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Model-Based Error Analysis of the Oscillometric Fixed-Ratio Blood Pressure Measurement Method

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Abstract*—We investigated factors affecting the accuracy of the oscillometric fixed-ratio blood pressure measurement method. We specifically applied a parametric sensitivity analysis to a mathematical model of oscillometry. We found that changes in arterial stiffness at zero transmural pressure and pulse pressure represent major factors that can potentially cause large error in the method. In particular, our theoretical analysis demonstrates that the fixed-ratio method predicts (1) higher systolic and lower diastolic blood pressures as the artery stiffen over the zero transmural pressure regime and (2) higher systolic and lower diastolic blood pressures as the pulse pressure increases. Further, the impact of pulse pressure on these errors is more obvious as the artery stiffens.

I. Introduction

Oscillometry is a widely used method for non-invasive blood pressure measurement. This method involves the use of an occlusive cuff applied to the arm over the brachial artery. The cuff acts as both an actuator and sensor. More specifically, after the cuff is inflated to a supra-systolic pressure level, it is slowly deflated to a sub-diastolic pressure level. Hence, during the deflation period, the brachial artery transmural pressure varies from negative to positive values. Since brachial artery compliance varies greatly around zero transmural pressure, the amplitude of the brachial artery volume oscillation is markedly altered. This alteration, in turn, causes the amplitude of the pressure oscillation sensed by the cuff to likewise vary. Because brachial artery compliance is maximal at zero transmural pressure, mean arterial pressure (MAP) is determined as the cuff pressure for which the amplitude of oscillation is maximal. However, systolic and diastolic pressures are determined heuristically as the cuff pressures for which the amplitude of oscillation is some fixed ratio of its maximal value [1].

Several investigators have developed mathematical models of oscillometry to improve its understanding [2]. A few investigators have used these models to test factors that affect the accuracy of the fixed-ratio method [3-5]. However, either only a limited number of model parameters were varied or the parameters were adjusted over a narrow physiologic range. As a result, the reported model-based errors of up to 15-20% are significantly smaller than the errors observed experimentally [6-8].

In this paper, we revisit the topic of model-based error analysis of the oscillometric fixed-ratio blood pressure measurement method. We apply a thorough parametric sensitivity analysis to a previously developed mathematical model to determine which model parameters affect accuracy the most. We then show that the errors can be much higher for a realistic range of parameter values.

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II. Methods

A. Mathematical Model

We used the oscillometric model developed by Drzewiecki et al. [3]. The model is illustrated in Fig. 1 and includes the following components: pressure-dependent and nonlinear brachial artery compliance ("Arterial P-A Relationship"), occlusive cuff mechanics accounting for Boyle's law ("Inflation/Deflation") and nonlinear pressure-volume relationship of the cuff ("Cuff Bladder"), and the brachial artery pressure waveform.

In particular, the cross-sectional area of the brachial artery (A) is determined from the transmural pressure, that is, the difference between brachial artery pressure P_a and cuff pressure P_c ($P_{TM} = P_a - P_c$), as follows:

$$A = C_a(P_{TM}) = d \cdot \ln(aP_{TM} + b)/[1 + \exp(-cP_{TM})], \quad (1)$$

where C_a is arterial compliance, and the parameters a, b, c, and d are subject-dependent empirical constants. The effect of the parameters a, b, c and d on C_a is graphically demonstrated in Fig. 2. The parameter a slightly shifts the zero transmural pressure location corresponding to the

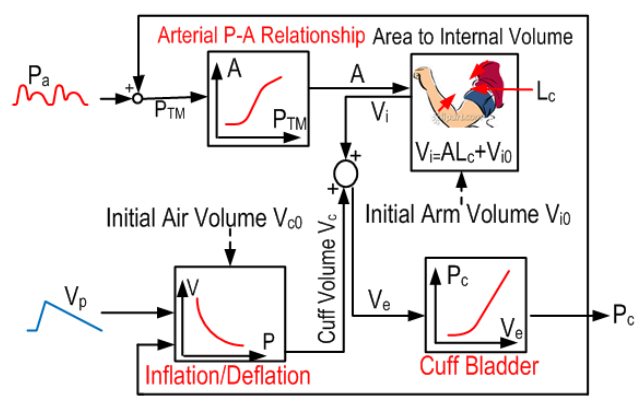

Fig. 1. Mathematical model of oscillometry [3].

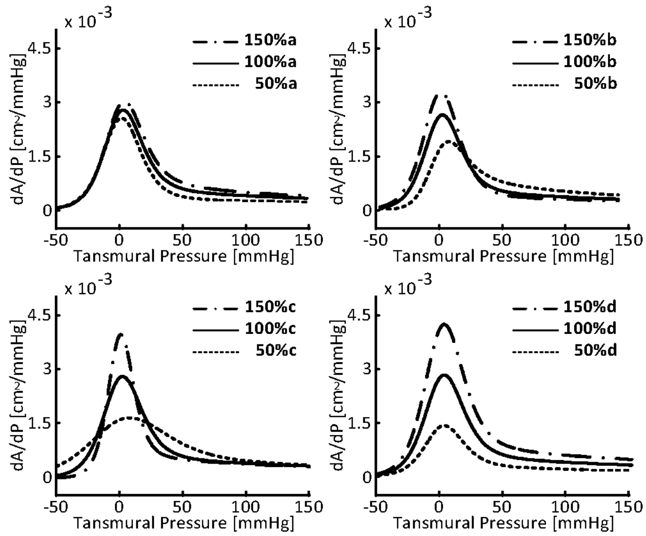

Fig. 2. Brachial artery compliance-transmural pressure relationship for different model parameter values.

maximum C_a. The parameters b and c play a crucial role in altering the arterial compliance characteristics. On one hand, decreasing b and c results in a decrease in the arterial compliance in the neighborhood of zero transmural pressure. On the other hand, their effects are distinct outside of this regime. First, decreasing b has different impact on arterial compliance characteristics in the negative and positive transmural pressure regimes. The effect of decreasing b in the negative transmural pressure regime is mostly shifting the arterial compliance curve to the right but not changing the width of the arterial compliance curve itself. In the positive transmural pressure regime, a decrease in b mostly yields an increase in the width of the arterial compliance curve itself (see the 30 mmHg transmural pressure range in the upper right panel of Fig. 2, where the slopes of the curves become reversed), with a slight shift of the arterial compliance curve to the right. In contrast to b, decreasing c results in a widening of the arterial compliance curve over the entire pressure range. Finally, the parameter d acts as a scale factor. Hence, by defining arterial stiffness as the change in pressure divided by the change in area around zero transmural pressure, arterial stiffness increases as b, c, and d decreases. Note that decreasing b and c increase arterial stiffness defined in this way by both reducing the amplitude of the curve and expanding its width.

The following equation dictates the brachial artery pressure waveform:

$$P_a(t) = \overline{P_a} + A_0 \sin(2\pi f_{HR} \cdot t/60) + A_1 \sin(4\pi f_{HR} \cdot t/60 + \phi_1) \quad (2)$$

where $\overline{P_a}$ is the MAP, f_{HR} is the heart rate (HR) frequency [Hz], and A_0, A_1, and ϕ_1 are empirical constants. Other model details including the occlusive cuff and parameter values can be found in Drzewiecki et al [3].

B. Error Analysis

To identify the major factors affecting the accuracy of the fixed-ratio method, we performed a parametric sensitivity analysis. In this analysis, we examined seven model parameters as candidate factors: pulse pressure (PP), MAP, HR, and the arterial compliance parameters a, b, c, and d. We did not include the parameters related to the occlusive cuff in the analysis, because these parameters can be regarded as fixed once a particular cuff is chosen (note that although the parametric sensitivity analysis results are presented here for only the bladder cuff from [3], the results were comparable for both the bladder and the CritikonDuracuf cuffs in [3]).

We investigated the impact of each model parameter by quantifying the changes in oscillometric blood pressure measurement errors caused by +/-50% variations in each parameter. More specifically, we first simulated the oscillometric waveform using the nominal parameter values. We then obtained the systolic, diastolic, and mean blood pressure errors via the fixed-ratio method and the maximal oscillation, respectively. We repeated this process with +50% and -50% variations to each of the parameters.

In the above analysis, we implemented changes in MAP and HR by directly altering $\overline{P_a}$and $f_{HR}$and PP by multiplying a factor of 1.5 (for 50% increase) and 0.5 (for 50% decrease) to both A_0 and A_1. We used a systolic fixed ratio of 0.61 and a diastolic fixed ratio of 0.74, as they yielded systolic and diastolic blood pressure errors near zero for the nominal parameter values.

Finally, to scrutinize the impact of the significant parameters, we examined the blood pressure errors over a realistic range of those parameters.

III. Results and Discussion

The Table summarizes the results of the parametric sensitivity analysis. On one hand, there were appreciable changes in systolic and diastolic blood pressure errors. On the other hand, the MAP error was not notably affected by any of the parameters included in the analysis. It can be inferred that changes in the brachial artery pressure waveform (manifested by PP, MAP, HR) and arterial compliance (manifested by a, b, c, and d) do not largely alter the oscillometric measurement of MAP, since it is determined by the cuff pressure at which maximum oscillation occurs. In other words, alterations of a, b, c, and d do not significantly change the location of maximum arterial compliance.

The Table indicates that PP and arterial compliance at ero transmural pressure (manifested by $b$and c) are the most critical factors affecting accuracy; both systolic and diastolic blood pressures were largely impacted by variations in these

TABLE . PARAMETRIC SENSITIVITY ANALYSIS OF OSCILLOMETRIC BLOOD PRESSURE MEASUREMENT ERRORS.

	PP +50%	PP -50%	MAP +50%	MAP -50%	HR +50%	HR -50%	*a* +50%	*a* -50%	*b* +50%	*b* -50%	*c* +50%	*c* -50%	*d* +50%	*d* -50%
SP	-9.37	+14.1	-3.02	+3.33	+0.33	-0.62	+3.60	+3.60	+3.93	-16.8	-4.72	+21.9	+0.40	-0.40
DP	+6.99	-9.93	-1.75	+5.73	-1.34	+3.90	+3.51	+3.51	+3.72	-14.1	+4.77	-19.5	-0.02	-0.10
MAP	+0.53	-0.92	-0.14	+0.44	-0.01	-0.13	+0.15	+0.38	+0.41	-1.59	+0.13	-0.55	+0.03	-0.00

Errors are reported as relative errors i.e. the difference between the error upon parametric perturbation and the error under nominal parameter setting divided by the error under nominal parameter setting.

parameters. In particular, the Table suggests that the fixed-ratio method tends toward underestimating systolic and overestimating diastolic blood pressures as PP increases. The table also suggests that decreasing b results in underestimation of both systolic and diastolic blood pressures, whereas decreasing c yields overestimation of systolic blood pressure and underestimation of diastolic blood pressure. On the other hand, the arterial compliance parameter d hardly impacted the errors. Hence, increasing arterial stiffness as defined above specifically via an increase in the width of the brachial artery compliance curve is a crucial factor.

To scrutinize the impact of PP and the parameter c on the fixed-ratio method, systolic and diastolic blood pressure errors were computed over a range of physiologically relevant PP and c values. As indicated in Fig. 3, a realistic range for c was determined from the study of human aortas at autopsy conducted by Richter and Mittermayer [9]. Fig. 4 illustrates the systolic and diastolic blood pressure errors over this range. The errors of both systolic and diastolic blood pressures gradually decrease in magnitude as PP increases, whereas they increase dramatically as c decreases. The errors are as high as 50 mmHg in the case of severe arterial stiffening. These model-based errors are consistent with several previous experimental investigations, which reported errors of comparable magnitudes. In particular, Coleman et al. [7] reported errors of up to 35 mmHg in their validation study on the OMRON MX3 Plus device, while Greeff et al. [8] reported errors up to 40-45 mmHg in their study with the OMRON MIT and OMRON M7 devices.

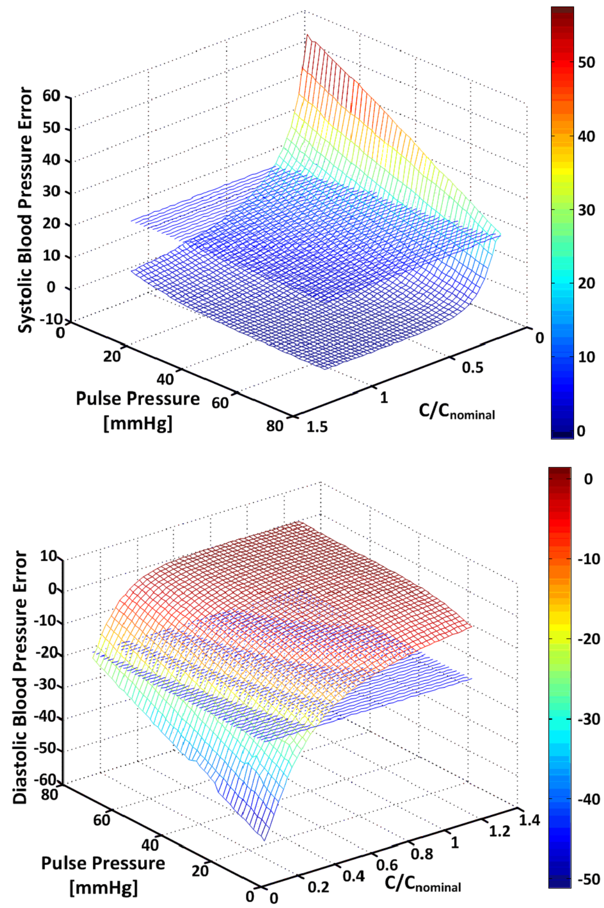

Fig. 4. Systolic and diastolic blood pressure errors over a realistic normalized c and pulse pressure range.

IV. Conclusion

In summary, in the fixed-ratio oscillometric blood pressure measurement method, systolic and diastolic blood pressures are determined as the levels of cuff pressure where its amplitude of oscillation reaches certain fixed ratios of the maximum oscillation (e.g. 0.55 for systolic and 0.85 for diastolic). While this method has been validated under nominal blood pressure levels and physiologic conditions, [10, 11], it is heuristic and potentially subject to great error during pathophysiologic circumstances.

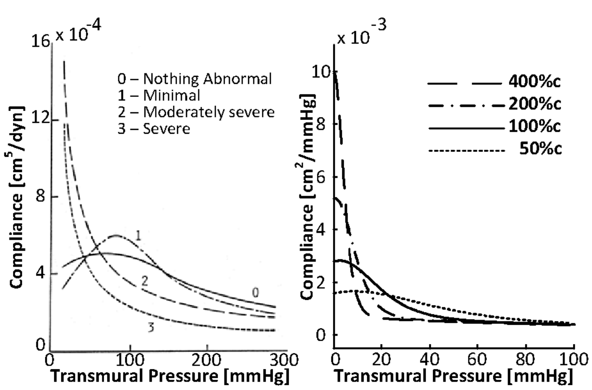

Fig. 3. Brachial artery pressure relationships determined experimentally from humans with varying degrees of atherosclerosis [9] and via the model for different values of the c parameter.

In this study, we investigated factors that could potentially affect the accuracy of the fixed-ratio method. We specifically applied a parametric sensitivity analysis to a mathematical model of oscillometry. We found that PP and arterial stiffness at zero transmural pressure are major factors.
affecting accuracy. In particular, our analysis revealed that across a realistic range of these factors, the blood pressure errors can be as large as 50 mmHg. Hence, these results have important implications when using the fixed-ratio method in patients with arterial disease.

Finally, our ongoing efforts are to explain the mechanisms by which arterial stiffness at zero transmural pressure and PP affect the accuracy of the fixed-ratio method.

References

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

[2] F.K. Forster, D. Turney. "Oscillometric determination of diastolic, mean and systolic blood pressure--a numerical model" *J Biomech Eng.* vol 108, pp. 359-364, Nov 1986.

[3] G. Drzewiecki, R. Hood, H. Apple. "Theory of the oscillometric maximum and the systolic and diastolic detection ratios", *Ann Biomed Eng.* vol 22(1), pp. 88-96, Jan 1994.

[4] M. Ursino, C. Cristalli, "A Mathematical Study of Some Biomechanical Factors Affecting the Oscillometric Blood Pressure Measurement" *IEEE Trans Biomed Eng.* vol 43, pp. 761-778, Aug 1996.

[5] R. Raamat, J. Talts, K. Jagomägi, J. Kivastik, "Errors of oscillometric blood pressure measurement as predicted by simulation". *Blood Press Monit.* vol 16, Oct 2011, pp. 238-45.

[6] A. Stang, S. Moebus, S. Möhlenkamp, N. Dragano, A. Schmermund, E.M. Beck, J. Siegrist, R. Erbel, K.H. Jöckel, "Algorithms for Converting Random-Zero to Automated Oscillometric Blood Pressure Values, and Vice Versa". *Am J Epidemiol.* vol 164, pp. 85-94, Jul 2006.

[7] A. Coleman, P. Freeman, S. Steel, A. Shennan. "Validation of the Omron MX3 Plus oscillometric blood pressure monitoring device according to the European Society of Hypertension international protocol", *Blood Press Monit.* vol 10, pp. 165-168, Jun 2005.

[8] A. de Greeff, Z. Beg, Z. Gangji, E. Dorney, A.H. Shennan, "Accuracy of inflationary versus deflationary oscillometry in pregnancy and preeclampsia: OMRON-MIT versus OMRON-M7", *Blood Press Monit.* vol 14, pp. 37-40, Feb 2009.

[9] H.A. Richter, and C.H. Mittermayer, "Volume elasticity, modulus of elasticity and compliance of normal and arteriosclerotic human aorta", *Biorheology,* vol 21, pp. 723-734, 1984.

[10] L.M. Vera-Cala, M. Orostegui, L.I. Valencia-Angel, N. López, L.E. Bautista, "Accuracy of the Omron HEM-705 CP for blood pressure measurement in large epidemiologic studies", *Arq Bras Cardiol.* vol 96, pp.393-398, May 2011.

[11] D. Longo, G. Toffanin, R. Garbelotto, V. Zaetta, L. Businaro, P. Palatini, "Performance of the UA-787 oscillometric blood pressure monitor according to the European Society of Hypertension protocol", *Blood Press Monit.* vol 8, pp. 91-95, Apr 2003.