Method for Evaluation of Trustworthiness of Oscillometric Blood Pressure Measurements

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Abstract—**Simple, unobtrusive, and reliable estimation of cardiovascular parameters is a challenge. We present a novel, simple, and noninvasive method called *Ratio2* that provides expected ranges for systolic and diastolic blood pressure values (SBP, DBP) estimated by any algorithm, and an evaluation of vessel compliance. *Ratio2* was developed in the frame of the oscillometric blood pressure estimation and it exploits the equality between the arterial blood pressure and the cuff pressure at the mean arterial pressure (MAP). This method is based on the observation that the brachial arterial blood pressure pulses, with MAP used as baseline, are characterized by a peak to trough ratio close to 2. This ratio is employed to characterize expected ranges for estimates of systolic and diastolic blood pressure. Any SBP or DBP measurement which is not contained in these intervals is deemed untrustworthy, and it is marked as such. *Ratio2* also provides parameters that are used in a mathematical model of arterial blood pressure (BP) to evaluate vessel stiffness. We tested the performance of the *Ratio2* method on 150 oscillometric recordings and their corresponding Omron BP estimates obtained from 10 healthy subjects. Results are encouraging, whereby, (a) out-of-range values obtained with the maximum amplitude algorithm (MAA) and the maximum/minimum slope algorithm (MMSA) methods were successfully detected, and (b) linear correlation between age and vessel compliance is –85% ($p<0.005$). Therefore, we conclude that the proposed work shows promise towards providing noninvasive BP monitors with an inbuilt mechanism for assessing the fidelity of their BP estimates along with an indicator of vessel compliance.**

Keywords—Mean arterial pressure; systolic; diastolic; blood pressure; vessel compliance; oscillometric waveform simulation

I. INTRODUCTION

Blood pressure (BP) is an important hemodynamic parameter that is routinely monitored to diagnose and manage conditions such as hypertension and hypotension [1-2]. Automatic noninvasive BP (NIBP) measurement is now regularly employed in many clinical settings [3-4]. Briefly, a typical automatic NIBP monitor records and analyzes oscillometric pulses generated during cuff deflation to provide an estimate of systolic (*SBP*) and diastolic BP (*DBP*) [5-6].

In clinical practice, BP estimation accuracy is important because even small measurement errors can lead to inaccurate diagnoses, and potentially life-threatening conditions like stroke and myocardial infarction [7-9] can occur. Despite advances in technology and an increase in clinical use, automatic NIBP monitoring still faces challenges vis-à-vis accuracy and reliability. Chronic patient conditions like atrial fibrillation (AF) and heart failure, and noise such as motion artifact tend to render NIBP estimation somewhat inaccurate and unreliable [10-12]. Notably, current NIBP monitoring technology provides no self-contained method to evaluate the fidelity and trustworthiness of BP estimates that it provides.

In addition to BP, arterial stiffness or vessel compliance is another important biomarker for cardiovascular health and function [13-14]. Researchers have proposed various methods for noninvasive assessment of arterial stiffness based on arterial pulse wave morphology analysis and pulse wave velocity (PWV) analysis [15-18]. However, these methods suffer from certain limitations, since both pulse wave morphology and PWV are intricately linked to a number of other factors like physical activity, blood pressure, and blood glucose level [19-20]. Therefore, arterial stiffness estimates that rely on pulse morphology and PWV may not be consistently accurate. Additionally, PWV measurement requires a reference heartbeat signal that needs to be acquired using auxiliary electrocardiogram (ECG) or pulse sensors. This adds complexity and obtrusiveness to the method of arterial stiffness assessment based on PWV analysis.

The research presented in this paper addresses the above-mentioned challenges in the field of NIBP estimation and noninvasive vessel compliance assessment. We present a novel and simple method that is based entirely on the oscillometric NIBP monitoring paradigm for: (a) providing accurate ranges within which *SBP* and *DBP* lie and (b) providing an assessment of vessel compliance.

This method, to which we refer to as *Ratio2,* was conceived to determine the limits *SBP2* and *DBP2* of the intervals that are expected to contain the true values of systolic and diastolic blood pressure estimated through oscillometric algorithms. An acceptance range for *DBP* evaluated using any NIBP estimation algorithm is between *DBP2* and *MAP2*. Similarly, an acceptance range for *SBP* evaluated using any NIBP estimation algorithm is between *MAP2* and *SBP2*.

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When *DBP* and/or *SBP* values fall outside their respective ranges, it implies that the NIBP estimation should be considered untrustworthy. After acquisition of an oscillometric waveform, the *Ratio2* method uses the pulse for which peak to trough ratio is closest to 2 to evaluate mean arterial pressure (*MAP2*), *SBP2*, and *DBP2* (suffix 2 since these are estimated using the *Ratio2* algorithm). For an actual oscillometric waveform, an equivalent simulated oscillometric waveform is generated using a mathematical model. This model comprises parameters from the actual oscillometric waveform as well as a parameter for vessel compliance. The compliance parameter in the model is fine-tuned until the simulated pulse for which peak to trough ratio tends to 2 is closest to the actual pulse for which this ratio tends to 2. The compliance at which this happens is reported as the compliance for the subject from whom this actual oscillometric waveform data was recorded.

The above method was tested on 150 actual oscillometric waveform recordings and their corresponding Omron NIBP estimates obtained from 10 healthy subjects. Results are promising whereby the maximum amplitude algorithm (MAA) and the maximum/minimum slope algorithm (MMSA) show 6 and 13 outliers respectively -- this implies that the MAA is performing better than the MMSA since the number of out of range estimates that MAA provides are less (6) than those provided by MMSA (13). Moreover, linear correlation between subject age and vessel compliance is –85% ($p<0.005$).

We thus conclude that our work has the potential to provide NIBP monitors with a self-contained method for evaluating the ‘goodness’ of their BP estimates along with an accurate assessment of vessel compliance.

II. METHODS

A. Dataset

The dataset for this study comprises 150 oscillometric recordings that were obtained from 10 healthy subjects (15 recordings per subject) using an NIBP monitoring prototype that we developed, along with their corresponding NIBP estimates of *SBP* and *DBP* determined with an Omron monitor. The NIBP estimates made by the Omron monitor serve as reference measurements for the oscillometric recordings. Out of the 10 subjects, 6 were males while 4 were females, and their age range was 24 years to 63 years. More details about this dataset can be found in our earlier published work [21].

B. Ratio2 Algorithm

The main steps of the *Ratio2* algorithm are presented in Fig. 1. First, the oscillometric recording or the cuff deflation curve (CDC) is filtered using a Butterworth band pass filter (bandwidth = 0.5-20 Hz) to obtain the oscillometric waveform (OMW) data. We then find the oscillometric pulse whose peak to trough ratio is closest to a threshold of 2 (Steps 2-4, Fig. 1). This occurs when the cuff pressure is equal to mean arterial pressure which we mark as *MAP2*. At this stage, the system is under equilibrium, that is, the internal arterial pressure is equal to the externally applied cuff pressure. Therefore, the corresponding oscillometric OMW pulse is akin to an intra-arterial blood pressure (ABP) pulse, i.e., the former pulse can be derived by vertically stretching the latter.

The values of the peak and the trough of the arterial blood pressure pulses are proportional to the peak and the trough of the OMW pulse at MAP:

$$MAP2\text{-}DBP2 \sim tr_k \tag{1}$$

$$SBP2\text{-}MAP2 \sim pk_k \tag{2}$$

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Input:   Cuff deflation curve (CDC)
Outputs: $MAP2$, $DBP2$, $SBP2$
1. Filter CDC to get oscillometric waveform (OMW) data.
2. Create a vector called $R = [r_1, r_2, \ldots, r_n]$ such that each element $r_j$ of $R$ is the absolute ratio of peak ($pk_j$) to trough ($tr_j$) of each OMW pulse ($r_j = |pk_j/tr_j|$).
3. Define a threshold ($th$) such that $th = 2$.
4. If $R$ has no crossings with $th$ or if it has one unique crossing with $th$, then,
       a. Choose the nearest neighbor from $R$ to $th$ as the Ratio2 indicator $r_k$.
       b. Choose the CDC value corresponding to the temporal location of $r_k$ as $MAP2$.
   else
       a. Create an envelope of the amplitude of the OMW pulses using the maximum amplitude algorithm (MAA).
       b. Choose the maximum amplitude value of the envelope as $m_k$.
       c. Choose the CDC value corresponding to the temporal location of the maximum amplitude value $m_k$ as $c_k$.
       d. Find values $c_j$ in CDC that correspond to temporal locations of values $r_j$ in $R$.
       e. From the CDC values $c_j$ choose the value nearest to $c_k$ as $MAP2$.
       f. Choose the value in $R$ corresponding to the temporal location of $MAP2$ as the Ratio2 indicator $r_k$.
   end
5. Find $\chi = 3\cdot[MAP2/(2\cdot tr_k + pk_k)]$,
       where, $tr_k$ and $pk_k$ are the trough and peak values respectively of the oscillometric pulse corresponding to $r_k$.
6. Find $DBP2 = \chi tr_k - \chi tr_k \cdot \mathrm{abs}(pk_k / tr_k - 2) / 2$
7. Find $SBP2 = \chi pk_k + \chi pk_k \cdot \mathrm{abs}(pk_k / tr_k - 2) / 2$
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Fig. 1. *Ratio2* algorithm

In (1) and (2), *DBP2* and *SBP2* are the systolic and diastolic pressures that can be derived from the oscillometric pulse under equilibrium whose trough value is tr_k and whose peak value is pk_k.

We explore finding a factor χ such as

$$DBP2 = \chi \cdot tr_k \quad (3)$$

$$SBP2 = \chi \cdot pk_k \quad (4)$$

The following classical formula for *MAP* [22] is supported by the observation that in most of the cases the brachial arterial blood pressure pulse is characterized by (SBP-MAP)/(MAP-DBP) = 2

$$MAP = [DBP + (1/3) \cdot (SBP - DBP)] \quad (5)$$

χ is obtained by substituting values from (3) and (4) into (5):

$$\chi = 3 \cdot [MAP2/(2 \cdot tr_k + pk_k)] \quad (6)$$

Since we know *MAP2* (Step 4, Fig. 1), we can find the value of χ. Once we know χ, we can use (3) and (4) to find the values of *DBP2* and *SBP2* (Steps 5-7, Fig. 1).

C. Outlier Detection

Fig. 2 shows the plot of the OMW peak to trough ratio versus the cuff pressure for an oscillometric recording. As per the *Ratio2* algorithm, *MAP2* (center dashed vertical line = 67 mmHg) is where this ratio tends towards the threshold 2 (dashed horizontal line). Also shown are the calculated *DBP2* (left dashed vertical line = 47 mmHg) and *SBP2* (right dashed vertical line = 105 mmHg) values. Therefore, for this recording, *Ratio2* algorithm indicates that the *DBP* and *SBP* values estimated using any NIBP algorithm should lie within their respective ranges shown by horizontal double-headed arrows. That is, (*DBP2* < *DBP* < *MAP2*) and (*MAP2* < *SBP* < *SBP2*) or (47 mmHg < *DBP* < 67 mmHg) and (67 mmHg < *SBP* < 105 mmHg).

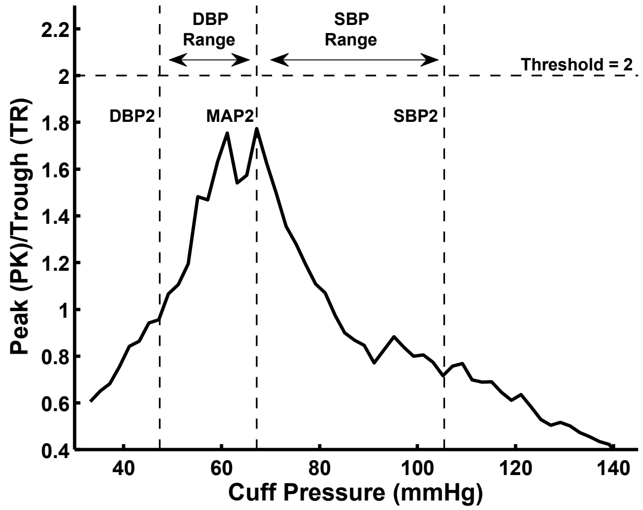

Fig. 2. Plot of oscillometric peak to trough ratio versus cuff pressure for one recording

If the *DBP* and *SBP* values estimated using any given NIBP algorithm are outside of these intervals, then we can question the quality of the oscillometric recording, or the correctness of the NIBP estimation algorithm, or there might be some other underlying factors for this anomaly. This provides a self-contained method for generating an alarm to check for the fidelity of the oscillometric recording as well as for scrutinizing the NIBP algorithm used to analyze it.

SBP2, and DBP2 are the estimated thresholds by the model for a given trace that are used to detect outliers. Uncertainty arises whether these thresholds are reliable or not. Ideally, we should get no outliers from the Omron references, while we may have some outliers from the experiments. Lower SBP2 will squeeze the acceptance range for SBP and we may get some outliers from the experiments that are not really outliers (false positives). Conversely, higher SBP2 would expand the acceptance range and we might accept traces that are not acceptable (false negatives). Similarly, lower DBP2 will not find all outliers and higher DBP2 may detect wrongly outliers. Thresholds estimated with the proposed method have found two out of range SBP values from Omron from a total of 150 recordings, while more outliers were detected when estimating SBP and DBP with MAA or MMSA algorithms. Outliers detected from MAA and MMSA algorithms are shown in table III. Removing outliers from the traces increases the accuracy of the experiments which is the objective of the work. To this end, we estimated absolute value of differences of estimated blood pressures from the respective Omron references before and after excluding the outliers for each of the MAA and MMSA algorithms. Next, we estimated mean and standard deviation of the differences for SBP and DBP and both algorithms to show the uncertainty of the model. As shown in Table IV, removing outliers have improved accuracy of the experiments for each algorithms, because mean and standard deviation of the differences from Omron references have decreased after removing the outliers.

D. Vessel Compliance Evaluation

The second application of the *Ratio2* algorithm is to evaluate vessel compliance. Based on the work reported in [23], we have developed a mathematical model that simulates the intra-arterial blood pressure (*Pa*) for an actual oscillometric recording as a function of various cardiovascular parameters, including vessel compliance. The relationship between various simulator parameters are given by,

$$P_a(t) = MAP + c_0 \cdot \cos(2 \cdot \pi \cdot HR/60 \cdot t) + c_1 \cdot \cos(4 * \pi \cdot HR/60 \cdot t + \varphi) \quad (7)$$

$$P_t(t) = P_a(t) - P_c(t) \quad (8)$$

$$A(t) = d \cdot \ln(a \cdot P_t(t) + b) / (1 + e^{-c.Pt(t)}) \quad (9)$$

In (7) - (9), P_a is the simulated arterial pressure, *MAP* is the mean arterial pressure, *HR* is the heart rate, c_0 and c_1 are amplitude constants of the main and second harmonic respectively, P_c is the cuff pressure, P_t is the trans-mural pressure, *A* is the arterial lumen area, and *a*, *b*, *c*, and *d* are arterial pressure constants. [23]

The parameter *c* in (9) is the vessel compliance. Initial simulator values are presented in Table I.

TABLE I. INITIAL SIMULATOR VALUES

Symbol	Name	Value	Units
MAP	Mean Arterial Pressure	95	mmHg
HR	Heart Rate	75	beats/minute
c_0	Amplitude of fundamental frequency	10	mmHg
c_1	Amplitude of second harmonic	9	mmHg
φ	Phase Angle	1.2	radians
a	Constant	0.03	mmHg^{-1}
b	Constant	3	dimensionless
c	Compliance	0.1	mmHg^{-1}
d	Constant	0.08	cm

Inputs: Maximum cuff pressure (CP_{max}), minimum cuff pressure (CP_{min}), recording time (T_{rec}), reference values for *SBP*, *MAP*, *DBP*, and heart rate (*HR*) for a given actual oscillometric recording

Output: Vessel compliance (*c*)

1. Use the blood pressure simulator described in (7)-(9).
2. Find minimum and maximum acceptable values for compliance parameter *c* used in the simulator.
3. Change *c* in the simulator from its minimum to maximum values with step sizes of 0.001.
4. Estimate *Ratio2* indicator r_k for the simulated OMW data (as per Step 4, Fig. 1).
5. Compare *Ratio2* indicator r_k of simulated OMW data with the *Ratio2* indicator r_k of actual OMW data.
6. Choose compliance *c* such that simulated r_k is closest to actual r_k.

Fig. 3. Vessel compliance evaluation algorithm

The main steps of the vessel compliance evaluation algorithm are presented in Fig. 3. Briefly, for an actual OMW data, a simulated OMW is created using the simulator described above. The compliance parameter *c* is varied from its lowest value to its highest value in steps of 0.001. The *Ratio2* indicator r_k is computed for the simulated OMW data and compared with the r_k value of the actual OMW data for each changing value of *c*. The value of *c* for which the simulated r_k is closest to the actual r_k is reported as the compliance *c* of the subject from whom the actual OMW data was recorded.

III. RESULTS

We used the Maximum Amplitude Algorithm (MAA) [5] and Maximum/Minimum Slope Algorithm (MMSA) [24] to estimate *SBP*, *MAP*, and *DBP* for all the 150 oscillometric recordings. We compared these values with the corresponding estimates of *SBP*, *MAP*, and *DBP* made by the reference Omron device. Please note that since the Omron monitor does not provide a reading for *MAP*, we calculated the Omron *MAP* using (5). *MAPs* for the MAA and MMSA were derived directly from the maxima of their respective envelopes. In Table II, we present the mean and standard deviation (SD) of all the 150 NIBP estimates made by the MAA, MMSA, and the reference Omron device. We observe that the mean values of the NIBP estimates provided by all three methods are within 5 mmHg and the SDs are similar.

Next, we used the *Ratio2* algorithm to detect outliers for the *SBD* and *DBP* estimates made by the MAA, MMSA, and the reference Omron monitor. Results for this analysis are presented in Table III. The first row shows the number of outliers detected for each method. The second and third rows show the mean difference and the SD of the mean differences respectively of the outliers from the acceptance range boundaries. the MAA and MMSA show 6 and 13 outliers respectively. This implies that the quality and reliability of the NIBP estimates made by the reference Omron monitor is better than the MAA and MMSA. The linear regression between age and mean vessel compliance for all 10 subjects is presented in Fig. 4. The plot shows a steady decrease in vessel compliance with increasing age. The R^2 value characterizing the goodness of a linear fit is 0.72. The linear correlation coefficient is –85% (p<0.005). This high and significant negative correlation suggests that the vessel compliance estimates made by our method are informative.

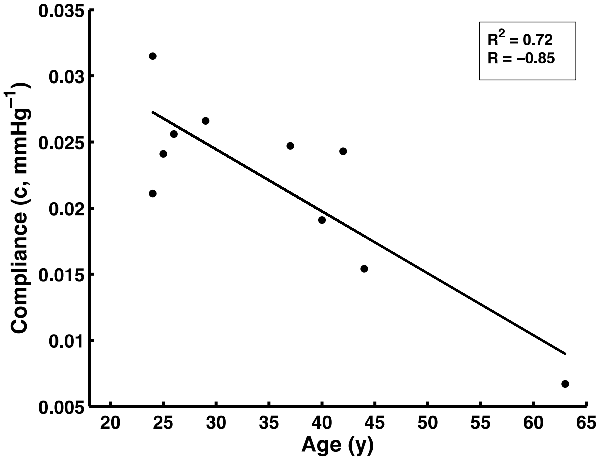

Fig. 4. Linear regression between age and mean vessel compliance for all 10 subjects

In Fig. 5, we present the linear regression between the *Ratio2* indicator (r_k) and vessel compliance for all the 150 actual oscillometric recordings. The plot shows an increase in vessel compliance with increasing r_k. The R^2 value is 0.91 and the linear correlation is 95% (p<0.001). This strong and significant positive correlation between r_k and compliance confirms that employing the *Ratio2* algorithm for compliance estimation is justified.

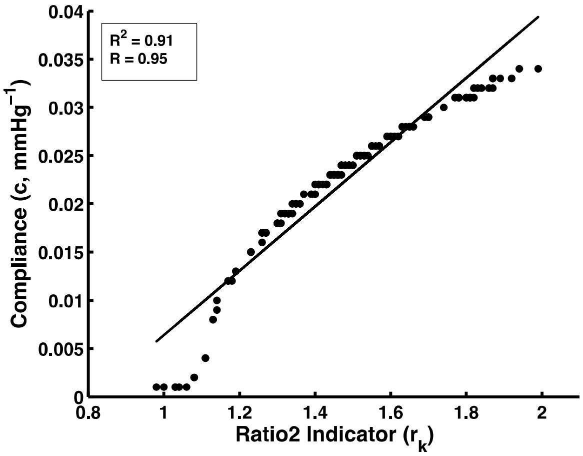

Fig. 5. Linear regression between *Ratio2* indicator and vessel compliance for all 150 actual recordings

TABLE II. MEAN AND SD OF THE 150 NIBP ESTIMATES MADE BY MAA, MMSA, AND THE REFERENCE OMRON DEVICE

Algorithm Results (150 Recordings)	**Omron (mmHg)**			**MAA (mmHg)**			**MMSA (mmHg)**		
	SBP	***MAP***	***DBP***	***SBP***	***MAP***	***DBP***	***SBP***	***MAP***	***DBP***
Mean	106.65	82.10	69.85	111.06	84.30	71.08	107.39	84.30	70.10
SD	13.21	8.83	7.37	11.89	8.99	7.40	12.86	8.99	9.06

TABLE III. RESULTS FOR OUTLIERS DETECTED USING *RATIO2* ALGORITHM

***Ratio2* Results (150 Recordings)**	**MAA (mmHg)**		**MMSA (mmHg)**	
	SBP	***DBP***	***SBP***	***DBP***
Number of Outliers	6	0	4	9
Mean Difference of Outliers from Range Boundary	5.59	0	4.59	38.2
SD of Differences of Outliers from Range Boundary	5.89	0	7.04	11.58

TABLE IV. ACCURACY OF THE RESULTS BEFORE AND AFTER REMOVING THE OUTLIERS

Experiments Accuracy (150 Recordings)	**MAA (mmHg)**				**MMSA (mmHg)**			
	BEFORE		***AFTER***		***BEFORE***		***AFTER***	
	SBP	***DBP***	***SBP***	***DBP***	***SBP***	***DBP***	***SBP***	***DBP***
Mean (Absolute (Omron–Estimate))	5.66	3.35	5.45	3.31	6.17	4.59	6.11	3.67
Standard Deviation(Absolute (Omron–Estimate))	4.59	2.75	4.25	2.71	5.14	4.76	5.03	2.97

TABLE V. EVALUATION OF SIMULATOR PERFORMANCE

Simulator Performance (150 Recordings)	**MAA (mmHg)**			**MMSA (mmHg)**		
	SBP	***MAP***	***DBP***	***SBP***	***MAP***	***DBP***
Absolute (Mean(Omron)–Mean(Recording))	4.40	2.20	1.23	0.74	2.20	0.25
Absolute (Mean(Omron)–Mean(Simulated))	5.51	5.10	11.32	4.66	5.10	13.17
Differences of Mean Values	1.10	2.90	10.09	3.92	2.90	12.92

In Table V, we present results of the evaluation of the performance of our BP simulator for all 150 recordings. Here, we apply the MAA and the MMSA to actual and corresponding simulated OMW data to estimate NIBP parameters. We then find the absolute differences between mean of these NIBP estimates and the NIBP estimates made by the reference Omron monitor. Finally, we find the absolute differences for NIBP estimates between actual and simulated OMW data. We observe that the performance of our BP simulator is satisfactory whereby differences between mean values of NIBP estimates made on actual and simulated OMW data are in the range of 1.10 mmHg to 10.09 mmHg for the MAA and 2.90 mmHg to 12.92 mmHg for the MMSA (last row, Table V). We also note that the mean absolute differences are slightly higher for *DBP* (10.09 mmHg to 12.92 mmHg). However, these results are acceptable, especially in light of the results that we got for vessel compliance estimation (Fig. 4 & Fig. 5).

IV. CONCLUSION

In this paper, we have presented the *Ratio2* method that relies on oscillometric pulse peak to trough ratios and their closeness to an empirical value of 2 to provide reliable ranges for *SDP* and *DBP* estimated using any given algorithm, and a useful assessment of vessel compliance.

Results on a dataset of 150 oscillometric recordings and 150 analogous Omron NIBP measurements obtained from 10 healthy subjects are promising. The *Ratio2* algorithm detects the least number of *SBP* and *DBP* outliers (2/150) for the Omron monitor as compared to the MAA (6/150) and the MMSA (13/150) outliers (Table III). Since we did not properly fine-tune the MAA and MMSA, the better performance of the Omron reference monitor (148/150 estimates in-range) is logical. This also shows indicates that the *Ratio2* method offers an effective and efficient way to detect NIBP measurement outliers.

Moreover, vessel compliance, estimated using the *Ratio2* method and arterial BP modeling, shows a significant correlation of –85% (p<0.005) with subject age (Fig. 4). As individuals age, their arteries get stiffer and hardened. That is, their vessel compliance reduces. This is exactly what the correlation analysis between estimated vessel compliance and subject age shows. This suggests that the vessel compliance evaluated by our method provide useful information.

The main advantage of our method is that it is simple and it can enable existing NIBP monitors to self-evaluate the quality of the BP estimates that they produce as well provide a reliable estimate of vessel compliance. Moreover, since this method relies on estimating the ratios of peaks to troughs of the oscillometric pulses (pulse extrema) for vessel compliance estimation, it is less prone to lower signal to noise ratios.

On the other hand, methods such as pulse morphology analysis that look for intricate changes in pulse shape would require signals with a higher signal to noise ratio to be effective and efficient.

We have shown promising results on a dataset of 150 recordings collected from 10 healthy individuals. Therefore, future work will involve testing and augmenting our method to work equally efficiently on diverse patient populations – for example elderly patients and patients with chronic conditions like atrial fibrillation.

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