy}. For the evaluation of the HB method, we first determined mean RS_{xy} and RD_{xy} from known SP in DP measured by the OSZ4 device. Results displayed in Table 2 show that the amplitude ratios $RS_{xy} << RD_{xy}$ for most of the E_{xy}, except for the E_{pd} where $RS_{pd} \approx RD_{pd}$, and E_{dc} where $RS_{dc} >> RD_{dc}$. Values of RS_{pp} and RD_{pp} are similar to values published in the literature (see [2] and references therein), and most similar to those patented by Ramsey et al. [7], where they claimed values of (RS_{pp}, RD_{pp}) equal to (0.5, 0.69) for normal, and (0.45, 0.72) for rapid deflation rates, respectively. For the case of E_{pp} shown in Fig. 2a, where the measured (SP/DP) values with the OSZ4 device were (122/83), we got (122/79) and (122/81) mm Hg using HB and SB methods, respectively.

C. 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

Table 3 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

the American Association for the Advancement of Medical Instrumentation (AAMI) [8]. The criteria for fulfilling the BHS protocol are that the tested device must achieve at least grade B (50% of readings falling within 5, 75% within 10 and 90% within 15 mm Hg of the mercury standard). The criteria for fulfilling the AAMI protocol are that the tested 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.

In this study, we used a modified combination of BHS and AAMI protocols for the evaluation of different methods for automatic determination of the SP and DP values. For each E_{xy} we applied the HB and SB (with and without constraints) algorithms to estimate SP and DP values and compared them with the measured reference values. Since we are not a medical laboratory, we were not able to measure the mercury standard reference. Instead we measured SP and DP with the OSZ4 device. As in the BHS protocol we used grading criteria, but instead of using a certain percentage of readings falling within 5, 10 and 15 mm Hg of the reference values, we found the total number of cases falling within 1, 3, 5, 7 and 10 mm Hg of the reference values. Results were classified into 6 grades according to the rule given in Table 2. For all estimations of SP and DP, the classification values V_{SP} and V_{DP} were found and a combined classification value V_{SP+DP} was calculated using the following formula biased to the worse of the two classification values:

$$V_{SP+DP} = \mathrm{round}\left(\frac{\min(V_{SP},V_{DP}) + 4\cdot\max(V_{SP},V_{DP})}{5}\right). \qquad (1)$$

As in the AAMI protocol, we calculated $|\Delta p|$±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

Table 4 displays some quantitative evaluation parameters for the evaluation of HB method, such as C - the total number of cases classified as good (up to 5 mm Hg difference between the estimated and the measured SP and DP), F - the number of failed cases (a difference above 10 mm Hg), r - the linear regression correlation, Δp ±SD - the mean difference and its standard deviation in mm Hg, $|\Delta p|$±SD - the mean absolute difference and its SD in mm Hg, and Δp_m - the maximum difference in mm Hg. The results show that we obtained the best SP and DP values for the pressure pulses envelopes E_{py}, especially for E_{pp} where there were no failed cases (grade F) and most of the 92 cases were classified as good (grade C or above), i.e. 87 for SP and 86 for DP. Other evaluation parameters for E_{pp} were quite similar for the SP vs. DP results: 0.953 vs. 0.954 (r), 0.13±3.0 vs. -0.56±2.5 mm Hg (Δp ±SD), 2.2±1.9 vs. 1.8±1.8 mm Hg ($|\Delta p|$±SD), and 10 vs. 8 mm Hg (Δp_m). The results for the Korotkoff type of envelopes E_{ky} were also rather good. The best SP estimations were obtained using E_{kp} (C=26 out of 32, F=1, r=0.87, Δp=-1.8±4.3, $|\Delta p|$=3.7±2.7, and Δp_m =-11) and the best DP estimations were obtained using E_{kc} (C=31, F=0, r=0.965, Δp=-0.2±2.0, $|\Delta p|$=1.5±1.3, and Δp_m=8). For other types of envelopes,

Table 4 Summary of classification results for the HB method

E_{xy}	Type	C	F	r	Δp±SD	$\|\Delta p\|$±SD	Δp_m
	SP	87	0	0.953	0.13±3.0	2.2±1.9	10
E_{pp}	DP	86	0	0.954	-0.56±2.5	1.8±1.8	8
	SP+DP	85	0	0.992	-0.22±2.8	2.0±1.9	10
	SP	84	1	0.89	0.15±5.2	3.0±4.3	39
E_{pc}	DP	89	1	0.957	-0.48±2.3	1.6±1.7	-11
	SP+DP	84	0	0.984	-0.17±4.1	2.3±3.3	39
	SP	77	3	0.91	0.34±4.1	2.9±2.9	-17
E_{pd}	DP	81	1	0.92	-0.45±3.4	2.5±2.4	-11
	SP+DP	75	1	0.986	-0.06±3.8	2.7±2.7	-17
	SP	67	10	0.63	-1.1±9.8	5.1±8.5	-55
E_{dp}	DP	78	4	0.81	-0.37±6.0	3.5±4.9	35
	SP+DP	65	2	0.93	-0.74±8.1	4.3±7.0	-55
	SP	55	20	0.69	1.5±10	6.7±8.0	-56
E_{dc}	DP	53	16	0.65	0.59±9.0	6.5±6.2	35
	SP+DP	32	11	0.92	1.0±9.7	6.6±7.1	-56
	(SP	66	6	0.8	-0.93±6.4	4.6±4.5	-27
E_{dd}	DP	75	3	0.89	-1.1±4.1	2.9±3.1	18
	SP+DP	60	3	0.971	-1.0±5.4	3.7±4.0	-27
	SP	26	1	0.87	-1.8±4.3	3.7±2.7	-11
E_{kp}	DP	29	0	0.94	-0.24±2.6	2.0±1.7	7
	SP+DP	26	0	0.986	-1.0±3.6	2.8±2.4	-11
	SP	24	2	0.78	0.20±6.4	4.3±4.7	21
E_{kc}	DP	31	0	0.965	0.20±2.0	1.5±1.3	6
	SP+DP	25	0	0.976	0.20±4.7	2.9±3.7	21
	SP	23	2	0.83	-2.0±4.9	4.1±3.3	-14
E_{kd}	DP	27	1	0.88	-0.82±4.1	3.0±2.9	12
	SP+DP	21	0	0.978	-1.4±4.5	3.5±3.1	-14

classification results were not so promising, especially for SP estimations, while DP estimations were still rather good for the E_{dp} and E_{dd} type of envelopes.

Table 5 displays some quantitative evaluation parameters for the evaluation of SB method. The results for the pressure pulses envelopes E_{py} clearly show that better results for SP were obtained by using the SB method with constraints, than the SB method without constraints. For E_{pp} we obtained 82 cases classified as good and only 5 failed cases if we applied constraints in the SB method, while we obtained only 48 cases classified as good and as many as 35 failed cases if we applied the SB method without constraints. On the other hand, constraints did not improve the results for DP. For E_{pp} and E_{pc} we got slightly better results without constraints, and for E_{pd} we got slightly better results with constraints. The results for the derivatives of pressure pulses E_{dy} showed that the SB method failed in estimating SP from E_{dd} (59 failed cases) and in estimating DP from the E_{dc} envelopes (60 failed cases). On the other hand, we got rather good results for the Korotkoff type of envelopes E_{ky}, especially for the DP values. For the SP values we got 6, 6, 7 failed cases and mean differences Δp equal to -5.5±4.9, -5.2±5.2 and -5.9±5.1 mm Hg for the E_{kp}, E_{kc} and E_{kd} envelopes, respectively. Therefore, the estimated SP obtained by the SB method using the E_{ky} envelopes was on average 5-6 mm Hg lower than the measured SP obtained by the OSZ4 device.

It is also interesting to note that the estimated DP obtained using E_{kc} with the HB and SB algorithms gave excellent classification results, see Tables 5 and 6. The reason why the SB method performs well for this case is obvious - the rapid change of E_{kc} coincides with the maximal slope. On the other hand, the reason why it also works with the HB method is not so straightforward at first glance. RD_{kc} for this case (0.42) has a relatively high SD (0.19) and it is not very realistic to expect a good performance of the HB method, which is based on a fixed height ratio. However, due to the rapid change of the E_{kc} amplitudes around the DP, the pressure level in the cuff only slowly changes in this case, and the HB method gives a good estimation of the DP. The same dependence can be observed in other types of E_{xy}.

Table 5 Summary of classification results for the SB method

E_{xy}	Type	C	F	r	Δp±SD	$\|\Delta p\|$±SD	Δp_m
E_{pp}	SP	82	5	0.9	-0.67±4.6	3.0±3.6	-18
	DP	79	2	0.91	-0.68±3.6	2.7±2.5	-11
	SP+DP	74	1	0.983	-0.68±4.2	2.8±3.1	-18
E_{pc}	SP	58	20	0.76	-4.5±7.5	6.2±6.2	-31
	DP	80	1	0.94	-0.99±3.2	2.4±2.3	-11
	SP+DP	56	1	0.962	-2.7±6.0	4.3±5.0	-31
E_{pd}	SP	68	8	0.8	0.41±6.7	4.4±5.0	23
	DP	73	7	0.82	0.97±5.4	3.8±3.9	-20
	SP+DP	63	5	0.963	0.69±6.1	4.1±4.5	23
E_{pp}^*	SP	48	35	0.68	-8.1±9.9	9.2±8.9	-35
	DP	81	1	0.93	-0.12±3.3	2.3±2.3	-11
	SP+DP	44	5	0.93	-4.1±8.4	5.8±7.3	-35
E_{pc}^*	SP	4	85	0.74	-21±7.6	21±7.5	-36
	DP	86	1	0.94	-0.39±2.9	2.1±2.1	-11
	SP+DP	4	6	0.88	-11±12	11±11	-36
E_{pd}^*	SP	72	7	0.85	-1.9±5.6	4.0±4.3	-20
	DP	69	11	0.78	2.2±6.5	4.4±5.2	33
	SP+DP	59	4	0.957	0.15±6.4	4.2±4.8	33
E_{kp}	SP	19	6	0.83	-5.4±4.9	5.6±4.6	-18
	DP	30	0	0.95	0.96±2.5	2.0±1.8	7
	SP+DP	19	0	0.979	-2.2±5.0	3.8±3.9	-18
E_{kc}	SP	19	6	0.8	-5.3±5.2	5.7±4.7	-18
	DP	30	0	0.971	1.4±1.9	1.7±1.6	7
	SP+DP	20	1	0.978	-2.0±5.1	3.7±4.0	-18
E_{kd}	SP	18	7	0.82	-5.9±5.1	6.0±4.9	-18
	DP	29	0	0.93	0.61±2.9	2.0±2.1	-8
	SP+DP	18	1	0.976	-2.6±5.3	4.0±4.3	-18

*SB-method without constraints

IV. Conclusions

We performed a case study on 23 healthy volunteers to evaluate two known algorithms, HB an SB, for the automatic determination of SP and DP values using different representations of the measured data. 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. We found that the HB method can be applied to the E_{xy} envelopes that exhibit a rapid change of E_{xy} amplitudes around DP or SP. The evaluation study of selected E_{xy} (E_{pp} for both algorithms) gave acceptable results regarding the reference.

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Corresponding author:

Author: Vojko Jazbinsek
Institute: Institute of Mathematics, Physics and Mechanics
Street: Jadranska 19
City: SI-1000, Ljubljana
Country: Slovenia
Email: vojko.jazbinsek@imfm.uni-lj.si