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Blood Pressure Estimation Using Maximum Slope of Oscillometric Pulses

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***Abstract*— A new oscillometric pulse index (OPI) derived from the maximum slope (MS) of each pulse in the oscillometric blood pressure waveform is proposed for blood pressure estimation. Maximum slope for each pulse is obtained using the first derivative of the pulse and an envelope of the values corresponding to the maximum slopes is obtained. The maximum of the envelope is taken as the mean arterial pressure (MAP) and the systolic blood pressure (SBP) and diastolic blood pressure (DBP) estimates are obtained as a fraction of the MAP, similar to the traditional maximum amplitude algorithm (MAA). The proposed algorithm is tested on 18 healthy subjects. The MAP, SBP and DBP estimates obtained from the proposed algorithm are compared with those obtained from a commercial blood pressure device and with the estimates obtained using the MAA and morphological qualitative measures available in the literature.**

Keywords- Oscillometric waveform, Oscillometric pulse index, Slope method, Pulse morphology, Blood pressure, Maximum Amplitude Algorithm.

I. Introduction

Oscillometric method appears to be the most well known method for blood pressure measurement [1]. A cuff with embedded pressure sensor is placed on the arm or the wrist and the pressure is slowly deflated. As the occluding cuff is slowly released, oscillation pulses will appear on the cuff deflation waveform [2]. It was earlier shown that blood pressure estimates can be obtained through quantitative measures that describe the morphology of these pulses [3]. Earlier studies have identified morphology of the pulses as a predictor of cardiovascular diseases [4,5]. However, established blood pressure estimation algorithms for oscillometric blood pressure waveforms do not use the individual pulse characteristics except the height or the area of the pulse.

Almost all oscillometric algorithms estimate systolic blood pressure (SBP) and diastolic blood pressure (DBP) using the following steps: 1) From the deflation curve, the oscillometric waveform (OMW) is extracted [6] 2) From the OMW, an oscillometric pulse index (OPI) is derived and used to form the envelope. The OPI is derived using one of the mathematical criteria such as height of the pulse from the baseline, peak to peak height of the pulse or evaluating the area under every pulse [6] 3) Estimate of the systolic and diastolic blood pressure is done using either height or slope criteria. MAA algorithm is based on the height criteria. It uses the maximum peak of the envelope to estimate Mean Arterial Pressure (MAP) and uses a fraction of the peak to determine the time instants of systolic and diastolic pressure. SBP and DBP are then obtained by mapping the time instants to the deflation curve and reading the pressure points. There is no consensus on what values should be used for determining these fractions and generally the fractions range from 0.5 to 0.8 [7]. In the case of slope criteria, the points of maximum and minimum slope of the envelope curve are utilized to estimate the pressure.

Recently, oscillometric blood pressure signals were analyzed using pulse morphology under different pressure points and a correlation with age was presented [8]. Signal processing approach was utilized to estimate the pressures using pulse morphology in [3]. In order to estimate the pressures, several quantitative measures for the pulse were utilized. These studies paved way for effectively utilizing local variations in the pulse characteristics for blood pressure estimation. This was a significant paradigm shift from MAA, where the global characteristic of the waveform, namely the envelope of the peaks of the pulses was utilized for estimation. This paper uses the local characteristics of the pulse, namely the maximum slope of the pulse, to obtain the OPI and uses an MAA type approach to estimate the pressure.

In this paper, instead of using the maximum-minimum slope of the envelope curve, maximum slope of the individual pulses is used as OPI to form the envelope. Using this envelope, an approach to MAA is applied to estimate SBP and DBP. The proposed methodology embraces the slope criteria for obtaining the OPI and uses the height criteria for obtaining the estimates. The paper is organized in the following manner. Section II describes the data acquisition system and the experimental procedure. Section III presents the proposed blood pressure estimation methodology and Section IV presents the results and does a comparison on the estimates obtained using MAA, commercially available device and morphological qualitative measures described in [3] while Section V concludes the paper.

II. Data Acquisition

Oscillometric waveforms were obtained from healthy subject aged from 24 to 68 years (12 males, 6 females) for over 2-3 days with 5 trials per day. None of the volunteers had a known history of cardiovascular disease or was taking any vasoactive drugs. All subjects provided informed consent form to the blood pressure measurement, in accordance with the guidelines of the institutional research ethic board.

Measurements for comparison purposes were made with Omron (Model HEM-790ITCAN). Omron measurements were recorded using subjects' right arm before each trial. Since Omron only records the systolic and diastolic pressures, the following formula was used to calculate the Mean Arterial Pressure (MAP) from Omron measurements [9]:

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

All the recordings were taken using our blood pressure measurement prototype device [3]. A cuff was placed around the subject's left arm. After 60 seconds of obtaining blood pressure estimates with Omron, the cuff on the left arm of the subject was inflated around 30 mmHg above the systolic pressure and deflated slowly below the diastolic pressure. Each recording took 90 seconds. Following the SP10 standard, 3 minutes were allowed between each trial recording. At least 5 consecutive recordings were obtained for each subject. The subjects were seated in a chair with their arm at the level of the heart during the recording and asked to be relaxed, breathe normally and have minimum movement.

III. Proposed Methodology

For every detected pulse, the first derivative of the pulse is computed. The first derivative of the pulse has two positive peaks as shown in Fig 1. The first peak is several times higher than the second peak. The first peak corresponds to the point on the blood pressure pulse where the slope is the maximum. The maximum slope point is identified in each pulse of the OMW. The maximum slope point of every pulse in the OMW is used as OPI. The envelope is formed by plotting calculated maximum slope for each pulse versus time of that point from the oscillometric waveform as shown in Fig. 2a). To form the envelope of maximum slope points, curve fitting on OPI using spline interpolation is done (Fig 2.b). The peak of the envelope is identified. The cuff pressure reading corresponding to the location of the peak of the envelope is estimated as the MAP, similar to MAA. The left of the peak is assumed to contain the SBP reading while the right side of the curve is assumed to contain the DBP. Like the MAA, to obtain the time instant of the SBP and DBP estimates, a fraction of the MAP estimate is used. To obtain the time instant of SBP, a fraction of MAP, called systolic ratio is derived experimentally using the reference SBP estimates obtained from Omron determined using minimum least squares [6]. Similarly to obtain the time instant of an estimate of DBP, a fraction of MAP, called diastolic ratio is obtained experimentally using the DBP estimates obtained from Omron. For this paper, the systolic ratio and diastolic ratio was determined to be 0.75 and 0.5 using least squares technique. The region to the left of the MAP is used to estimate the SBP (called as systolic region in this paper) while the region to the right of the MAP is used for DBP (called diastolic region in this paper). The systolic point is obtained by choosing a point on the systolic region of the envelope that is close to the product of the systolic ratio and the MAP. The diastolic point is obtained similarly in the diastolic region using the diastolic ratio.

The corresponding points can be then mapped to the deflation curve and then taken as the estimates for SBP and DBP. Fig. 2c) illustrates the estimation process of obtaining MAP, SBP, DBP points obtained using the maximum slope envelope. The ordinate in Fig 2 has arbitrary units. The pressure estimates are read off the corresponding points on the cuff pressure.

IV. Results

The estimates from the standard MAA are obtained in order to do a comparative study. The OPI used for obtaining the envelope for MAA was peak to peak following the methodology in [6]. The MAP estimate is calculated for the Omron device using equation 1. Table I compares the SBP, DBP, and MAP estimates of the proposed method with MAA and Omron measurement averaged over all the subjects. The estimates of MS are slightly lower than those of MAA estimates and Omron measurements. Table II shows the mean and standard deviations of absolute errors of estimates of MS, MAA with Omron measurements as a reference for SBP and DBP. These are calculated using all the estimates obtained for 18 patients over 5 trials. Table II shows that the MS estimates are more biased than the MAA but have lower spread.

The MAP estimates for the proposed method, MAA, Omron device, Augmentation Index (AI), ΔT/T, Stiffness Index (SI), Reflection Index (RI) are presented in Table III. MAP estimation based on pulse morphology that utilizes AI, ΔT/T, SI and RI is detailed in [3]. The results are presented as an average of five consecutive trials. The SBP and DBP estimates are given in Tables IV and V respectively.

V. Conclusions

This study has demonstrated the applicability of a new oscillometric pulse index (OPI) derived from individual pulses for estimating blood pressure from non-invasive oscillometric measurements. Unlike previous work where the slope criterion was used for estimating the systolic and diastolic pressures from the envelope, this paper has used the slope criteria to derive the envelope. The proposed algorithm is conjectured to be more robust to some artifacts than MAA and needs to be verified through future work. In MAA, BP is estimated based on the amplitude of the first peak of the pulse. Amplitude of the pulse is in general more sensitive to additive noise than the shape of the pulse. Therefore, methods that derive the OPI from parameters based on the shape of the pulse have potential to provide more robust BP estimates.

It may be noted that estimations of systolic and diastolic blood pressure based on the height or the area of the pulse (MAA algorithm) that is most commonly used in practice is just one way to estimate blood pressure. The authors have demonstrated in [3] and through this paper that many other parameters can be extracted from the pulses of the oscillometric waveform and used in different ways to estimate blood pressure. Fusion of the BP estimates obtained through quantitative measures that describe the morphology of the pulses is a promising future direction.

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REFERENCES

[1] K.-G. Ng and C.F. Small, "Survey of automated noninvasive blood pressure monitors," J. Clin. Eng., vol. 19, pp. 452-475, 1994.

[2] G. Drzewiecki, R. Hood, and H. Apple, "Theory of the oscillometric maximum and the systolic and diastolic detection ratios," Ann. Biomed. Eng., vol. 22, pp. 88–96, 1994.

[3] M. Mafi, S. Rajan, M. Bolic, V. Z. Groza, H. Dajani, "Blood pressure estimation using oscillometric pulse morphology," IEEE Int. Conf. on Engineering in Medicine and Biology, Boston, Aug. 2011.

[4] G. Drzewiecki, R. Hood, and H. Apple, "Theory of the oscillometric maximum and the systolic and diastolic detection ratios," Ann. Biomed. Eng., vol. 22, pp. 88–96, 1994.

[5] T. Ellis, J. Mcnames, and M. Aboy, "Pulse morphology visualization and analysis with applications in cardiovascular pressure signals," IEEE Trans. Biomed. Eng., vol. 54, no. 9, pp. 1552-1559, 2007.

[6] S. Chen, V. Z. Groza, M. Bolic, H. R. Dajani, "Assessment of algorithms for oscillometric blood pressure measurement," Proc. Int. Instrumentation and Measurement Technology Conference, Singapore, May 2009.

[7] L. A. Geddes, "Handbook of blood pressure measurement," Humana Press, 1991.

[8] M. Mafi, M. Bolic, V. Z. Groza, H. Dajani, S. Rajan, "Oscillometric blood pressure pulse morphology," IEEE Int. Workshop on Medical Measurement and Applications, Bari, Italy, May 30, 2011.

[9] L.A. Geddes, M. Voelz, C. Combs, D. Reiner, and C.F. Babbs, "Characterization of the oscillometric method for measuring indirect blood pressure," Ann. Biomed. Eng., vol. 10, pp. 271-280, 1982.

TABLE I. COMPARISON OF MAA, MS AND OMRON ESTIMATES FOR MAP, SBP AND DBP

	MS (mmHg)	MAA (mmHg)	Omron (mmHg)
SBP	112.53 ± 10.15	114.06±6.7	114.13 ± 9.2
MAP	85.83 ± 7.2	87.64±4.73	87 ± 5.42
DBP	72.81 ± 6.95	72.82 ± 8.7	72.52 ± 4.8

TABLE II. COMPARISON OF MEAN AND STANDARD DEVIATION (STD) OF MEAN ABSOLUTE ERRORS BETWEEN MS, MAA AND OMRON MEASUREMENTS

Mean Abs Error	MS (mmHG)	MAA (mmHG)
Mean SBP	4.99	4.69
STD SBP	3.04	3.70
Mean DBP	4.71	4.31
STD DBP	2.46	3.48

TABLE III. ESTIMATES OF MAP FOR MAA, MS ALGORITHMS, READINGS FROM THE OMRON DEVICE, AND A NUMBER OF ALGORITHMS THAT RELY ON PULSE MORPHOLOGY

MAP	MS	AI	ΔT/T	SI	RI	MAA	OMR
S1	90.4	88.2	88	89	89	86.8	89.8
S2	98.4	94	93.8	96.4	96.4	91.2	95.8
S3	86.8	79.2	79	80	81.8	88	82.8
S4	93	88.6	88.6	89.4	89.8	90.4	89.6
S5	83.6	79.4	81.6	81.2	81	90.4	81.6
S6	83.2	81.6	82.8	83	79.6	83.8	81.4
S7	91.8	89.2	89.4	92	91.4	91.4	93.4
S8	86.2	89	90.6	90.6	91	84.8	89.6
S9	76.8	74	74	75.2	76.2	75.2	74.8
S10	83.6	81	83.2	81.8	82.6	81.8	81.4
S11	72.4	69.8	70.8	71.6	71.2	74.8	71.4
S12	76	74.2	74.6	74.2	74.4	74.4	74
S13	88	83	83	83.2	83.4	83.8	83.6
S14	89	92.8	92.4	92.2	92.4	94.2	92.4
S15	73	67.8	68.2	68.6	69	68.2	70.4
S16	87.2	87	87	86.6	86.8	87	87.6
S17	89.2	91.6	91.2	89.4	90.6	87.4	88.4
S18	87.4	82.8	81.6	83.8	83	83.8	86

TABLE IV. ESTIMATES OF SBP FOR MAA, MS ALGORITHMS, READINGS FROM THE OMRON DEVICE, AND A NUMBER OF ALGORITHMS THAT RELY ON PULSE MORPHOLOGY

SBP	MS	AI	ΔT/T	SI	RI	MAA	OMR
S1	123.2	120.6	121.4	124	123.6	119.8	123.2
S2	129.2	129.4	129.2	130.4	131.2	121	129.2
S3	104.4	102	101.8	103.2	101.4	109.4	101.8
S4	117.6	116.8	118.8	117.8	117.4	114	113.6
S5	109.2	104	104.8	105.8	106	115.4	105.4
S6	111.8	110	111.2	112	111	107.8	109
S7	118.8	121.6	123	124.2	123.4	116.2	118.8
S8	106.2	106.8	107	106.2	107.4	105	108.8
S9	101.8	102.4	102.6	103.6	102.4	102.2	98.2
S10	106.8	107.4	108.4	108.6	109.6	109.8	105.2
S11	94.8	102.4	100.6	100.8	101.4	93	93
S12	101	98	98.8	100.2	104.6	104.2	101.6
S13	115.4	114.8	115.2	116	115.6	112.4	116.6
S14	120.6	119.6	118.4	119.4	119.6	122.8	120.2
S15	95.2	94.4	95.2	98.4	99.4	91.2	91.2
S16	113.8	112.6	110.4	113	112	116.2	113
S17	112.6	112.4	113	1132	113	110.2	111.8
S18	116.6	116	117	117.6	118.2	116.8	114.8

TABLE V. ESTIMATES OF DBP FOR MAA, MS ALGORITHMS, READINGS FROM THE OMRON DEVICE AND A NUMBER OF ALGORITHMS THAT RELY ON PULSE MORPHOLOGY

DBP	MS	AI	ΔT/T	SI	RI	MAA	OMR
S1	66.8	72.2	72.8	72.8	73.2	65.8	73.2
S2	80.8	77.4	79.2	75.2	77.2	78.6	79.2
S3	78	74.8	75	75.4	76	75.8	73.6
S4	81.8	74.2	74.6	74.2	74.2	76.8	77.6
S5	72	70.2	68.4	73.2	72.6	78	70
S6	69.6	72.2	72.8	71	73	69.8	67.6
S7	82.6	84	84.4	83.6	83.6	80.6	81
S8	78.6	88.2	88.6	86.2	85.8	81	80.6
S9	66	63.4	63.8	63.4	64	69.8	63.4
S10	72.8	71	71.2	70.4	70.6	72.2	69.6

S11	62.8	70.6	69.4	69.6	70	67	61
S12	62.4	62	63.4	64.4	63.8	64.4	60.6
S13	74.8	72.8	73.8	72.6	72.8	70.6	70.4
S14	75.8	71.4	71	70.6	72	72.6	79
S15	62.6	63.2	64.2	64.4	65	64	60.4
S16	75.2	68.2	69.2	71.4	70.8	70.6	75.2
S17	78.4	79.8	81.6	82.2	82.4	76.8	77.4
S18	74	66	66.6	63.8	63.6	70.4	72.2

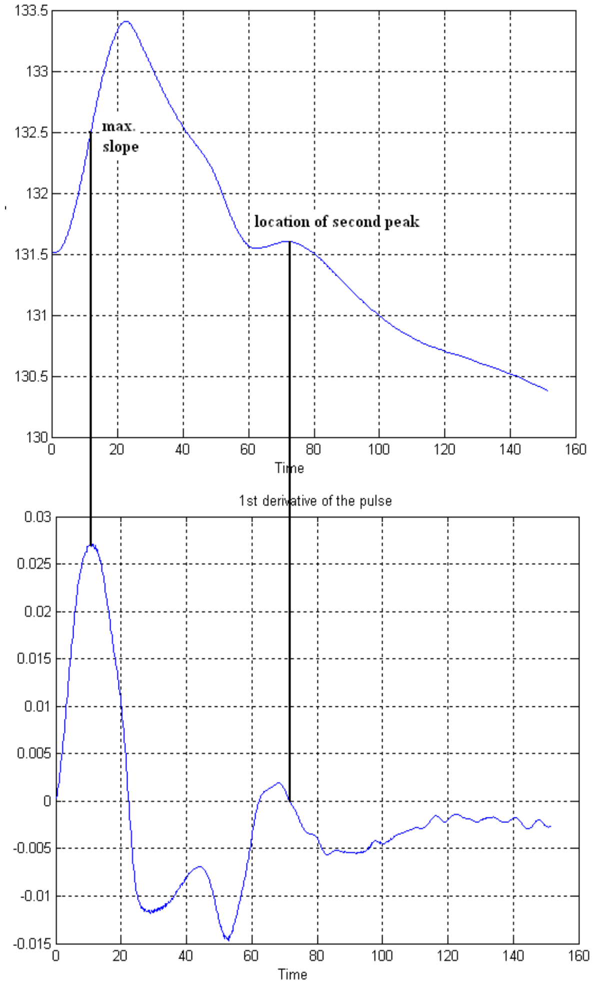

Figure 1. A pulse of the oscillometric waveform (above) and its first derivative (below)

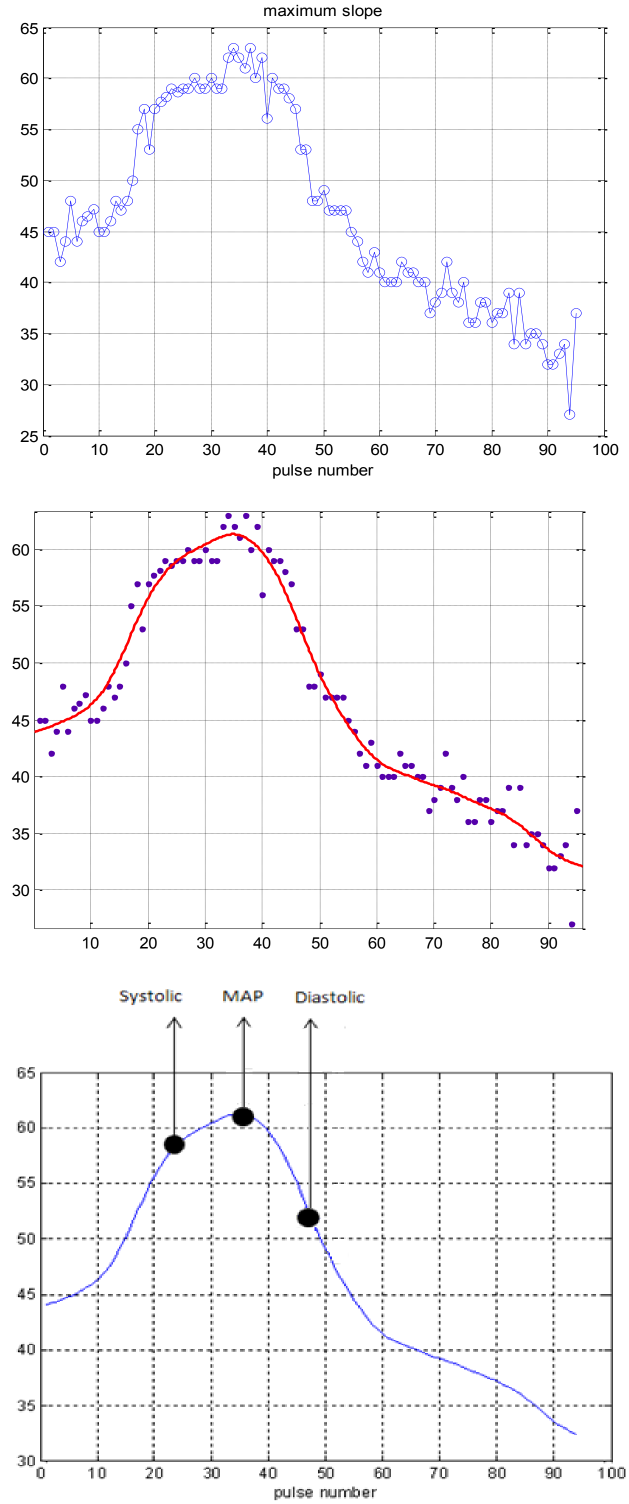

Figure 2. a) Top: Raw OPI waveform using MS, b) Middle: Curve Fitted Envelope c) Bottom: Envelope showing the estimates