33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Blood Pressure Estimation using Oscillometric Pulse Morphology

Majid Mafi, Sreeraman Rajan, Miodrag Bolic, Voicu Z. Groza, Hilmi R. Dajani
School of Information Technology & Engineering (SITE)
University of Ottawa
Ottawa, ON, Canada
{mmafi080,mbolic, groza, hdajani}@site.uottawa.ca
sreeraman@ieee.org

Abstract- **A novel pulse morphology-based approach for estimation of blood pressure from non-invasive oscillometric blood pressure measurement is presented. Quantitative measures that describe the pulse morphology are utilized to obtain the estimates of mean arterial, systolic, and diastolic pressures. Preliminary results obtained from a small set of measurements are used to demonstrate the feasibility of the proposed approach. The estimates obtained through pulse morphology-based approach is compared with those obtained from a commercial blood pressure device.**

Keywords- Oscillometric waveform, Pulse morphology, Blood Pressure.

I. INTRODUCTION

Blood pressure (BP) is recognized as one of the vital signs and is widely used to monitor the physiological condition of human beings along with other vital signs such as heart rate, breathing rate and temperature. Of the various methods available for blood pressure measurement, the oscillometric method appears to be one of the most popular methods [1]. In this method, cuff is placed around the arm or the wrist and is slowly deflated from an initial pressure higher than the systolic value; a transducer is connected to the cuff and it senses the pressure inside the cuff. A waveform which is known as oscillometric waveform can be extracted from decreasing pressure curve which is produced by the pressure transducer in the cuff. As the occluding cuff is slowly released, oscillation pulses will appear on the cuff deflation waveform [2] (Fig. 1). Moreover, as the cuff is deflated, the characteristics of the pulses change, and these changes could contain important information about the blood pressure. This paper demonstrates that blood pressure estimates can be obtained through quantitative measures that describe these pulses.

Pulses in the oscillometric waveform generally show two distinct peaks: an early systolic peak related to the forward pressure wave and a diastolic peak related to the reflected pressure wave. Any change in the cardiovascular system would affect the paths of the forward and reflected pressure waves and in turn changes the characteristics of the pulses. This information is reflected in the morphology of the pulse over the span of a single cardiac cycle [2]; thus by studying the pulse morphology, one can obtain useful health information about the cardiovascular system. Morphology of the pulse has been identified as a candidate tool to predict some cardiovascular diseases such as heart attack, or heart failure [4] as there are characteristic changes in the pulse with aging, atherosclerosis, and hypertension due to the increase of stiffness of large arteries.

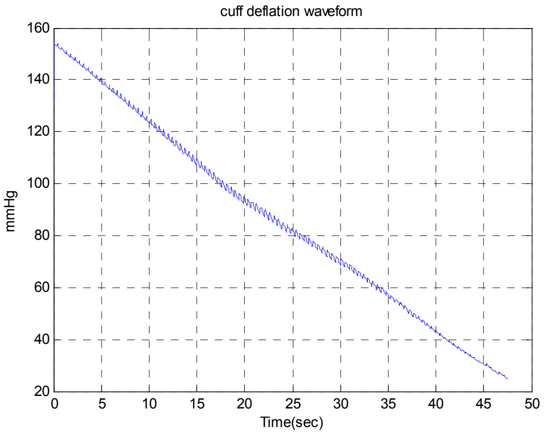

Fig. 1: Cuff deflation waveform

Even though there has been a proliferation of oscillometric devices in the market, the algorithms used for estimation of the pressures are still proprietary and only a few algorithms have appeared in the literature. The Maximum Amplitude Algorithm (MAA) is the most commonly mentioned algorithm in the literature. MAA uses the maximum peak of the envelop of the oscillometric waveform and linearly relates it to the systolic and diastolic pressures using empirically obtained ratios [1, 3]. The choice of ratio is mostly data driven. Also, algorithms such as MAA do not capture the relationship between the estimates and the signal characteristics. A review of the various algorithms used for estimating the blood pressure from oscillometric waveforms, palpation or auscultation is available in [1]. Pulse morphology has been studied in [3-8] at steady state pressures but has not been applied for estimating pressures from oscillometric waveforms.

In this paper, a signal-based approach is used to estimate the systolic and diastolic blood pressures. Pulse morphology is utilized to derive a methodology to estimate the arterial blood pressures. A number of qualitative measures for the pulses are obtained from the pulse morphology at various deflating cuff pressures. Using these measures systolic, diastolic and mean arterial pressures are determined.

The remainder of the paper is organized as follow, in Section II; the data acquisition methodology used in this research is introduced while in Section III the quantitative measures and the methodology used in the paper are described. Preliminary results using the proposed method are presented in section IV, and the paper is concluded in section V.

II. DATA ACQUISITION

Oscillometric waveforms were obtained from 10 healthy subjects aged from 24 to 68 years (6 males, 4 females) for over 2-3 days with 5 trials per day. Volunteers were asked to seat and let their arm at the level of the heart during the recording. The duration of each measurement was around 40-50 seconds and the resting period between two consecutive trials was 3 minutes. None of the volunteers had a known history of cardiovascular disease or was taking any vasoactive drugs. They were also requested not to take any kind of medication during the period of recording.

The cuff of an Omron monitor (Model HEM-790ITCAN) was placed around subjects' right arm and the blood pressure was recorded before each trial. This measurement was used for comparison purposes. Since the Omron device only records the systolic and diastolic pressures, the following formula was used to derive the Mean Arterial Pressure (MAP) from Omron measurements [10]:

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

The device used in this experiment collected both oscillometric waveform and ECG simultaneously. The recorded ECG was not used in the analysis and its instrumentation is not explained here. The device had four main components namely an analog ECG amplifier, an analog pressure transducer (Vernier Pressure transducer BPS-BTA, Beaverton, OR, USA), a mini direct current (DC) air pump, and a screw controlled manual pressure release valve. The analog voltage output of the Vernier pressure transducer was connected to a National Instruments ^{TM} C Series 9239 analog input module (NI-9239) mounted on a Compact DAQ data acquisition board, to be simultaneously sampled and quantized. Passing through the NI-9239 module, this analog signal was conditioned, buffered, and then sampled by a 24-bit delta-sigma analog-to-digital converter (ADC) at 1000Hz. The digitized signal was transferred to a PC with a USB cable. PC-based National Instrument ^{TM} LabVIEW development environment was used for acquisition of signals. Software in Matlab® (The MathWorks Inc., Natick, MA, USA) was written for reading, processing, and analyzing the acquired pulse signals.

III. METHODOLOGY

After measuring SBP and DBP with Omron on the right arm, the cuff of our device was inflated on the left arm of the subject with roughly 30 mmHg above the systolic pressure and deflated slowly below the diastolic pressure. All the pulses were detected from the cuff deflation pressure waveform. The following quantitative measures were obtained for every detected pulse and utilized in the estimation of the systolic (SBP), diastolic (DBP), and mean arterial pressures (MAP).

A. Augmentation Index (AI)

Augmentation Index is defined as the difference of systolic peak (F) and diastolic peak (P) of pulse waveform over the systolic peak (F) (Fig. 2). It is expressed as a percentage of the pulse pressure [6-7, 12]:

$$AI = \left[\frac{(F-P)}{F}\right] \times 100\% \tag{2}$$

B. Reflection Index (RI)

Reflection Index is related to vascular tone and is defined as the diastolic peak (P) over the systolic peak (F) and expressed as a percentage [5, 12]:

$$RI = \frac{P}{F} \times 100\% \tag{3}$$

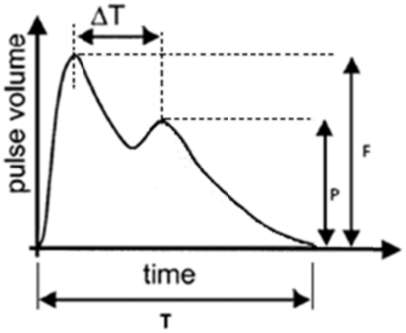

Fig. 2: Typical pulse contour and its characteristics, based on [4]

C. Stiffness Index (SI)

Stiffness Index can be calculated as following [4, 12]:

$$SI = \frac{h}{\Delta T} \quad (4)$$

where ΔT, measured in second, is the time difference between systolic and diastolic peak (figure 2) and h is the height of the subject. Stiffness Index should not be considered as a direct measure of large arteries stiffness but can be a possible indicator of stiffness of the arteries.

D. ΔT/T ratio

ΔT is the measure of transit time between the subclavian artery and reflection sites and has been used to define a non-invasive measure of large artery stiffness while T is the duration of the pulse. Similar to the previous measures, ΔT is the time difference between systolic and diastolic peaks. Due to the change in stiffness of arteries in elderly people, it is observed that ΔT and T increase with age [8, 12].

For every detected pulse, the above mentioned quantitative measures were calculated. The quantitative measures of the oscillometric pulse morphology varied across the cuff pressure waveform. The respective global maximum or minimum in each of the quantitative measures was identified. The pulse corresponding to this maximum or minimum was used for estimating the MAP. Since every pulse has a different pressure range, the average of the maximum and the minimum pressure in the selected pulse was taken as MAP value.

If the MAP was obtained using global minimum, then the region around the local maximum to the left of the global minimum was defined as the systolic pressure region and the local minimum to the right of the global minimum was identified as the diastolic pressure region (see Figures 3, 4). If the MAP was obtained using global maximum, then the region around the local minimum to the left of the global maximum was identified as the systolic region and the local maximum to the right of the global maximum was identified as the diastolic pressure region (see Figures 5 and 6). The systolic region, MAP and the diastolic region for AI (Figure 3) are presented in Figures 7, 8 and 9 respectively. In this work, 9 pulses were considered in the systolic and diastolic regions with the pulse corresponding to the local maximum or local minimum as the center pulse. The pressure of each pulse was calculated as the average of its maximum and minimum pressures. Then the mean of all the nine pulses and median of all the pulses were calculated and used as systolic/diastolic pressure estimates depending on the region that was considered during the estimation.

IV. RESULTS

Figures 3-6 present the various quantitative measures of the oscillometric pulse morphology for all the detected pulses in the cuff deflation waveform for one subject. The AI and ΔT/T curves had unique global minima that corresponded to MAP pulse, while the unique global maxima in SI and RI curves corresponded to the MAP pulse. The arterial compliance is maximum at MAP when internal pressure is equal to the external pressure and that would make the maximum amplitude at MAP and make pulse different than the pulses around the MAP [13]. It may be noted that for a given subject, in a given trial, all the MAP estimates were the same. The systolic and diastolic regions were slightly different in each measure. However, this did not produce huge variation in the pressure estimates, indicating the robustness of the approach. Of the various measures, SI was the least smooth curve. The estimated systolic, diastolic mean and median values were compared with Omron measurements and MAA algorithm in Tables II-IV. The difference between the estimation and Omron and MAA measurements were mostly within a +/-5 mmHg bound. Table V contains the estimated MAP using different measures, the MAP for Omron calculated using equation (1) and MAP estimated from MAA algorithm. It is very clear that MAP estimation is stable as MAP is obtained from distinct minimum or maximum of the measures of the oscillometric pulse morphology.

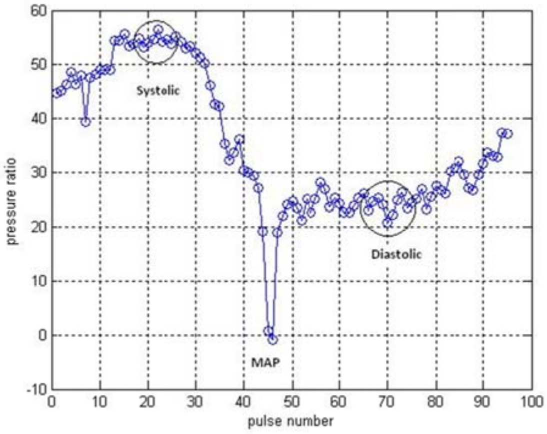

Fig. 3: Augmentation Index

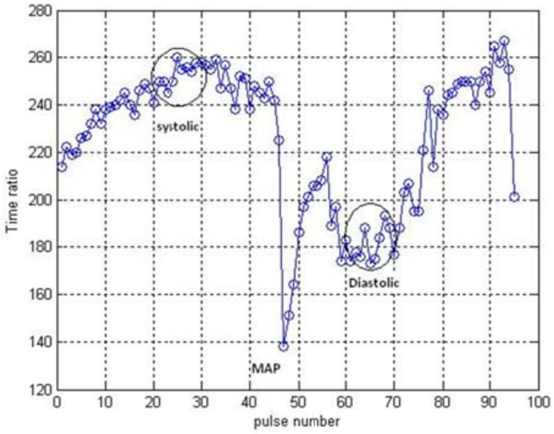

Fig. 4: ΔT/T Ratio

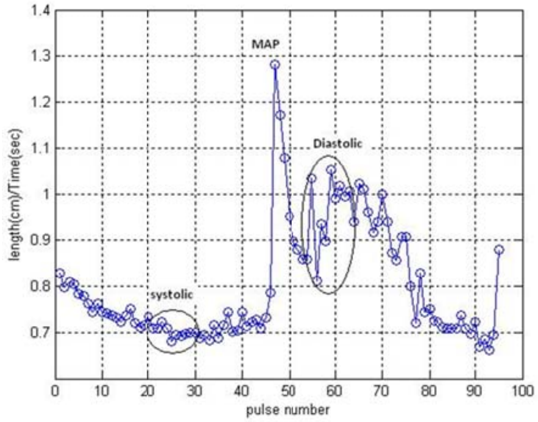

Fig. 5: Stiffness Index

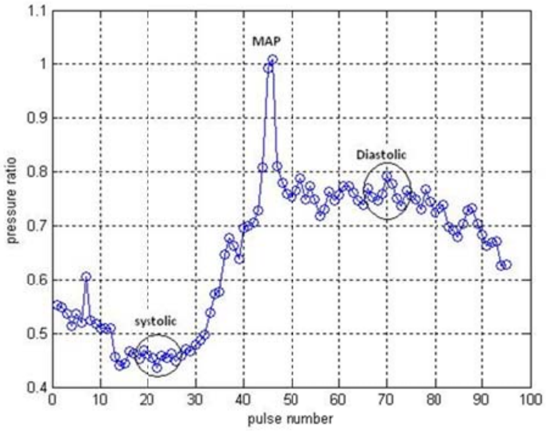

Fig. 6: Reflection Index

TABLE I. SBP (MMHG) BASED ON MEAN OF 9 PULSES

SBP (mean)	AI	ΔT/T	SI	RI	MAA	Omron
Subject 1	126	127	127	125	128	132
Subject 2	119	123	123	119	121	132
Subject 3	105	114	114	105	113	114
Subject4	123	129	128	123	124	130
Subject 5	122	124	124	122	123	127
Subject 6	125	126	124	125	114	119
Subject 7	117	125	122	122	107	120
Subject 8	115	111	110	115	112	110
Subject 9	120	119	118	120	118	122
Subject 10	123	118	118	123	111	119

TABLE II. SBP (MMHG) BASED ON MEDIAN OF 9 PULSES

SBP (median)	AI	ΔT/T	SI	RI	MAA	Omron
Subject 1	127	124	124	127	128	132
Subject 2	118	124	124	118	121	132
Subject 3	104	115	115	104	113	114
Subject4	122	128	127	122	124	130
Subject 5	123	125	125	124	123	127
Subject 6	121	124	119	120	114	119
Subject 7	122	122	122	119	107	120
Subject 8	116	110	110	115	112	110
Subject 9	121	119	119	120	118	122
Subject 10	123	116	116	122	111	119

TABLE III. DBP (MMHG) BASED ON MEAN OF 9 PULSES

DBP (mean)	AI	ΔT/T	SI	RI	MAA	Omron
Subject 1	67	73	78	67	69	75
Subject 2	76	78	78	76	81	76
Subject 3	69	79	79	69	78	73
Subject4	71	73	73	71	70	78
Subject 5	70	69	69	70	67	71
Subject 6	79	87	84	79	72	84
Subject 7	68	68	69	71	67	73
Subject 8	72	75	75	72	80	79
Subject 9	73	74	73	73	74	70
Subject 10	73	75	75	73	76	78

TABLE IV. DBP (MMHG) BASED ON MEDIAN OF 9 PULSES

DBP (median)	AI	ΔT/T	SI	RI	MAA	Omron
Subject 1	69	72	71	68	69	75
Subject 2	76	77	77	76	81	76
Subject 3	69	80	80	69	78	73
Subject4	71	73	73	71	70	78
Subject 5	69	67	67	69	67	71
Subject 6	81	83	84	81	72	84
Subject 7	71	70	69	76	67	73
Subject 8	71	75	75	72	80	79
Subject 9	73	74	74	73	74	70
Subject 10	72	75	75	74	76	78

TABLE V. MAP (MMHG)

MAP	AI	ΔT/T	SI	RI	MAA	Omron
Subject 1	93	93	94	93	86	94
Subject 2	90	91	90	90	95	95
Subject 3	90	90	90	90	89	87
Subject4	90	92	92	90	94	95
Subject 5	88	89	89	88	82	90
Subject 6	94	95	95	95	84	96
Subject 7	87	87	88	87	82	89
Subject 8	90	91	91	90	93	89
Subject 9	87	88	88	87	88	87
Subject 10	91	87	87	91	89	92

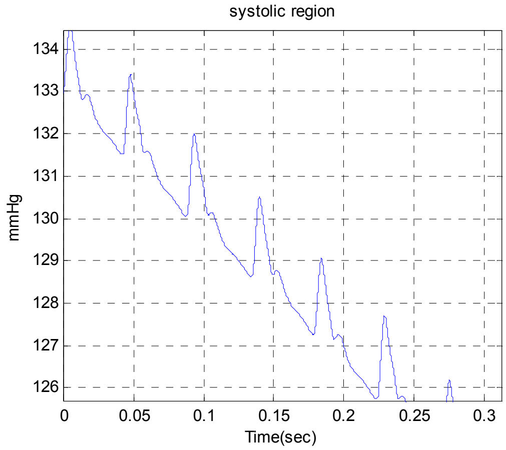

Fig. 7: Systolic region of the oscillometric waveform

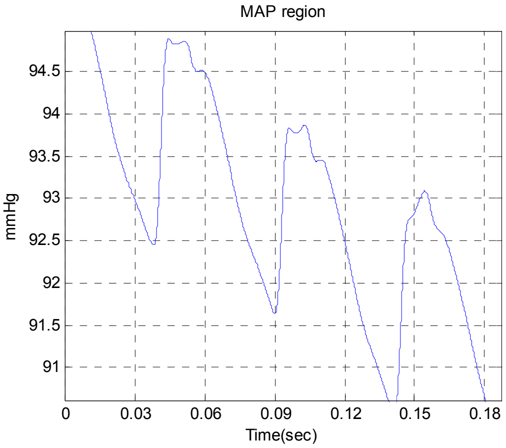

Fig. 8: MAP region of the oscillometric waveform

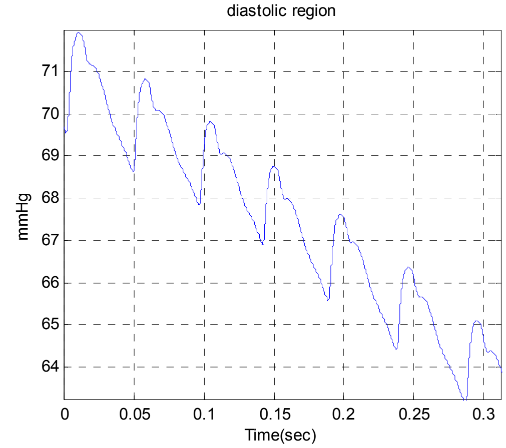

Fig. 9: Diastolic region of the oscillometric waveform

V. CONCLUSION

Our preliminary study has demonstrated the feasibility of using oscillometric pulse morphology for estimating blood pressure from non-invasive oscillometric measurements. Unlike MAA approach, the proposed approach uses the pulse morphology of every detected pulse. As MAA uses the envelope information, the local variations of the pulse characteristics is not considered in the algorithm. The proposed approach may be able to provide more measures that may be of diagnostic value than MAA. Advanced signal processing techniques such as fusion of estimates are being developed to make the estimation robust and to obtain more insight into the characteristics of the oscillometric pulses.

ACKNOWLEDGMENT

The authors would like to thank Dr. Ismail Batkin, Dr. Saif Ahmad, and Mr. Mohamad Forouzanfar for their help in this research project.

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] T. Ellis, J. Mcnames, and M. Aboy, "Pulse morphology visualization and analysis with applications in cardiovascular pressure signals," IEEE Transaction on Biomedical Engineering, vol. 54, no. 9, pp. 1552-1559, 2007.

[4] S.C. Millasseau, R.P. Kelly, J.M. Ritter, and P.J. Chowienczyk, "Determination of age-related increases in large artery stiffness by digital pulse contour analysis," Clinical Science, vol. 103, pp. 371-377, 2002.

[5] J.M. Padilla, E.J. Berjano, J. Saiz, L. Facila, P. Diaz, and S. Merce, "Assessment of relationship between blood pressure, Pulse Wave Velocity and digital volume pulse," Computers in Cardiology, vol. 33, pp. 893-896, 2006.

[6] I.B. Wilkinson, N.H. Mohammad, S. Tyrrell, I.R. Hall, D.J. Webb, V.E. Paul, T. Levy, and J.R. Cockcroft, "Heart rate dependency of Pulse Pressure amplification and arterial stiffness," American Journal of Hypertension, vol.15, pp. 24-30, 2002.

[7] R. Kelly, C. Hayward, A. Avolio, and M. O'Rourke, "Noninvasive determination of age-related changes in the human arterial pulse," Circulation, vol.80, pp. 1652-1659,1989.

[8] V.K. Jayasree, T.V. Sandhya, and P. Radhakrishnan, "Non-invasive studies on age related parameters using a blood volume pulse sensor," Measurement Science Review, vol. 8, section 2, no. 4, pp. 82-86, 2008.

[9] D. Korpas, J. Halek, and L. Dolezal, "Parameters describing the pulse wave," Physiol. Res., vol. 58, pp. 473-479, 2009.

[10] L.A. Geddes, M. Voelz, C. Combs, D. Reiner, and C.F. Babbs, "Characterization of the oscillometric method for measuring inderect Blood Pressure," Annals of Biomedical Engineering, vol. 10, pp. 271-280, 1982.

[11] P. von Dadelszen, M.P. Ornstein, S.B. Bull, A.G. Logan, G. Koren, and L.A Magge, "Fall in mean arterial pressure and fetal growth restriction in pregnancy hypertension: a meta analysis," Hypertension, vol. 355, pp. 87-92, 2000.

[12] M. Mafi, M. Bolic, V.Z. Groza, H. Dajani, S. Rajan, "Oscillometric Blood Pressure pulse morphology" accepted at IEEE International Workshop on Medical Measurement and Applications (MeMeA 2011), Bari, Italy, May 30, 2011.

[13] G. Drzewiecki, R. Hood, and H. Apple, "Theory of the oscillometric maximum and the systolic and diastolic detection ratio", Annals of Biomedical Eng., Vol. 22, pp. 88-96, 1994.