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BILATERAL PPG SYSTEM WITH AR AND VAN DER POL SCREENING METHODS FOR PAD ESTIMATION IN HEMODIALYSIS PATIENTS

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ABSTRACT

Peripheral arterial disease (PAD) is highly encountered in hemodialysis patients. The rate of cardiovascular disease-associated hospitalization and mortality among those PAD patients is higher than non-PAD subjects. Early detection of PAD could prevent peripheral limbs problems such as numbness, limp, and amputations, especially in hemodialysis patients' foot. The ankle brachial index (ABI) is a widely used tool for PAD screening; however it has many clinical limitations and is not suitable for the patients with vascular sclerosis. Therefore, the aim of the present study is to develop a bilateral photoplethysmography (PPG) system with Van der Pol (VDP) Oscillator detector based on Burg autoregressive (AR) method for PAD estimation. The proposed system could track the bilateral symmetry or asymmetry of PPG signals and classify the grade of PAD in hemodialysis patients. The test results from 32 patients showed that the proposed system has high accuracy of classification (over 90%) for hemodialysis patients.

KEY WORDS

Peripheral Arterial Disease (PAD), Van der Pol (VDP), photoplethysmography (PPG), hemodialysis.

1. Introduction

Based on the knowledge of access hemodynamics on dialysis patients, PAD occlusion and failure lead to thrombosis, resulting in repeated puncturing of the arteriovenous accesses and long-term use[1-2], such as construction of an arteriovenous fistula (AVF) and blood vessel prosthesis. Likewise, problems remain with long-term indwelling vascular catheters for hemodialysis patients. However, the problems of patency and cost still remain; therefore, the interior of the vascular accesses can cause intimal hyperplasia and aneurysmal deformability. Any narrowing of the interior of the access increases the physical stress on the vascular wall and produces vibrations, turbulent flow, development of vascular devastation or a high level of vascular damage due to arteriosclerosis is a serious problem, resulting in difficulties in VA-related surgeries. A greater than 50% narrowing of the lumen diameter in the vascular access might result in a need for percutaneous transluminal angioplasty (PTA) or surgical intervention [3-4].

The PPG is a good method for studying peripheral blood volume pulsations by detection and temporal analysis of skin back-scattered optical reflection, and decision-making method to evaluate the PAD. The objective of this study is to build a frequency-based Van der Pol (VDP) oscillator to evaluate the degree of PAD in hemodialysis patients, and apply Burg autoregressive (AR) method as a parametric method [5-6], used in estimating the power spectral density (PSD) for frequency-domain signal processing, purporting to smooth the spectra and find characteristic frequencies from the recorded PPG signals. The oscillation overshoot (OS) is an approximating function of the damping factor in proposed system could determine the severity of PAD. The schematic diagram of the device used is shown in Fig. 1.

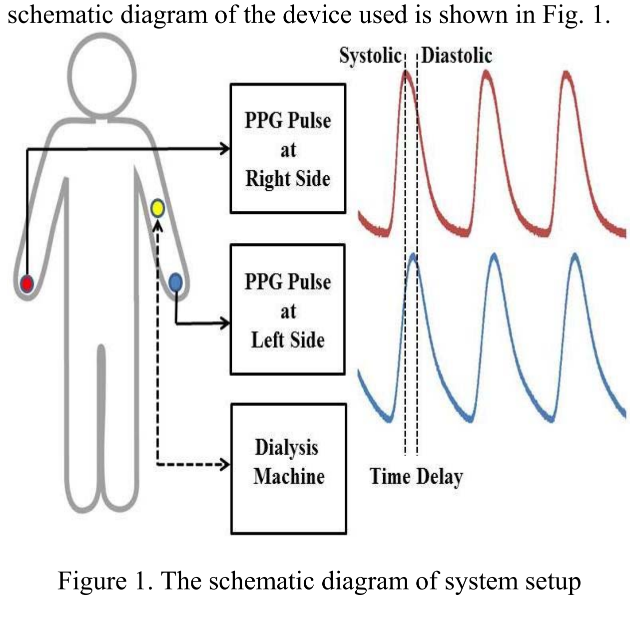

Figure 1. The schematic diagram of system setup

2. METHODOLOGY

2.1 System Design

Using the bilateral non-invasive measurement, two

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optical sensors (reflection mode), consisting of light sources, photo-detectors, trans-impedance amplifiers, and high-pass filters, were placed at the right and left fingers near infrared (NIR) has large differences in the extinction coefficients of de-oxyhaemoglobin and oxyhaemoglobin. Thus, the light source 940 nm NIR was chosen in this optoelectronic design. The reflection mode, including light source and photo-detector, was positioned side by side with 5mm spacing, and the light is directed down into the skin and is backscattered from the skin adjacent to the photo-detector [7]. Two optoelectronic probes (circle shape, diameter: 20.0 mm, height: 8.2 mm) were synchronized using a data acquisition controller. PPG signals are captured at a sampling rate of 1 kHz for 15 minutes. A DAQ card (National Instruments DAQ Card, 16 Channels, 1.25 MS/s) served as an analog-to-digital (A/D) converter between the optical measurement system and a computer. Locating each pulse foot (PF)-pulse foot (PF) interval of PPG signals, 800 sampling data were acquired within a sampling window. In this study, we utilized the Burg AR method to estimate the PSD of PPG signals. The suitable AR order can be used to identify the peak spectra. Fig. 2 shows the variation of residual energy versus AR model order. We use model orders, from order 1 to order 30, to calculate the sum of the residual energy (SORE) to obtain the suitable number of orders. Akaike's final prediction criterion is used to select the model order [7-8]. Generally, low AR orders result in poor spectral estimates, and high AR orders result in reduced spectral broadening and better spectral estimates, but increased computation time. For considering convergent condition, we considered SORE to stop the Burg AR algorithm. Considering the non-stationary nature of PPG signals, it can be seen that the model orders between 5 and 10 the distribution of residual energy reach the residual flatness and guarantee the convergent condition (residual energy <0.1). Then, the Burg method using model order $P=6$ with optimal coefficients was used to estimate the PSD.

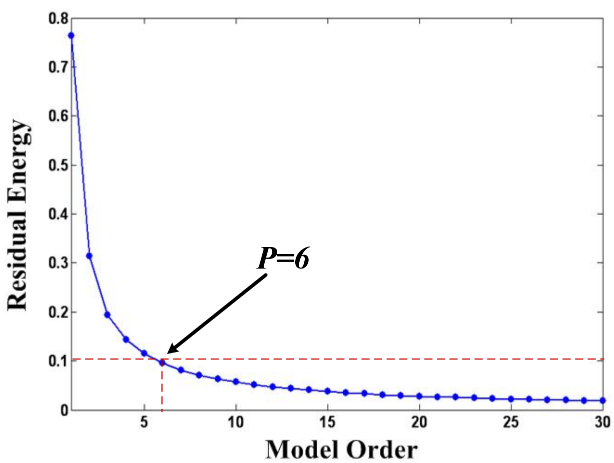

Figure 2. Variation of residual energy versus AR model order

2.2 VDP Screening with PSD

PAD can develop in the arteries of most visceral organs and extremities. Atherosclerosis in the brain and heart draws much attention for clinical diagnosis and intervention; by contrast, limb PAD is underestimated by the patients, even in hemodialysis whose progress of vascular atherosclerosis is accelerated by the metabolic disease.

PPG is a non-invasive technique placed at great toes, index fingers, and ears, and to monitor blood pressure, blood oxygen saturation (SaO_2), and blood volume changes in an artery or a vascular bed of tissue. A PPG signal consists of AC and DC components. The AC component reveals physiological information, such as cardiac synchronous changes in the blood volume with each heartbeat and vasomotor activity [9-10]. Time-domain and frequency-domain parameters have been used to detect the degree of PAD severity for hemodialysis patients with normal condition, mild-to-moderate disease, and severe disease.

In the convention method [9, 11], for the time-domain parameters, ECG R-peak as a timing reference is used to obtain pulse rise time (RT), pulse transit time (PTT) from R-peak to pulse foot (PTTf), pulse transit time from R-peak to pulse peak (PTTp), and PPG amplitude (plus foot-to-plus peak amplitude), as shown in Fig. 3. The timing parameters, PTT and RT, are prolonged as due to the increase of peripheral vessel resistance, and the amplitude (AMP) and shape of pulse waves are smoothed [11]. Parameters, PTT and AMP, and shape differences vary with ages for individual sites, but the smallest variations with age occur at the finger sites. Thus, bilateral differences in the timing parameters, ΔPTTf, ΔPTTp, and ΔRT, provide time delay information for the estimation of PAD. Bilateral differences in spectrum are similar and are used to distinguish between the normal subjects and PAD subjects.

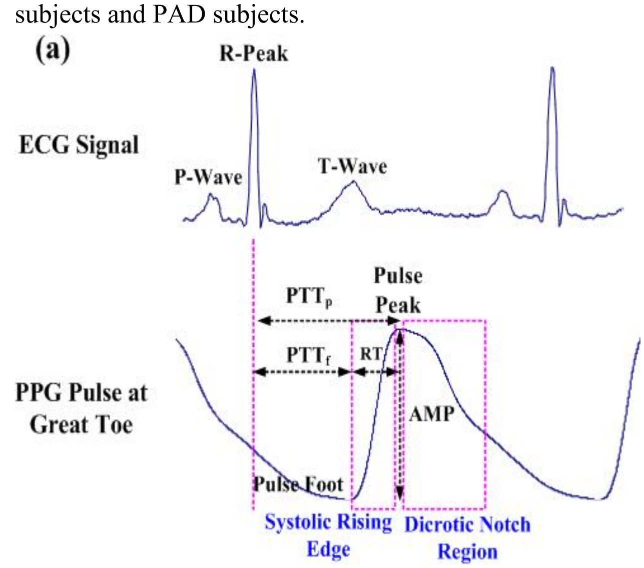

Figure 3. ECG and PPG signals and pulse landmarks [7]

This study uses frequency-based parameters to estimate the degree of PAD. The PSD are estimated using the Burg AR method. The VDP system is used to quantify the features of the right and left side PSD. It is an oscillator with nonlinear damping that is defined by a second-order differential equation. The formulation has the form of an autonomous system with two state variables. The state equations are evaluated as below [12]:

$$\frac{d\phi_r(\omega)}{d\omega} = \phi_l(\omega) \quad (1)$$

$$\frac{d\phi_l(\omega)}{d\omega} = -\phi_r(\omega) - \alpha[(\phi_r(\omega))^2 - 1]\phi_l(\omega) \quad (2)$$

Where $\phi_r(\omega)$ and $\phi_l(\omega)$are the functions with respect to frequency ω, $\phi_r(\omega)$ is the PSD of the right side PPG signal, except for ω=0, and $\phi_l(\omega)$ is the PSD of the left side PPG signal, right and left are denoted by the subscripts r and l. The parameter α is a control parameter, and α>0 reflects the degree of nonlinearity of the system [13]. When the term, $(\phi_r(\omega))^2$, becomes dominant, the VDP system becomes a nonlinear equation with positive damping. The dynamics of the system are stable and are restricted to a fixed point.

Equation (2) gives the frequency of self-oscillation, as determined by a real parameter α, and demonstrates dissipation or damping. If the parameter, α=0, then equation (2) reduces to that for a simple harmonic oscillator. When the PSD, $\phi_r(\omega)$ and $\phi_l(\omega)$, are different (not symmetrical), $\phi_l(\omega)$ provides the damping in the VDP oscillator that results in self-sustained oscillations. The multiple peaks and amplitudes of these peaks demonstrate the nonlinearity of the frequency spectrum. PSD $\phi_l(\omega)$ is used to determine the response of the VDP oscillator. The VDP system demonstrates a damped sinusoidal response for a general second-order system. The transient response consists of a sinusoidal oscillating waveform with exponentially decaying amplitude. The sinusoidal frequency is called the damped frequency of oscillation.

In order to evaluate the discrete frequency spectrum, the PSD is estimated using the Burg AR method. Assuming a set of n points from the PSD, ϕ_i, i=1, 2, 3, …, n, (n=500 in this study), the continuous VDP system can be modified as a discrete VDP system. Therefore, the discrete VDP system that is proposed for the estimation of PAD, as

$$\Phi_r[i] = \phi_l[i] \quad (3)$$

$$\Phi_l[i] = -\phi_r[i] - \alpha[(\phi_r[i])^2 - 1]\phi_l[i] \quad (4)$$

where the index, i, is the integer scale of the frequency, i =1, 2, 3, …, n. A bifurcation is a fundamental change in the nature of a solution. For different initial conditions, $\phi_r[i=1]$ and $\phi_l[i=1]$, the output, $\Phi_l[i]$, given by equation (4), has a step response that is characterized by a damped oscillation in the frequency domain. It exhibits a rich variety of nonlinear dynamic behaviors and generates the limit cycle for small α value, and develops into relaxation oscillations when α becomes large. If the VDP oscillators use different PSD, the oscillations become unstable, as the amplitudes of spectra peaks increase. The percentage overshoot $OS\%$ is given by the following equation (5).

$$OS\% = \left(\frac{c_{\max} - c_{\min}}{c_{\min}}\right) \times 100\% \quad (5)$$

The percentage overshoot OS% defines the amount by which the oscillation overshoots the minimum value cmin=b. The term cmax is determined by curve fitting the function at the maximum value as equation (6)

$$c_{\max} \approx b - \exp(-(\xi\pi/\sqrt{1-\xi^2}))(\cos\pi + \frac{\xi}{\sqrt{1-\xi^2}}\sin\pi)$$

$$= b + \exp(-(\xi\pi/\sqrt{1-\xi^2}))$$

$$c_{\min} = b \quad (6)$$

The percentage overshoot is a function only of the index ξ and allows the determination of the $OS\%$, given the index ξ. The final equation allows a solution ξ is given by the following equation (7).

$$\xi = \frac{-\ln(b \times OS\%)}{\sqrt{\pi^2 + \ln^2(b \times OS\%)}} \quad (7)$$

3. Experimental Results

To demonstrate the effectiveness of the proposed method, the 32 subjects were used to design the gold standard of PAD assessment using the VDP oscillator from selected 6 subjects (three groups: Normal, Mild-to-moderate, and Severe) were used to test. This study was approved by the hospital research ethics committee (IRB). In a clinical examination, the ankle brachial index (ABI) was used as an early screening method to decide the degree of PAD. The degrees were categorized by clinical manifestations, ABI values, and angiographic findings. For preliminary PAD estimation using the ABI, the indices signify ABI > 0.9 for normal subjects and PAD subjects with Mild-to-moderate, 0.5 < ABI < 0.9 (at least one limb) for subjects with Severe, ABI <0.5, as shown in Table 1. Despite the non-invasive nature of the examination to assess death rate and cardiovascular diseases in high-risk patients, the accuracy of the ABI measurement is reduced in patients with calcified blood vessels, caused by conditions such as diabetes and chronic renal failure. However, measurement of the ABI must be repeated several times (>10 minutes) and is of limited use in routine vascular screening in a primary care setting [14]. Bilateral timing parameters could offer a quick assessment for the screening of PAD in primary care. Bilateral measurements simultaneously acquire PPG signals from the right and left finger. The absolute timing differences are used to reference one side of the body (right side) with the contra-lateral side (left side), in order to calculate the parameters, PTTf, PTTp and RT, so various ranges are obtained for specific groups. Each parameter has a mean value and a specific range between maximum (Max) and minimum (Min) values. A comparison of the bilateral differences demonstrates that these parameters increase as the severity of the disease increases. Therefore, clinical physicians would consider timing differences to be a good reference for PAD assessment. The result demonstrates the computational efficiency and accurate diagnosis achieved by proposed system.

Table 1. Comparison of All Parameters

Parameter (Mean)	ABI ≥ 0.9 (Nor)	$0.5 \leq$ ABI < 0.9 (MD)	ABI < 0.5 (SD)	Accuracy
Quantity	***13***	***11***	***8***	
ΔPTTf (ms)	0.5-7.6	5.5-25.7	25.6-36.8	78%
ΔPTTP (ms)	0.4-22.3	14.3-55.5	46.2-56.8	79%
ΔRT (ms)	1.3-15.6	3.8-32.6	12.7-36.3	82%
Indexξ	**0.52–0.64**	**0.64–0.67**	**0.72–0.78**	**92%**

4. Conclusion

The VDP oscillator was able to detect bilateral PPG signals to estimate severity of PAD in hemodialysis patients. Using the bilateral frequency spectra, the VDP oscillator shows the step damped oscillation responses with mild and severe severity, respectively, with the increasing amplitudes of damped oscillation as PAD severity worsening. For an improved diagnostic design, the proposed method can be combined with fuzzy inference system to derive an index for the diagnosis of PAD. The proposed method has a potential to build a portable device for home health care.

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