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Predict Blood Pressure by Photoplethysmogram with the Fluid-Structure Interaction Modeling

Jianhong Chen[1], Wenrui Hao[2,*], Pengtao Sun[3] and Lian Zhang[4]

[1] *Wilshire Advisors LLC, Los Angeles, California, USA.*
[2] *Department of Mathematics, Pennsylvania State University, University Park, Pennsylvania, USA.*
[3] *Department of Mathematical Sciences, University of Nevada Las Vegas, Las Vegas, Nevada, USA.*
[4] *In-Chao Institute Ltd, Shenzhen, China.*

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Abstract. Blood pressure (BP) has been identified as one of the main factors in cardiovascular disease and other related diseases. Then how to accurately and conveniently measure BP is important to monitor BP and to prevent hypertension. This paper proposes an efficient BP measurement model by integrating a fluid-structure interaction model with the photoplethysmogram (PPG) signal and developing a data-driven computational approach to fit two optimization parameters in the proposed model for each individual. The developed BP model has been validated on a public BP dataset and has shown that the average prediction errors among the root mean square error (RMSE), the mean absolute error (MAE), the systolic blood pressure (SBP) error, and the diastolic blood pressure (DBP) error are all below 5 mmHg for normal BP, stage I, and stage II hypertension groups, and, prediction accuracies of the SBP and the DBP are around 96% among those three groups.

AMS subject classifications: 35Q92, 35Q30, 76M10

Key words: Blood pressure prediction, fluid-structure interaction, PPG.

1 Introduction

The importance of blood pressure (BP) is well-recognized. High blood pressure or hypertension, the systolic blood pressure (SBP) $\geq$130 mmHg or the diastolic blood pressure (DBP) $\geq$ 80 mmHg, is the leading risk factor for several diseases such as stroke, heart disease, and kidney disease [1]. Uncontrolled hypertension can seriously hurt important organs like heart, brain, kidney, and eyes [2] and lead to complications including heart

*Corresponding author. *Email addresses:* chenjianhongcn@gmail.com (J. Chen), wxh64@psu.edu (W. Hao), pengtao.sun@unlv.edu (P. Sun), zhanglian@in-chao.com (L. Zhang)

attack, heart failure, metabolic syndrome, and dementia [3]. In 2017, about half a million deaths in United States are caused by hypertension. Approximately half of adults in United States (108 million or 45%) have hypertension while only 24% of them have their condition under control [4]. Therefore it's extremely important to have an accurate and efficient tool to measure the BP in practice.

There are two ways to measure the BP: invasive and non-invasive ways [5, 6]. For the invasive one, invasive devices are used to insert into the blood vessel to monitor the continuous BP. Although it is very accurate, the expensive cost, the physiological pain of invasion into the vessel and the inconvenience of portability greatly limit its range of application [7]. On the other hand, the sphygmomanometer is the most popular non-invasive method to measure the BP based on the Korotkoff sounds. An underlying problem is that the measured BP is instantaneous only and is very hard to be longitudinal [8].

In order to measure the continuous BP non-invasively, one way is to use photoplethysmogram (PPG) and electrocardiogram (ECG) signals to predict the continuous BP. The idea is to use the pulse wave transit time (PWTT), computed by subtracting ECG R-wave peak time from the PPG peak time or the PPG maximum slope time, to predict the SBP and the DBP. For example, Jeong et al. [9] and Zhang et al. [10] assumed the linear relationship between PWTT and SBP on small datasets ($n=2$, $n=14$); Fung et al. [11] extended the linear relationship to a nonlinear model by considering the body structure and fundamental physics, particularly the conservation of energy and obtained an error of -0.0790 ± 11.32 mg on a large dataset ($n=4,660$). There is also a different non-invasive way, which uses the arterial applanation tonometry technique to measure continuous BP [12–14]. It involves measuring the speed of pulses travel within the arterial system and the blood pressure changes they create.

With burst of deep learning in many fields like natural language processing, computer vision and so on [15], some researchers applied neural networks in predicting the BP: Su et al. [16] extracted 7 representative handcrafted features including PWTT, heart rate, etc. from the PPG and ECG signals then used recurrent neural networks (RNN) to predict the BP. The best RMSE for the SBP and the DBP were 3.73 mmHg and 2.43 mmHg respectively on a dataset ($n=84$). Ibtehaz et al. [17] used segments of PPG signal only as a 1D image input and applied convolutional neural networks (CNN) to predict the BP. Their mean absolute errors of DBP and SBP prediction were 3.449 ± 6.147 mmHg and 5.727 ± 9.162 mmHg, respectively.

Despite the acceptable prediction error, there are two disadvantages in the previous methods: First, most of these methods were based on the PPG and ECG signals which are not easy to be recorded simultaneously; Second, the model generalizability on large datasets is unclear. For example, the linear regression model might be too simple while deep learning neural networks containing thousands or even millions of parameters might have the over-fitting issue.

Since BP is the force the blood flow exerts on arterial walls of the blood vessels as it is pushed through the body by the heart, the computational hemodynamics with various models in fluid dynamics and fluid-structure interactions (FSI) has significantly