Quantification the Effect of Ageing on Characteristics of the Photoplethysmogram Using an Optimized Windkessel Model

Doostdar H.¹, Khalilzadeh M. A.²*

ABSTRACT

Background: With increasing age, some changes appeared in specifications of vessels which including dimensions and elasticity in theirs. The changes in parameters such as resistance, ineritance and compliance vessels appear and eventually changes in the environmental pulse releases are in circulation. These changes clearly appear in specification of photoplethysmogram particularly in the size and position signals second peak is observed.

Aim and scope: The aim of study was to Circulatory system modeling using windkessel electrical model for evaluation blood flow and Its matching with the photoplethysmogram’s signal for investigate the reasons for changes of Characteristics of the Photoplethysmogram. The first purpose of this paper is to examine the age-related parameters in the Photoplethysmogram’s signal and finally the diagnosis of cardiovascular disease using the model and photoplethysmogram’s signal.

Methods: In this study we followed some of these effects to the circulatory system by using the windkessel electrical model. The algorithm in this project appeared by optimization with the matrix coefficients of state space windkessel electrical model. Optimize of the coefficients matching with the output of the model and the photoplethysmogram’s signal. Photoplethysmogram’s signals from 50 healthy subjects with the age range of 20 to 50 years, shows that outputs the model and photoplethysmogram’s signal in terms of error rate and cross-correlation algorithm in a fully automate, was consistent. Wavelength of the Photoplethysmogram’s signals were 950 nm and The sampling rate was set at 50 Hz.

Results: Simulation results show that aging reduces the signal amplitude and delay of the second peak occurs. These changes were seen as reduce the rate of compliance and increase the rate of resistance and ineritance windkessel electrical model of circulation.

Conclusion: The high accuracy of the results led to being able to identify the age range and some cardiac arrhythmias in individuals. All the simulations were done in matlab software environment.

Keywords
Photoplethysmogram(PPG), Quantification, Windkessel’s electrical model, State space variable

Introduction

We can model circulation systems in order to find the parameters of pressure, flow and blood volume. Among the variables that are involved in the value of these parameters, we can point to the dimensions and elasticity of vessels, fluid density at standard conditions and viscosity of vessel [1]. For better analysis of the cir-
culatory system, we model the basic variables with electrical variables such as strength iner-

tance and compliance (capacitance). Electrical

t model of the circulatory system is known to

windkessel electrical model. This model was

first performed by Frank who was a German

physiologist in 1899 [2]. This simple model

includes the Resistors and capacitors. Later

approached for further research and data mod-

eling with data obtained from physiological

experiments, Burattini considering the elasticity

of arteries an inductor added to the model

[3]. Edmond Zahedi with an improved model

could be very close to the actual data in 2007

[4]. one Of the variables mentioned above is

compliant which is same as inverse of arterial

stiffness, this variable is the most important

parameter which effect on the release of per-

ipheral pulses and blood flow as a structural;

aging effect on arterial stiffness [5]. Arterial

stiffness based on compliant can be defined as

follows (eq 1):

\[
C = \frac{dv}{dp}
\]  

(1)

In this equation, dv is arterial blood volume

and dp is arterial blood pressure. At a constant

blood pressure, arterial stiffness depends on

changes in blood volume that is associated with

arterial thickness and radius [6]. With in-

creasing age, thickness and radius of the ves-

sel will change considerably, which leads to

increased arterial stiffness and ultimately lead
to gradual changes in volume of the elastin

and collagen content of the arterial wall [7]. In

recent decades much research has been done

about the effects of aging on the cardiovascu-

lar system - the human vasculature. For these

purpose invasive and noninvasive techniques

have been used include the angio graphic, ultra-
sound, PPG &… [8]. According to the above

photoplethysmogram (assessment of blood

volume) associated with large eartery stiff-

ness and can be used as a noninvasive, inex-

pensive, easy way and it gives us important

information on peripheral arterial pressure and

increasing age. The LRR is known PPG as a

non-invasive use of non-visible infrared light

beam to the skin [9]. The blood volume in the

skin and tissue, infrared light is absorbed. We

can be observed the changes in blood volume by

measuring light absorption. We can see

Blood volume and heart rate changes through

the vascular system [10]. PPG signals mea-
sured between the domains and the pulse of

a peak to peak at different wavelengths and

its dependence on the optical absorption fea-
tures of human blood provides information

on health status [11,12]. Based on statements

photoplethysmogram machine invented by

Musu from Turin, Italy in 1870 ;it was repu-
tation Polysmotography in Italy and it was

published for the first time in the Journal of

American Scientists in July 1872 [13]. Hertz-

men, Spealman and Matthes introduce theory

which show that changes in blood levels can

be assessed and measured with light of trans-

mission in the finger in 1930 [14]. The above

changes in professional photoplethysmogram

signal are intimately linked with changes in

arterial compliance. In this paper we pres-
tent an improved model and a new algorithm
to optimize the model parameters were much
closer to the actual data. Primary goal of this
modeling is: having quantified between age &
photoplethysmogram’s waveform signal and

the ultimate goal was presented system detect
age and some Cardiac Arrhythmia by using
signal PPG and model and algorithm which
presented Submitted article.

Materials and Methods

In this study, at first we sign up photople-
thysmogram’s signal 50 healthy subjects. In
the next stage of the Circulatory system was
model with a 13-element & improved wind-
kessel electrical model. Electrical model of
the circulatory system in the next stage in the
heart of every subject in the software simula-
Effect of Ageing on Characteristics of the Photoplethysmogram

The recorded signal

Photoplethysmogram’s signals were recorded from 50 healthy subjects (30 men and 20 women) ranged in age from 20 to 50 years. Signal is recorded using non-invasive method was based on infrared. We use Wavelength of 950 nm in this method and transmission mode was recorded through their fingers. We was chosen translation method because it has lower noise than the reflection mode. For digitizing and storing the data in the computer system was used Power Lap, thus the text format by software CHART saved data in the computer. The sampling rate of the Photoplethysmogram’s signals was set at 50 Hz. Then the signal for processing and later work was enter to content area. To eliminate noise in the signal contains artifact motion and rhythm of breathing and high frequency noise of power in city we passes signal through band pass filter (.2 - 30 Hz) . we tried to use filter without Phase delays or distortion in the signal. Signal recorded in aquasi-clinical environment with a temperature of 20°C was performed. The registration period lasted a minute and people were asked to state that any type of food And drink eat affects blood vessels and also the record of 2 hours before exercise and avoid smoking [8]. Photoplethysmogram wave form signal de-

pends on temperature conditions, including human breathing, physical activity and cardiovascular system. The purpose of this paper is to examine the age-related parameters, so as possible other parameters affecting the signal photoplethysmogram were removed. For better analysis, the Photoplethysmogram’s signals was normalized to X(t) so that all values were within the range (0,1). Data normalization defined as follows (eq 2):

\[ X(t) = \frac{PPG - PPG_{\text{min}}}{PPG_{\text{max}} - PPG_{\text{min}}} \]  

where \( PPG_{\text{max}} \) and \( PPG_{\text{min}} \) are the maximum and minimum values of Photoplethysmogram’s signals.

Windkessel electrical model

Windkessel electrical model is used to simulate many human circulatory systems. This model described the relationship between aortic blood flow and aortic blood pressure in the human vascular system [7]. Among these models we can pointed out to Frank’s model which was published in1899. This model includes Resistors and capacitors. Later Burattini was complete the model by adding a parallel resistance and capacitance. Burattini later added an inductor in series with the resistance, to the model to consider the inertia of blood flow. We used the Model which has complete matching with photoplethysmogram signal from the finger. This model, respectively gain the addition of blood back to the Edmond Zahedi’s model which was published in 2007. This model consists of 5 parts in the table 1 is shown:

| Anatomical components       | Arterial segment |
|-----------------------------|-----------------|
| Aorta                       | A               |
| brachial(the arm)           | B               |
| Radial and ulnar            | C               |
| Capillaries                 | D               |
| The return of blood to the heart | E              |

Table 1: Arterial system segmentation
In this study each of the circulatory system sin the above table has been modeled with the Burattini’s model. Finally; we gained an improved windkessel electrical model with 13 elements. Figure 1 is an electric model which is simulated in software Simulink content.

**Figure 1:** Modified 13-elements Windkessel model

For modeling Left ventricular pressure we used a variable frequency sinusoidal and some other element including diodes, inductors, capacitors and resistors. This resource was based on the frequency and duration of systolic and diastolic heart of every individual [15]. Note that the left ventricular pressure signal was very important in optimizing the parameters of this model, we tried the signal is much closer to reality. Figure 2 Example of left ventricular pressure in a subject shows:

**Figure 2:** Example of left ventricular pressure in a subject
The optimization algorithm

To adjust the model parameters and the implementation of photoplethysmogram we were used fully automatic algorithm in the MATLAB programming environment. Based on this algorithm, first we designed input source that was related to left ventricular pressure, with the heart rate and systole and diastole time of each individual. Then based on previous studies we change the parameters of the model in a certain range, so the output model was obtained. Then the output model is compared with photoplethysmogram signal of each person. This compares was performed with the cross-correlation between signal and error rates (difference between model output and the signal photoplethysmogram). Finally, if these two criteria were more or less of experimentally obtained in the experiments final decision would be taken. According to above if the output of model was matched with a PPG signal; the algorithm terminates, otherwise the algorithm is repeated and the parameters were set again. Block diagram of the algorithm are in figure 3:

![Block diagram of the algorithm](image)

**Figure 3**: Block diagram of the algorithm for the automatic optimization of state space variables of the Windkessel’s electrical model.

Results

Photoplethysmogram signals recorded from 50 subjects were ranged in 10 age groups. The age groups were selected based on age. Age group (21-23) years, (24-26) years, (27-29) years, (30-32) years, (33-35) years, (36-38) years, (39-41) years, (42-44) years, (45-47) years, (48-50) years. For each age group by using the algorithm windkessel electrical model was optimized. After optimal the matrix coefficients of the state-space windkessel electrical model, these coefficients to the numerical value of inductance, capacitance and resistance, which became part of the model parameters. Figure 4 is shown the output of the model after optimized the parameter with PPG signal for five age groups. Numerical results of the model parameters optimized for the 5 age group are in table 2:
Table 2: Optimized parameter for 13-element Windkessel model

| Arterial segment | A | B | C | D | E |
|------------------|---|---|---|---|---|
| Parameter        | RA  | LA  | CA | RB  | LB  | CB  | RC  | LC  | CC  | RD  | RE  | LE  | CE  |
| Group            | Ohm | H   | Farad | Ohm | H   | F   | Ohm | H   | F   | Ohm | H   | F   |     |
| 21-23            | 0.85 | 5.2 | 460 | 1700 | 70  | 120 | 2800 | 650 | 22  | 2.8 | 6200 | 110 | 760  |
| 27-29            | 0.85 | 5.2 | 410 | 1760 | 72  | 96  | 3250 | 710 | 19  | 2.8 | 7200 | 126 | 610  |
| 36-38            | 0.9  | 5.8 | 310 | 2720 | 83  | 78  | 5600 | 820 | 18  | 2.9 | 7950 | 160 | 480  |
| 42-44            | 1.2  | 6.2 | 160 | 3960 | 89  | 40  | 8200 | 890 | 9   | 3.1 | 9800 | 198 | 320  |
| 48-50            | 1.2  | 6.3 | 80  | 4850 | 96  | 29  | 9960 | 920 | 4.3 | 3.2 | 11200| 210 | 301  |

Figure 4: Recorded PPG and simulated PPG signal from a 13-element Windkessel model for a subject aged: (a) 21 years; (b) 28 years; (c) 37 years; (d) 43 years; (e) 50 years
Discussion

In this study we sought to quantification photoplethysmogram signal by using wind-kessel electrical model and improved it with 13 elements. PPG signal reveals Changes in regional blood volume of the tissue. We can be achieve, a lot of information about the circulatory system with this survey, blood volume and high correlation with arterial compliance [7]. This information can help us to identify the effects of aging and diseases [11,12]. Results from the signals recorded in the age range state din the paper showed that with increasing age and a reduction in peak amplitude of the signal delay occurs in the second peak of PPG. The reason for the decrease in systolic blood vessels increase in diameter and it is older [16,17]. This study showed that increase in vascular resistance and compliance inpiration and reduction in the rate model will be associated with the circulatory system. The results of this study have very high accuracy because we tried the left ventricular pressure is very close to the reality. Also the optimization algorithm presented in this study calculated the model parameters with high accuracy by that we can be identified the age and some cardiac arrhythmias in individuals. For diagnosis Age range of individuals, after modeling and optimization of model parameters, a second signal was given to determine the age and arrhythmia detection algorithm, so with high accuracy, we could identify the age and diagnosis on the presence of cardiac arrhythmias. This algorithm was founded on the model output is optimized for an age range of the signal in individual ppg was adapted in the same age group. Accordingly, we can identify some cardiac arrhythmias such as aortic stenosis was present in two individuals. It was determined that if the signal was consistent with age and the age range was higher than it was diagnosed. In this study Diagnostic threshold was considered as a pilot for 10 years. This thresh-

old was identified two subjects, who had aort-
ic valves tenosis. The correct diagnosis was made according to a cardiologist. Finally, we need more research in this area, but we can find that a system designed could help us to diagnose some cardiovascular diseases based on noninvasive photoplethysmogram method.

Acknowledgments

This project was supported by the Islamic Azad University of Mashhad.

Conflict of Interest

None

References

1. Snyder MF, Rideout VC, Hillestad RJ. Computer modeling of the human systemic arterial tree. J Biomech. 1968;1:341-53. PubMed PMID: 16329438.
2. Frank O. Die Grundform des arteriellen Pulses. Z Biol. 1899;37:483-526.
3. Burattini R, Gnudi G. Computer identification of models for the arterial tree input impedance: comparison between two new simple models and first experimental results. Med Biol Eng Comput. 1982;20:134-44. PubMed PMID: 7098569.
4. Zahedi E, Chellappan K, MohdAlauddin A, Singh H. Analysis of the Effect of ageing on rising edge characteristics of the photoplethysmogram using a modified windkessel model. Cardiovasc Eng. 2007;7:172-81. doi: 10.1007/s10558-007-9037-5. PubMed PMID: 17992571.
5. Allen J, Murray A. Modelling the relationship between peripheral blood pressure and blood volume pulses using linear and neural network system identification techniques. Physiol Meas. 1999;20:287-301. PubMed PMID: 10475582.
6. Fung YC. Biodynamic circulation.1sted. New York: Springer-Verlag; 1984. p. 406.
7. McDonald DA. Blood flow in arteries. Baltimore: Williams & Wilkins; 1960.
8. Allen J, Murray A. Age-related changes in the characteristics of the photoplethysmographic pulse shape at various body sites. Physiol Meas. 2003;24:297-307. PubMed PMID: 12812416.
9. Anderson RR, Parrish JA. The optics of human skin. J Invest Dermatol. 1981;77:13-9. PubMed PMID: 7252245.
10. Hertzman AB, Spealman CR. Observations on the finger volume pulse recorded photoelectrically. *Am J Physiol*. 1937;119:334-5.

11. Allen J, Murray A. Development of a neural network screening aid for diagnosing lower limb peripheral vascular disease from photoelectric plethysmography pulse waveforms. *Physiol Meas*. 1993;14:13-22. PubMed PMID: 8477229.

12. Allen J, Murray A. Similarity in bilateral photoplethysmographic peripheral pulse wave characteristics at the ears, thumbs and toes. *Physiol Meas*. 2000;21:369-77. PubMed PMID: 10984205.

13. D’Agrosa LS, Hertzman AB. Opacity pulse of individual minute arterie. *J Appl Physiol*. 1967;23:613-

20. PubMed PMID: 6061375.

14. Zweifler AJ, Cushing G, Conway J. The relationship between pulse volume and blood flow in the finger. *Angiology*. 1967;18:591-8. PubMed PMID: 6053551.

15. Rideout VC. Mathematical and computer modeling of physiological systems. New Jersey: Prentice Hall; 1996.

16. Milnor WR. Hemodynamics. Baltimore: Williams & Wilkins; 1982.

17. Westerhof N, Elzinga G, Sipkema P. An artificial arterial system for pumping hearts. *J Appl Physiol*. 1971;31:776-81. PubMed PMID: 5117196.