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Blood Pressure Variation Trend Analysis Based on Model Study

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Abstract— **Blood pressure variability is an important risk factor of stroke and cardiovascular diseases, but people often ignored it because of the inconveniences of continuous blood pressure measurement. For the last decade people use ambulatory blood pressure measurement to estimate the trend of the blood pressure curve, but this method need to set a cuff around the upper arm and fully occluding the arm's blood circulation during the recording period, makes people feel uncomfortable and affects the quality of sleep.**

Now an innovative method can estimate blood pressure using electrocardiogram(ECG) and photoplethysmopraphy (PPG). The time delay between R peak and PPG feature point is reversely related to blood pressure. This is a potential method to improve comfort during measurement and the sensor can be designed as a wearable device.

This study collects ten patient's data from the MIMIC II database, including ECG, PPG and arterial blood pressure (ABP) to verify the blood pressure estimate result. Five different blood pressure regression models with pulse arrival time (PAT) as the main parameters, heart rate, pulse wave interval and pulse width as auxiliary parameters were proposed. Blood pressure regression analysis through different blood pressure models.

Analysis of correlation and consistency in different blood pressure regression models in units of 60 seconds. The highest correlation between ABP and PPG is the peak of PAT. The blood pressure regression model $\mathbf{PAT_{ALL} - BP}$ is the best result. ABP with ECG correlation is 0.89 better than ABP with PPG correlation of 0.87. In consistency, PPG has the highest RRratio of 0.67, while ABP has the highest RRratio of 0.81. Comparing the regression models $\mathbf{PAT_{HR}}$-BP with $\mathbf{PAT_{HR,PPI} - BP}$, whether ABP or PPG can also see a slight improvement in consistency.

I. Introduction

Hypertension is a major factor in causing cardiovascular diseases. Clinical research indicates that ages 40–69 years, middle-aged person each difference of 20 mm Hg usual systolic blood pressure (SBP) or 10 mm Hg usual diastolic blood pressure (DBP) is associated with more than a twofold difference in the stroke or cardiovascular disease death rate [1]. According to 2017 *American Heart Association* published guidelines for the treatment of high blood pressure [2], reduce the standard of hypertension decreased SBP to 130 mmHg and DBP to 80 mmHg, this change considers years of research and illustrates the importance of early prevention. The proportion of American adults with high blood pressure is estimated to rise from the original 32% to 46%, this data shows that the blood pressure monitoring is very important. In addition to the normal blood pressure range, the stroke rate increases with age [3]. The circadian rhythm of blood pressure is also a topic that has been widely explored. For the study of stroke and daily time points, statistics pointed out in midnight-early morning and early morning-noon these two times are prompt period. Another study pointed out that the normal nighttime blood pressure drops by 10-20% of the daytime blood pressure, but if the nighttime blood pressure drops little or increases, the population of this group has a higher risk of stroke [4][5]. Of course, it is not difficult to find that the stroke risk is more dependent on the blood pressure variability of the day and night.

At present have a blood pressure measurement method that has both a sleeveless, non-invasive, non-inductive and wearable device. The principle of blood pressure estimation is the negative correlation between blood pressure and Pulse Transit Time (PTT)[6], and divided by time is distance, called Pulse Wave Velocity (PWV). PTT will decrease when blood pressure rises, and vice versa. PTT estimation is measured by Electrocardiogram (ECG) and Photoplethysmogram (PPG). According to different literature if consider the R wave, PPG feature point contains the pre-shot time (PEP), it should be called the pulse arrival time (PAT).

Moens and Korteweg establish a mathematical model of M-K to derive blood pressure before 1878 (as formula 1) [7], and Geddes proposed in 1911 that the elasticity coefficient is not a constant and index related to pressure and deriving the extended M-K model [8]. All of the above shows the relationship between PTT, PWV and BP, from the perspective of vascular physiology, vascular elasticity, arterial wall thickness, blood concentration and blood vessel diameter are all important factors.

$$PWV = \frac{L}{PTT} = \sqrt{\frac{tE_0 e^{\alpha P}}{\rho d}} \quad (1)$$

(D = length of blood vessel, t = degree of vessel walls, d = diameter of blood vessel, ρ = blood concentration, E0 = elastic coefficient, α = vascular coefficient, P = blood pressure)

Regression models of blood pressure, PTT or PAT and a mathematical model of blood pressure has been continuously proposed. Most of development theory is extended for time delays or added corrections that affect blood pressure. H.Y. Xiang et al. proposed formula 2 [9]. Some literatures suggest that heart rate change has a very high correlation with changes in blood pressure. Therefore, the heart rate correction is added

to the regression model as formula 3 [10]. If consider the change in blood output, can use the PPG amplitude [11]. The blood vessels Peripheral resistance and elasticity of the wall, considering that the width of the PPG waveform will indirectly affect the blood pressure value [12]. Based on these correction factors, some studies have developed the following blood pressure regression formula 4 [13].

$$\mathrm{BP} = a \cdot Time\ Delay + b \quad (2)$$

$$\mathrm{BP} = a \cdot Time\ Delay + b \cdot \mathrm{HR} + \mathrm{c} \quad (3)$$

$$\mathrm{BP} = a \cdot Time\ Delay + b \cdot \mathrm{HR} + \mathrm{c} \cdot \mathrm{PW} + \mathrm{d} \cdot \mathrm{AMP} + \mathrm{e} \quad (4)$$

The senior of the laboratory after all samples were subjected to common model regression and independent model regression, it is concluded that each person is very different due to personal physiological parameters, Therefore, regression with independent models will have a good correlation (5) [14].

$$\mathrm{BP} = a \cdot Time\ Delay + b \cdot \mathrm{HR} + \mathrm{c} \cdot \mathrm{PW} + \mathrm{d} \cdot \mathrm{AMP} + \mathrm{e} \cdot \Delta\mathrm{AMP} + \mathrm{g} \cdot \Delta\mathrm{PPI} + \mathrm{h} \quad (5)$$

The correlation between PPT and BP is high or low in different literatures. Some literatures indicate that the phase inertia can be greater than 0.8[15] [16], however, some results indicate that the correlation only falls between 0.3 and 0.6 [17] [18].

The purpose of this study was to investigate the possibility of blood pressure estimation with pulse arrival time. Patient data using the online database MIMIC II to discuss pulse arrival time with some physiological parameters that affect blood pressure to predict blood pressure trends.

II. Methodology

In this study, the relationship between ECG and PPG was used to calculate the pulse arrival time (PAT). Signal analysis, simulation via online database MIMIC II, this database contains bedside monitoring equipment from the newborn to the adult in the intensive care unit (ICU) to record various physiological signals. This database almost has more than one ECG signal with different leads, some data include continuous arterial blood pressure (ABP) waveforms and PPG signal, and recording length is different, but the sampling frequency of all signals is only 125Hz. This study takes the ECG, PPG and ABP waveforms in the database to verify the stability of the "different mathematical models".

This study chose ten patients (Table 1), the data length is 140±25 minutes, and digital signal processing and find the parameters needs in the regression models of blood pressure.

Table 1. Patient number and data length comparison table

Sample code	**S1**	**S2**	**S3**	**S4**	**S5**
number	3000063	3100033	3100140	3118326	3125881
Data length (min)	161	133	158	149	147
Sample code	**S6**	**S7**	**S8**	**S9**	**S10**
number	3802508	3802623	3802888	3899400	3899730
Data length (min))	175	90	108	145	126

The main purpose of signal processing is to find out the parameters required in the blood pressure regression model. This part will deal with three kinds of signals ECG, PPG and ABP. First, digital filtering for ECG, PPG and ABP, the purpose reduce the interference of the noise on the algorithm detection feature points. ECG, PPG and ABP both pass a third-order Butterworth low-pass filter with a cutoff frequency of 20 Hz.

In this study only selected R waves of the ECG. In order to effectively search the location of the R wave, takes some modifications with reference to the R wave detection algorithm proposed by Sadhukhan and Mitra [19]. First, use the filter ECG signal is input into the first-order differentiator to calculate the slope, and then the signal is squared, then moving average filter is used to smooth the signal, and finally find the maximum value that is R waves. PPG signal is very similar to the ABP signal, and selected are common feature points the peak value of the signal, the valley value, the maximum slope point. The ABP signal takes the peak as the value of the calculated systolic blood pressure.

Pulse wave transit time, heart rate, pulse width and pulse wave interval were put into the blood pressure mathematical model as corrections, and there were different pulse wave characteristics in the pulse wave interval and pulse wave arrival time, as shown in Figure 1.

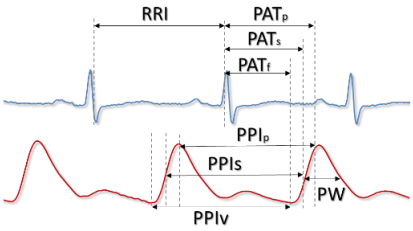

Figure1. characteristic parameters of blood pressure model

The mathematical model of blood pressure proposed in this study is based on past research, the blood pressure regression model used in the past is as shown in Equation 6. Because each measurement point has different recurring doubts, the amplitude-related parameters are removed and the Window average formula is corrected. The blood pressure model is deduced, and the correction is not in accordance with the original physiological derivation, and is rewritten into formula 7.

$$\mathrm{BP} = \mathrm{a} \cdot \mathrm{PAT} + \mathrm{b} \cdot \mathrm{HR} + \mathrm{c} \cdot \mathrm{PW} + \mathrm{d} \cdot \mathrm{AMP} + \mathrm{e} \cdot \mathrm{PPI} \cdot \Delta PAT + g \cdot \Delta HR + h \cdot \Delta AMP + i \cdot \Delta PPI + j \quad (6)$$

$$\mathrm{BP} = a \cdot PAT[n] + b \cdot \mathrm{HR}[n] + c \cdot \mathrm{PW}[n] + d \cdot \mathrm{PPI}[n] + e \quad (7)$$

Considering whether the linear regression project of blood pressure can be as small as possible, this study sorts and combines the time-related parameters of Equation 7 into Table 2, and performs blood pressure analysis through the following five blood pressure regression models.

Table 2. Blood pressure linear regression model used

Model number	Blood pressure model formula
PAT-BP	$BP = a \cdot PAT + b$
PAT_{HR}-BP	$BP = a \cdot PAT + b \cdot HR + c$
$PAT_{HR,PPI}$-BP	$BP = a \cdot PAT + b \cdot HR + c \cdot PPI + d$
$PAT_{HR,PW}$-BP	$BP = a \cdot PAT + b \cdot HR + c \cdot PW + d$
PAT_{ALL}-BP	$BP = a \cdot PAT + b \cdot HR + c \cdot PW + d \cdot PPI + e$

This study uses a binarization method, and use follow the formula (8), and the other parameter is RRratio definition is as in formula (9).

$$RRxy = \frac{1}{N^2}\sum_{i,j=1}^{N} R(i,j) \quad (8)$$

$$RRratio = \frac{RRxy}{RRxx} \quad (9)$$

III. Result

There are proposed five different models, including a combination of PAT, HR, PPI, and PW, the blood pressure regression analysis in per min are shown in Table 3 and 4. Among them, the highest correlation between ABP and PPG is the model $PAT_{ALL} - BP$. Both of them have the best results with peaks, ABP correlation is 0.89, and PPG is correlation 0.87.

Tables 3. Correlation coefficient of ECG and PPG for different BP models

Index	Foot	Peak	Slope
$PAT - BP$	0.64 ±0.13	0.69 ±0.13	0.66 ±0.20
$PAT_{HR} - BP$	0.75 ±0.11	0.77 ±0.09	0.73 ±0.14
$PAT_{HR,PPI} - BP$	0.76 ±0.11	0.79 ±0.09	0.75 ±0.13
$PAT_{HR,PW} - BP$	0.83 ±0.12	0.86 ±0.07	0.80 ±0.14
$PAT_{ALL} - BP$	0.84 ±0.11	0.87 ±0.07	0.81 ±0.14

Tables 4. Correlation coefficient of ECG and ABP for different BP models

Index	Foot	Peak	Slope
$PAT - BP$	0.65 ± 0.24	0.78 ± 0.18	0.65 ± 0.18
$PAT_{HR} - BP$	0.72 ± 0.18	0.82 ± 0.15	0.71 ± 0.15
$PAT_{HR,PPI} - BP$	0.76 ± 0.15	0.84 ± 0.15	0.75 ± 0.15
$PAT_{HR,PW} - BP$	0.84 ± 0.13	0.88 ± 0.15	0.81 ± 0.16
$PAT_{ALL} - BP$	0.85 ± 0.12	0.89 ± 0.15	0.83 ± 0.16

In consistency, the blood pressure is also returned in units of minutes. The results are shown in Table 5 and Table 6. The highest agreement between ABP and PPG is also the model $PAT_{ALL} - BP$. PPG has the highest RRratio of 0.67, while ABP has the highest RRratio of 0.81. Compared with $PAT_{HR,PPI} - BP$ and $PAT_{HR,PPI} - BP$, both ABP and PPG can also see a slight improvement in consistency.

Tables 5. Consistency of ECG and PPG for different BP models

Index	Foot	Peak	Slope
$PAT - BP$	0.54 ± 0.13	0.53 ± 0.15	0.47 ± 0.08
$PAT_{HR} - BP$	0.59 ± 0.16	0.58 ± 0.14	0.52 ± 0.12
$PAT_{HR,PPI} - BP$	0.61 ± 0.17	0.61 ± 0.14	0.54 ± 0.13
$PAT_{HR,PW} - BP$	0.63 ± 0.14	0.67 ± 0.07	0.59 ± 0.10
$PAT_{ALL} - BP$	0.64 ± 0.15	0.67 ± 0.09	0.60 ± 0.11

Tables 5. Consistency of ECG and ABP for different BP models

Index	Foot	Peak	Slope
$PAT - BP$	0.64 ± 0.18	0.75 ± 0.17	0.67 ± 0.17
$PAT_{HR} - BP$	0.68 ± 0.17	0.73 ± 0.16	0.68 ± 0.17
$PAT_{HR,PPI} - BP$	0.70 ± 0.17	0.74 ± 0.15	0.67 ± 0.15
$PAT_{HR,PW} - BP$	0.71 ± 0.15	0.80 ± 0.14	0.70 ± 0.15
$PAT_{ALL} - BP$	0.75 ± 0.15	0.81 ± 0.14	0.73 ± 0.15

IV. Conclusions and Future Applications

ECG with the ABP signal to derived the time parameter, different window length and blood pressure regression models the results, are better than the ECG with PPG. This results may be that ABP is an invasive pressure measurement, the most direct blood flow characteristics are obtained. However, PPG is an indirect measurement due to the amount of change in light caused by changes in blood pressure tube diameter.

MIMIC II online database resolution is 125 Hz, the blood pressure regression parameters that are closely relates to time. Therefore, there is a great possibility that error will increase. Whether use which model to estimate blood pressure, all physiological parameters cannot be fully considered and put into the model. In particular, physiological changes are not linear system, and other factors affecting blood pressure can only be use one low-pass filter to filtered.

In this study, only the key parameters PAT and the auxiliary parameters HR, PPI and PW. Including natural logarithm, reciprocal or square, etc., there are also studies specifically exploring the possibility of PEP estimation, let PAT eliminate the influence of PEP and get closer to the PTT. However, it is not easy to accurately predict PEP. If the signal is not matched with ECG and PPG, it is difficult to observe.

However, it is not easy to accurately predict PEP. If the signal is not matched with ECG or PPG, it is difficult to observe. Many researches have put in more different blood pressure related features. Discussions on either time parameter or amplitude parameter. There are also studies that integrate time and amplitude into a new feature, even giving blood pressure values through the shape of the wave.

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