ABOUT SRE

The Scientific Research and Essays (SRE) is published twice monthly (one volume per year) by Academic Journals.

Scientific Research and Essays (SRE) is an open access journal with the objective of publishing quality research articles in science, medicine, agriculture and engineering such as Nanotechnology, Climate Change and Global Warming, Air Pollution Management and Electronics etc. All papers published by SRE are blind peer reviewed.

Contact Us

Editorial Office: sre@academicjournals.org
Help Desk: helpdesk@academicjournals.org
Website: http://www.academicjournals.org/journal/SRE
Submit manuscript online http://ms.academicjournals.me/.
Editors

Dr. NJ Tonukari
Editor-in-Chief
Scientific Research and Essays
Academic Journals
E-mail: sre.research.journal@gmail.com

Dr. M. Sivakumar Ph.D. (Tech.)
Associate Professor
School of Chemical & Environmental Engineering
Faculty of Engineering University of Nottingham
Jalan Broga, 43500 Semenyih
Selangor Darul Ehsan
Malaysia.

Prof. N. Mohamed El Sawi Mahmoud
Department of Biochemistry, Faculty of Science, King Abdul Aziz University,
Saudia Arabia.

Prof. Ali Delice
Science and Mathematics Education Department, Atatürk Faculty of Education,
Marmara University, Turkey.

Prof. Mira Grdisa
Rudjer Boskovic Institute, Bijenicka Cesta 54,
Croatia.

Prof. Emmanuel Hala Kwon-Ndong
Nasara State University Keffi, Nigeria
PMB 1022 Keffi,
Nasara State.
Nigeria.

Dr. Cyrus Azimi
Department of Genetics, Cancer Research Center,
Cancer Institute, Tehran University of Medical Sciences,
Keshavarz Blvd., Tehran, Iran.

Dr. Gomez, Nidia Noemi
National University of San Luis,
Faculty of Chemistry, Biochemistry and Pharmacy,
Laboratory of Molecular Biochemistry, Ejercitodelos Andres 950-5700 San Luis,
Argentina.

Prof. M. Nageeb Rashed
Chemistry Department - Faculty of Science, Aswan South Valley University,
Egypt.

Dr. John W. Gichuki
Kenya Marine & Fisheries Research Institute,
Kenya.

Dr. Wong Leong Sing
Department of Civil Engineering, College of Engineering, University of Technology Malaysia,
Km 7, Jalan Kajang-Puchong,
43009 Kajang, Selangor Darul Ehsan, Malaysia.

Prof. Xianyi Li
College of Mathematics and Computational Science,
Shenzhen University,
Guangdong, 518060
P. R. China.

Prof. Mevlut Dogan
Kocatepe University, Science Faculty, Physics Department, Afyon, Turkey.

Prof. Kwai-Lin Thong
Microbiology Division, Institute of Biological Science, Faculty of Science, University of Malaya,
50603, Kuala Lumpur, Malaysia.

Prof. Xiaocong He
Faculty of Mechanical and Electrical Engineering,
Kunming University of Science and Technology, 253 Xue Fu Road,
Kunming, P. R. China.

Prof. Sanjay Misra
Department of Computer Engineering,
School of Information and Communication Technology Federal University of Technology,
Minna, Nigeria.

Prof. Burtram C. Fielding Pr. Sci. Nat.
Department of Medical Biosciences University of the Western Cape Private Bag X17,
Madderam Road,
Bellville, 7535,
South Africa.

Prof. Naqib Ullah Khan
Department of Plant Breeding and Genetics,
NWFP Agricultural University Peshawar 25130, Pakistan.
Editorial Board

Prof. Ahmed M. Soliman
20 Mansour Mohamed St., Apt 51, Zamalek, Cairo, Egypt.

Prof. Juan José Kasper Zubillaga
Av. Universidad 1953 Ed. 13 dept 304, México D.F. 04340, México.

Prof. Chau Kwok-wing
University of Queensland Institute of Mexican Petroleum, Eje Central Lazaro Cardenas, Mexico D.F., Mexico.

Prof. Raj Senani
Netaji Subhas Institute of Technology, Azad Hind Fauj Marg, Sector 3, Dwarka, New Delhi 110075, India.

Prof. Robin J. Law
Cefas Burnham Laboratory, Remembrance Avenue Burnham-on-Crouch, Essex CM08HA, UK.

Prof. V. Sundarapandian
Indian Institute of Information Technology and Management-Kerala
Park Centre, Technopark Campus, Kariavattom P.O., Thiruvananthapuram-695581, Kerala, India.

Prof. Tzung-Pei Hong
Department of Electrical Engineering, And the Department of Computer Science and Information Engineering National University of Kaohsiung.

Prof. Zulfiqar Ahmed
Department of Earth Sciences, Box 5070, Kfupm, Dhahran-31261, Saudi Arabia.

Prof. Khalifa Saif Al-Jabri
Department of Civil and Architectural Engineering College of Engineering, Sultan Qaboos University P.O. Box 33, Al-Khod 123, Muscat.

Prof. V. Sundarapandian
Indian Institute of Information Technology & Management-Kerala
Park Centre, Technopark Campus, Kariavattom P.O., Thiruvananthapuram-695581, Kerala, India.

Prof. Masno Ginting
P2F-LIPI, Puspiptek-Serpong, 15310 Indonesian Institute of Sciences, Banten-Indonesia.

Prof. K.W. Chau
Hong Kong Polytechnic University Department of Civil & Structural Engineering, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China.

Prof. Xianyi Li
School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, P.R. China.

Prof. Konstantinos D. Karamanos
Université Libre de Bruxelles, CP 231 Centre of Nonlinear Phenomena and Complex Systems, CENOLIB Boulevard de Triomphe B-1050, Brussels, Belgium.

Prof. Thangavelu Perianan
Department of Mathematics, Aditanar College, Tiruchendur-628 216, India.

Dr. Ezekiel Olukayode Idowu
Department of Agricultural Economics, Obafemi Awolowo University, Ife-Ife, Nigeria.
**Fees and Charges:** Authors are required to pay a $550 handling fee. Publication of an article in the Scientific Research and Essays is not contingent upon the author's ability to pay the charges. Neither is acceptance to pay the handling fee a guarantee that the paper will be accepted for publication. Authors may still request (in advance) that the editorial office waive some of the handling fee under special circumstances.

**Copyright:** © 2012, Academic Journals. All rights Reserved. In accessing this journal, you agree that you will access the contents for your own personal use but not for any commercial use. Any use and or copies of this Journal in whole or in part must include the customary bibliographic citation, including author attribution, date and article title.

Submission of a Manuscript Implies: that the work described has not been published before (except in the form of an abstract or as part of a published lecture, or thesis) that it is not under consideration for publication elsewhere; that if and when the manuscript is accepted for publication, the authors agree to automatic transfer of the copyright to the publisher.

**Disclaimer of Warranties**

In no event shall Academic Journals be liable for any special, incidental, indirect, or consequential damages of any kind arising out of or in connection with the use of the articles or other material derived from the SRE, whether or not advised of the possibility of damage, and on any theory of liability.

This publication is provided “as is” without warranty of any kind, either expressed or implied, including, but not limited to, the implied warranties of merchantability, fitness for a particular purpose, or non-infringement. Descriptions of, or references to, products or publications does not imply endorsement of that product or publication. While every effort is made by Academic Journals to see that no in accurate or misleading data, opinion or statements appear in this publication, they wish to make it clear that the data and opinions appearing in the articles and advertisements herein are the responsibility of the contributor or advertiser concerned. Academic Journals makes no warranty of any kind, either express or implied, regarding the quality, accuracy, availability, or validity of the data or information in this publication or of any other publication to which it may be linked.
Photoplethysmogram second derivative review: Analysis and applications

Yousef K. Qawqzeh, Rubins Uldis and Mafawez Alharbi
Photoplethysmogram (PPG) and its second derivative of the photoplethysmogram (SDPTG) are simple and low cost optical techniques for detecting and tracking blood volume changes. The PPG waveform and its SDPTG have been used by many scholars to obtain valuable information about heart and cardiovascular system. Since PPG and SDPTG reflect blood volume changes, much work has been done on its application as a diagnostic tool for screening arterial structure and its related diseases and disorders. In this article, we first provide a short review of the effects of atherosclerosis in losing arterial elasticity. Secondly, we introduce the PPG waveform and discuss in details the analysis methods and applications of its SDPTG waveform. Finally, we demonstrate links between elastic properties of arteries, atherosclerosis, PPG and SDPTG. The main focus of the review is on the analysis methods and applications of SDPTG.

Key words: Photoplethysmogram (PPG), second derivative of the photoplethysmogram (SDPTG), atherosclerosis, aging, arterial stiffness, distensibility, morphological changes, endothelial function.

INTRODUCTION

The underlying cause of cardiovascular (CV) disease is atherosclerosis. Atherosclerosis can occur because of fatty deposits on the inner lining of arteries or thickening of muscular wall of the arteries from chronically elevated blood pressure (Joachim et al., 2015). Atherosclerosis does not usually produce any symptoms until a cardiovascular disease (CVD) occurs. Therefore the prediction of atherosclerosis might contribute a lot to disease stratification and risk prevention. Mainly, atherosclerosis starts with oxidation of low-density lipoprotein (LDL) particles in the arterial wall (Hanna et al., 2011). Oxidative modified LDL (oxLDL) damages the endothelium of the artery – a pathophysiology similar to that of vascular erectile dysfunction (ED) (Stocker and Keaney, 2004; Kirby et al., 2005). As a result, the elasticity of the arteries deteriorates. Impaired arterial elasticity and increased levels of circulating oxLDL as well as elevated fibrinogen and resting heart rate associate with subclinical atherosclerosis and increased risk of CVD events (Cooney et al., 2010). The development of atherosclerosis prevents endothelial cell from regulating blood flow. Moreover, the accumulation of atherosclerosis affects the propagation of blood which can be detected by the recording the PPG signal. A great
contribution to PPG research and development has been provided by Allen (2007). This article aims to extend the contribution by providing a topical review on the second derivative of PPG (SDPTG). The SDPTG can be used to reflect arterial characteristics. The changes of its five-waves (namely 'a', 'b', 'c', 'd', and 'e') can be utilized to study changes in vascular system and arterial elasticity. In addition, the SDPTG is used by many scholars to ease the detection of peaks, valleys, and inflection point on the original PPG waveform. This topical review seeks to bring SDPTG's analytical methods and applications in one pool to ease and facilitate linking and building of ideas and thoughts of SDPTG applications and utilizations.

PHOTOPLETHYSMOGRAM (PPG)

Several decades before the arrival of pulse oximetry, the simple PPG was used as a measure of tissue blood volume (Challoner, 1979). It is related to plethysmograph, the measurement of pulsatile tissue volume. The plethysmograph measures the volume changes in any and all blood vessels (Andrew et al., 2008). Arterial pulsations are the most significant (Whitney, 1953). The PPG is an optically obtained plethysmograph, which is a volumetric measurement of an organ. It can be used to detect blood volume changes in the microvascular bed of tissue (Challoner, 1979). The PPG is often obtained by using a pulse oximeter which illuminates the skin and measures changes in light absorption (Shelley and Shelley, 2001). The contour of the pulsatile component of the PPG signal has been found to include content descriptive of vascular health (Brumfield and Andrew, 2005). PPG pulse signals can be easily obtained from the tissue pads of the ears, fingers and toes where there is a high degree of superficial vasculature (Allen and Murray, 2003). It has widespread clinical application, with the technology utilized in commercially available medical devices, for example in pulse oximeters, vascular diagnostics and digital beat-to-beat blood pressure measurement systems (Allen, 2007).

The use of PPG's signal derivatives are developed actually to facilitate the accurate recognition of the PPG's points of interest and to ease the interpretation of the original PPG waveform. The use of PTG to study vascular aging, arterial stiffness, atherosclerosis, endothelium dysfunction and erectile dysfunction is highly appreciated. Aging is accompanied by increased stiffness of large elastic arteries, leading to an increase in pulse wave velocity (PWV) (Peskin and Rowen, 2010). Premature arterial aging, as determined by an elevated aortic PWV, is now recognized as a major risk factor for ischemic heart disease (Laurent et al., 2001). Vascular aging influences the contour of the peripheral pressure and volume pulse in the upper limb (O'Rourke and Kelly, 1993). Arterial stiffness can be measured noninvasively by the use of PPG technique (Qawqzeh et al., 2012).

TOPICAL REVIEW BACKGROUND

The second derivative of the PPG wave has characteristic contours (waves) that facilitated the interpretation of the original PPG waves (Takazawa et al., 1998). Therefore, the SDPTG was developed as a method allowing more accurate recognition of the inflection points and easier interpretation of the original plethysmogram wave (Elgendi, 2012). The SDPTG wave patterns is determined by the proportions of the b, c, d, and e waves to the 'a' wave. The second derivative of the finger PPG waveform is used to stabilize the baseline and enable the individual features to be visualized and detected easily (Elgendi, 2012). However, this topical review tries to provide a reference document for researchers interested in finding a promising screening tool based on the analysis of PPG waveform and it's SDPTG.

PPG SECOND DERIVATIVE (SDPTG)

The length of the vascular system and the inner diameter and wall thickness of vessels may modify the SDPTG wave pattern in the growth period. Thereafter, as the effects of these factors decrease, the increase in intravascular pressure and decreasing wall elasticity due to aging may affect the wave pattern (Iketani et al., 2000).

Toshiaki et al. (2007) sought to elucidate independent determinants of the SDPTG among various cardiovascular risk factors in middle-aged Japanese men. They observed no independent association between the SDPTG indices and blood leukocyte count or serum C-reactive protein levels. Raveendranadh et al. (2012) utilized the SDPTG to assess aortic stiffness and wave reflection in their study of cardiovascular effects of caffeine in healthy human subjects. Takazawa et al. (1998) performed a drug administration study to evaluate the clinical application of the SDPTG of the fingertip PPG waveform. They extracted an aging index (Al = b-c-d/e/a) based on SDPTG five waves. The developed aging index had a higher value for women than for men. Moreover, they concluded that the aging index might be useful for evaluation of vascular aging and for screening of arteriosclerosis. Takazawa et al. (1998) and Imanaga et al. (1998) observed that the effect of angiotensin on the value of b/a was contrary to that of nitroglycerin and the value of b/a was clearly affected by atherosclerosis indications.

However, a study by Toshiaki et al. (2006) described the association of SDPTG indices, the risk of CHD and Framingham risk score. They recorded SDPTG from a community without apparent atherosclerotic disorders. Their findings showed that SDPTG indices significantly correlated with the Framingham risk score in both genders, as well as several coronary risk factors. Figure 1 demonstrates the characteristics of PPG and its
Rubins (2008) described a novel algorithm based on SDPTG for analyzing simultaneously measured ear and finger photoplethysmography (PPG) signals. The developed algorithm separated the systolic wave and the diastolic wave of the PPG and fits each of them with the sum of two Gaussian functions. Tomoyuki and Toshiaki (2013) categorized SDPTG indices in combination with age, and they concluded that SDPTG indices differed in characteristics from components of MetS or inflammatory markers. Qawqzeh et al. (2014) utilized SDPTG to develop a statistical model for the assessment of high-risk atherosclerosis. Their analysis facilitates the recognition of PPG points of interests, in specific, the detection of PPG's diastolic peak and inflection valley.

Alberto (2002) used SDPTG for the assessment of arterial properties. Imanaga et al. (1998) utilized SDPTG to assess arterial distensibility. Šimek et al. (2005) utilized SDPTG for the assessment of arterial elastic properties. They concluded that early systolic indices discriminate independently between subjects with essential hypertension and healthy controls. SDPTG analysis facilitates the distinction of 5 sequential waves, called a, b, c, d, and e waves. The relative heights of these waves (b/a, c/a, d/a, and e/a ratios) have been related to age, atherosclerosis, arterial blood pressure, arterial stiffness, and the effects of vasoactive drugs. The b/a ratio has been related to aging and carotid distensibility (Peskin and Rowen, 2010). Following analysis of the correlation of the b/a, c/a, d/a, and e/a ratios with age, a more complex index “aging index (SDPTG-AI)” was defined as [(b–c–d–e)/a]. In a study to assess arterial distensibility in adolescents, the d/a ratio identified individuals at increased risk of developing atherosclerosis (Millasseau et al., 2006; Hyun et al., 2007) analyzed SDPTG to estimate vascular aging.

Luiz et al. (2000) compared SDPTG indices to pulse wave velocity (PWV) for the assessment of vascular aging and atherosclerosis in hypertensive patients. However, they claimed that SDPTG might be used for the assessment of vascular aging and atherosclerosis in hypertensive patients. Kristjan et al. (2014) developed a new algorithm to estimate arterial stiffness in diabetes patients using the SDPTG. They concluded that SDPTG-AI can be used to differentiate subjects with increased arterial stiffness from healthy subjects. In their study to clarify the role of blood lead level (Pb-B) as one of the cardiovascular risk factors (Orawan et al., 2010) the SDPTG was used to evaluate the cardiovascular risk. These results suggest that Pb-B is possibly an independent cardiovascular risk factor for bus drivers exposed to lower level of lead. Kan-Ichiro et al. (2003) utilized the analysis of SDPTG indices to determine whether migraine is accompanied by peripheral blood circulation disorder.

In a study by Qawqzeh et al. (2012) they developed an algorithm that can detect the desired points of interest in the original waveform based on the utility of PPG’s first
Figure 2. Description of the process of locating points of interest from PPG waveform and its first and second derivatives (Qawqzeh et al., 2012).

derivative and SDPTG. Figure 2 illustrates the method of locating points of interest based on the proposed algorithm. They concluded that the increases in thickness of the intima and media of the carotid artery, as measured by CIMT, are directly associated with a decreased of b/a index values and increased of PP values.

Hashimoto et al. (2002) tried to clarify the factors influencing two measures of arterial stiffness, pulse wave velocity (PWV) and the (SDPTG), and to evaluate their relationship in treated hypertensive subjects. Their findings indicated that the two measures of arterial stiffness, namely PWV and SDPTG, are regulated at least in part through different mechanisms, and that the one is not capable of acting as a surrogate marker of the other. This may be explained partly by the hypothesis that PWV and SDPTG reflect different arterial properties at central and peripheral sites. An algorithm has been developed by Chan et al. (2007) for the automatic beet-to-beet detection of left ventricular ejection time (LVET) based on the SDPTG. They concluded that the correlation between the PPG-Pow derived LVET and the aortic flow derived LVET was high and significant.

Atsushi et al. (2012) claimed that SDPTG analysis enables the evaluation of atherosclerosis and cardiovascular aging. In their study Mohamad et al. (2012) the aging index of the SDPTG (SDPTG-AI) was used for monitoring the arterial condition. They claimed that vascular response in resistance arteries plays an important role in blood pressure and the SDPPG-AI can be used to evaluate the vascular aging and screening of atherosclerotic patients.

A new algorithm has been introduced by Elgendi et al. (2014) for the detection of a waves and b waves from the SDPTG. They compared nine algorithms based on fixed thresholding, and they claimed that their new algorithm improved the detection rate using a testing set of heat stressed PPG signals containing a total of 1,540 heart beats. The SDPTG was utilized by Pilt et al. (2012) to characterize the changes in forehead’s PPG signal,
Table 1. Some applications of PPG and SDPTG.

<table>
<thead>
<tr>
<th>Application domain</th>
<th>Applications</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitoring</td>
<td>Monitoring arterial condition</td>
<td>Hyun et al., 2007; Mohamad et al., 2012</td>
</tr>
<tr>
<td>assessment and measurement applications</td>
<td>Assessment of high-risk atherosclerosis, Assessment of carotid distensibility, Assessment of Arterial elastic properties, Assessment of migraine</td>
<td>Qawqzeh et al., 2012, Peskin and Rowen, 2010; Østok et al., 2005; Kan-ichiro et al., 2003</td>
</tr>
<tr>
<td>Evaluation</td>
<td>Atherosclerosis evaluation</td>
<td>Atsushi et al., 2012; Orawan et al., 2010; Hashimotoa et al., 2002.</td>
</tr>
<tr>
<td>Estimation/prediction</td>
<td>Detection of the directional change LEVT, Estimating arterial stiffness, Aging index.</td>
<td>Chan et al., 2007; Kristjan et al., 2014; Takazawa et al., 1998; Imanaga et al., 1998; Luiz et al., 2000.</td>
</tr>
</tbody>
</table>

which might be caused by the stiffness of blood vessels. They normalized SDPTG’s waves (a wave to e wave) and correlated them with age. They concluded that the changes in the forehead vascular bed can be described with SDPTG signal normalized amplitudes b/a and d/a.

DISCUSSION ON SDPTG APPLICATIONS AND POSSIBLE CATEGORISATION

This topical review tries to bring-together most of analytical techniques and sought applications for SDPTG in clinical settings. The philosophical analysis used by several scholars in this field is addressed. However, characterizing and utilizing the great usages of PPG waveform and its SDPTG still not fully understood. For the purpose of understanding and discussion the SDPTG applications can be divided into four domains namely: (1) Monitoring applications, (2) Assessment and Measurement applications, (3) Evaluation applications, and (4) Estimation/prediction applications. Table 1 demonstrates these categories and the applications of PPG and SDPTG that come under its umbrella.

B/A INDEX

However, the analysis of SDPTG indices revealed that b/a index is the most promising index in the assessment of arterial health. It was affected by atherosclerosis indications (Alberto, 2002); It used to assess aortic stiffness and wave reflection (Chan et al., 2007); It used by Tomoyuki and Toshiaki (2013) to predict high-risk atherosclerosis. It utilized by Millasseau et al. (2006) to assess atherosclerosis and related arterial distensibility; It used by Pilt et al. (2012) to assess arterial elastic properties; It has been declared by Toshiaki et al. (2007) that b/a is related to aging and carotid distensibility. In addition, Tomoyuki and Toshiaki (2013) claimed that b/a has a negative relationship with atherosclerosis, the more the value of b/a index, the less the risk of atherosclerosis. It was independently associated with dyslipidemia (Alberto, 2002).

Therefore, the b/a index are found to be important factor in the study of arterial stiffness. It was illustrated that the b/a index reflects increased arterial stiffness, (Takazawa et al., 1998). It claimed by Imanaga et al. (1998) that the magnitude of b/a index is related to the distensibility of the peripheral artery. Moreover, Qawqzeh et al. (2014) demonstrated that b/a index reflects the existence of atherosclerosis.

C/A AND D/A INDICES

In addition, c/a index is used to discriminate independently between subjects with essential hypertension and healthy controls (Pilt et al., 2012). It found to reflect decreased arterial stiffness, (Takazawa et al., 1998). However, in regards to d/a index, it found to reflect decreased arterial stiffness as c/a index. It was utilized by Atsushi et al. (2012) to assess the risk for the development of metabolic components.

CONCLUSIONS

This topical review has introduced the technique of
SDPTG. It illustrated its main research activities by many scholars in the field. In addition, it demonstrated the great potential of SDPTG for use in different clinical measurements. PPG and its SDPTG technologies can be found in a wide range of medical devices that are available in clinical settings. The ability of measuring oxygen saturation, blood pressure, cardiac output, assessing autonomic function, detecting peripheral vascular disease, and also predicting the high-risk atherosclerosis reflects the important of these techniques in providing useful diagnostic tools. Many challenges remain with the technology, including the standardization of PPG measurements, data collection, indices quantification, improving repeatability, and establishing comprehensive normative data ranges for comparison with patients and for evaluating responses to therapy. However, the ability to bring PPG and its SDPTG as a diagnostic tool to clinical settings would be advance in science and therapy.

**Conflict of Interest**

The authors have not declared any conflict of interest.

**REFERENCES**


Scientific Research and Essays

Related Journals Published by Academic Journals

- African Journal of Mathematics and Computer Science Research
- International Journal of Physical Sciences
- Journal of Oceanography and Marine Science
- International Journal of Peace and Development Studies
- International NGO Journal