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The latest applications of photoplethysmography

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Abstract

The development of medicine and the ability to conduct effective therapy in increasingly severe cases create the need to develop new methods of continuous and non-invasive monitoring of the patient's condition. One of the techniques that is widely used in many fields of medicine is photoplethysmography (PPG). The analysis of the latest research indicates that PPG can have much more applications than the measurement of heart rate and arterial saturation of the patient — as shown by the latest research, it can be used in the measurement of many other key parameters.

The optimism is the multitude of areas in which PPG monitoring is attempted. There are more and more attempts to use photoplethysmography in diagnosis and evaluation of peripheral vascular diseases, assessment of circulation in diabetic patients and assessment of endothelial function. Authors are focusing on new applications of PPG, its advantages and limitations. Most of them agree that PPG can provide useful knowledge about the patient's condition while being a quick, easy-to-use and cost-effective technique.

The following review was created to critically analyze the latest technical developments and uses of PPG in clinical practice. Sources for the following article were found using the PubMed database using keywords such as "photoplethysmography", "oxygen saturation" and "pulse oximeter".

Key words: photoplethysmography, pulse oximeter, saturation

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Introduction

In recent years, photoplethysmography (PPG) has become one of the basic and most frequently used tools designed to monitor the patient's vital parameters. PPG owes its popularity to, among others, its non-invasiveness, the ability to perform continuous measurement and ease and convenience of use. What's more, monitoring with the use of PPG provides simultaneous information about the circulatory system and the respiratory system [1, 2].

To perform a measurement of blood perfusion through tissue, PPG uses the emission of light waves [3]. The possibility of using this technique was suggested for the first time by Herrman in 1937 when he described devices using the emission of light waves to measure changes in the volume of blood flowing through the patient's finger during the Valsalva test [4]. It is worth noting that Hertzman used a simplified model of light behaviour developed on the basis of Beer-Lambert law, whose assumption was that the absorption of light is directly proportional to the density and thickness of the layer and the absorption coefficient of the medium through which light passes [5]. Thanks to the advances in physics and the work of Paul Mannheimer [6], this model has been improved, thanks to which new possibilities of interpreting the PPG wave have emerged.

The unfiltered wave obtained by the photoplethysmograph is complicated and composed of many smaller components. Today, it is recognized that its appear-

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ance is a resultant of the cooperation of circulatory, respiratory and autonomic systems and their influence on the flow of both arterial and venous blood [7]. A multitude of factors affecting the blood flow and factors variable individually (such as the different thickness of the finger, skin colour, content of subcutaneous fat) can cause many difficulties in reading and interpretation of the PPG wave. An example is a fact that until today there is no known method of PPG calibration, which means that one cannot compare the absolute numbers received in different people and it is impossible to set one reference point, which would facilitate, for example, the development of blood pressure measurement technique [5].

The device for PPG (pulse oximeter) consists of two main parts — a light source (usually in the infrared band, with a wavelength of ~ 940 nm) and a detector. The sensor's task is to measure the amount of light that has been absorbed or reflected by the blood flowing through the tissue [8]. It should be remembered that the flow of blood through even small arteries is not continuous. Such a pulsatile flow causes repetitive changes in the characteristics of the received light [9], which allows for the calculation of, for example, the heart rate rhythm. The development of two models of the PPG sensor operation has resulted in the widespread use of this device and the possibility of its use in new fields. The original model assumed the placement of a light source and a detector on two sides of the tissue being examined. In this way light, which was passed through absorbent substances, was detected and quantified [10]. The disadvantage of this model was the application limited to superficial tissues, transmitting the right amount of light. The latest devices have a light source and a sensor located on the same side. In this system, the amount of light reflected from the skin is measured, which allows it to be applied in places too thick for transmission of light (as on the wrist, for example), which allowed placing pulse oximeters in bracelets or watches [11].

As already mentioned, the measurement of PPG is based on the measurement of the properties of the light transmitted through or reflected by tissue. The measurement result depends mainly on the blood flow and degree of its oxygenation [8]. It is assumed that the PPG signal is affected by two main components: DC, which represents the constant absorption of light passing through the tissue and AC, which is generated by pulsating blood flow caused by heartbeat [12]. What is more, it is considered that the AC component is only characteristic of the arteries [13], which means that the results of the obtained measurements show the degree of oxygenation of just the arterial [14].

The above-mentioned diagram of the PPG sensor operation does not of course cover all technical issues related to reading, however, their detailed discussion goes beyond the scope of this study.

The purpose of the following review was to critically analyze the latest technical developments and applications of photoplethysmography in clinical practice. Sources for the following article were found using the PubMed database using keywords such as "photoplethysmography", "oxygen saturation" and "pulse oximeter".

CURRENT APPLICATION OF PHOTOPLETHYSMOGRAPHY IN ANGIOLOGY

Diagnostics and assessment of peripheral vessels

Peripheral arterial disease (PAD) is a relatively common disease that reduces the quality of life and its expectancy [15]. It is considered that this morbidity is present in 15–20% of people over 70 years of age. but the symptoms occur only in ¼ of patients [16, 17]. It should also be noted that it often coexists with other conditions, such as coronary heart disease and cerebrovascular narrowing [16]. Currently, one of the basic tests performed on the suspicion of PAD is to examine the Ankle Brachial Pressure Index (ABPI), which is characterized by high sensitivity (95%) and specificity (99%) in comparison to, for example, CT angiography (CTA) [18]. This study, however, has its drawbacks — its result depends on the experience of the investigator, and ABPI itself is impossible to measure in people who have had significant calcification of the arteries, which results in the lack of susceptibility of such vessels to compression [19]. Therefore, the CTA study [20] is considered a gold standard in many countries, which is, however, a long-term and invasive study [21]. An alternative to CTA may become PPG technology, which is non-invasive, safe for the patient, cheap and easily available [15].

Yali Zheng et al. [22], in their research on PAD diagnostics, focused on one of the characteristics that can be read by means of ECG and PPG — pulse arrival time (PAT). PAT is the time that elapses between the appearance of the R waveform in ECG and the detection of a pulse wave by a sensor placed above one of the peripheral arteries [22]. The team, mentioned above, decided to investigate the relationship between PAT and ABPI values in patients diagnosed with PAD in order to assess the role and usefulness of PAT in the diagnosis of this disease. Researchers pointed to the PAT_{ratio} index defined as the quotient of PAT_{index} and PAT_{toe}, showed statistically significant differences between the research

Table 1. The possible applications of PPG in angiology

Application of PPG	Advantages	Disadvantages
PAD diagnostics and assessment	• Diagnosis does not depend on the experience of the investigator, as it is in the case of ABPI assessment • PPG is a non-invasive, cheap and easily accessible study in the contrary to CTA • Good sensitivity and specificity	• Further research and the determination of appropriate ranges of diagnostic standards are necessary • Obtained results may be influenced by patient's BP and height • Lack of reference standards • Need for proper device's calibration • Results can be altered in patients with diabetic neuropathies
Chronic vein insufficiency (CVI) diagnostics Diagnostics of DVT	• Non-invasive nature • The simplicity of the test • Low cost and non-invasiveness • High sensitivity and negative predictive value	• Not provide information about the severity of CVI or about results of surgical treatment • Relatively low specificity and positive predictive value — DVT needs to be confirmed in duplex ultrasound • No steadily established cut-off points for RT and VP measurements
Assessment of blood circulation in diabetic patients Assessment of endothelial function	• Simplicity and low costs of implementation • Reliability in the assessment of disorders in microcirculation in patients with type 2 diabetes • PPG can provide as accurate results as FMD which is considered a golden standard in endothelial function assessment • PPG examination is easier to perform than FMD	• Difficulties in the assessment of vascular complications of diabetes, due to neuropathy and high arterial stiffness • High sensitivity to interferences

group and the control group. What's more, they have a strong correlation between ABPI and PAT_{ratio}. The authors believe that the results of their research can provide further into defining the normative ranges of bilateral PAT difference for PAD diagnosis my minimising the influence of blood pressure (BP) and height of the subjects. The study also raises the issue that different normative ranges should be defined for the diagnosis of PAD when PAT is measured at different postures due to a different hydrostatic pressure difference of lower and upper body in standing and sitting posture. Based on the results of their study, the authors found that the term PAT_{ratio} has the potential to diagnose and assess the severity of PAD, however, further research and the determination of appropriate ranges of diagnostic standards are necessary [22].

Clinical practice shows that a single technique can be used in many different ways, which are supposed to increase e.g. simplicity of use in clinical situations, as well as the sensitivity and specificity of measurements. The same situation can be observed in the case of Peripheral Vascular Disease (PVD) diagnostics using PPG. In one of his studies, Høyer et al. [23] decided to compare the methods displaying the derived curie with a truncated signal of the pulsation and showing the full pulse signal. In a single-blinded comparative trial on a sample of 69 patients (38 with suspected PVD), the data obtained from the measurements using the two above-mentioned techniques using the PPG signal and using an occlusive cuff were compared. In their conclusions, the researchers point out the lack of statistically significant differences in the results obtained using different techniques, which means that they can be used with similar sensitivity and specificity, especially since they are characterized by low inter-observer variability. However, the authors draw attention to several limitations of PPG techniques, such as the lack of a reference standard and the need to calibrate the device properly, so that excessive filtering or amplifying the signal does not cause errors in the interpretation of results [23].

New data on the use of PPG for PAD diagnostics is provided by a study conducted in Newcastle upon Tyne, whose results were published in 2018 [15], carried out on a group of 84 participants (43 healthy,

31 with advanced PAD, 10 results rejected due to the poor quality of measurements). In their study, scholars have proven that many of the components of the PPG signal, such as amplitude variability, Pulse Arrival Time Variability (PAT) and frequency-domain variability are altered in people with PAD, reflecting changes in the autonomic nervous system, reduced smooth muscle activity of arteries and NO-dependent endothelial activity [24]. The authors also raise the issue of the necessity of further testing in patients with diabetes due to the diabetic neuropathy present in this group of patients. Researchers after publishing their results suggested that the study of some of the components of the multi-site PPG signal, among others, limb signal synchronization, PAT and amplitude variability may be important in the diagnosis and early detection of PAD, while paying attention to the advantages of this study (low cost, non-invasive and safety for the patient) [15].

One of the interdisciplinary problems of today's medicine associated with the occurrence of PVDs is the issue of monitoring and treatment of chronic limb ischemia. Such ischemia results not only in resting pain in the limbs but also in the formation of difficult to heal wounds, ulcers and infections, which result in a significant reduction in the quality of life, as well as the risk of disability [25]. What is more, ischemia not only affects the healing of limb wounds but also hinders the necessary treatment, e.g. impairing the treatment of wounds after amputation [26]. The problem of wound healing was taken by Pan et al. [26] in its meta-analysis. The ability to predict the healing potential is particularly important for surgeons who have to choose between further conservative and surgical treatment. This particularly applies to wounds in patients with diabetes and developed angiopathy [27]. The data necessary to make such a decision can provide a measurement of skin perfusion pressure (SPP). The SPP technique itself is considered to be a sufficiently accurate predictor of wound healing potential especially in patients with limb ischemia. However, it is controversial to determine the exact cut-off point for the results [26]. The most popular measurement method for the SPP evaluation is the Doppler laser, but recent tests indicate that PPG can also be used for this purpose [28]. Although some scientists point to the limitations of this study and the need to standardize measurement methods, further development of this technique can be expected [29].

The use of PPG is not limited to the examination of arterial vessels but is also useful in examining venous vessels. Deep venous thrombosis (DVT) of the lower limbs is a disease affecting approximately 2.5–5% of the general population and carries a high risk of death due to the pulmonary embolism (PE) [30]. Many methods can be used in DVT diagnostics, all of which unfortunately have their limitations [31]. In the diagnosis of DVT for many years, attempts have been made to implement research using Digital Photoplethysmography (D-PPG), which measures the refilling time (RT) of calf veins during resting time after they have been emptied by exercise by measuring the extent of blood displacement from the calf veins, based on the absorption of emitted infrared light by haemoglobin in red cells, and characteristics of the reflected light from dermal microcirculation [32, 33].

In a study carried out by Sharif-Kashani et al. [31] 337 legs were examined in 169 patients who had a high risk of developing DVT. The results of the study confirm that D-PPG can be considered as an acceptable and reliable test in screening for DVT in patients at high risk of developing this disease. As researchers pointed out, using the appropriate cut-off point for RT and venous pump (VP) values, D-PPG sensitivity reaches 100%, while at the same time combining cut-off points for RT and VP, this test achieves a specificity of 82.9%.

The results of the above study confirm the results obtained by Chanean Ruangsetakit et al. In their study, they embraced 127 legs with visible oedema in 80 patients with suspected DVT, and then compared the results of RT and VP obtained by means of D-PPG with duplex ultrasound results. Researchers found that the optimal cut-off point for RT is 19–21s. In this case, the sensitivity of the study is 94%, negative predictive value 92%, specificity 58% and a positive predictive value 52%. In their conclusions, the authors stressed that D-PPG may be a useful screening test in DVT diagnosis in people at high risk of this disease, however, the positive result of the study requires confirmation in the duplex USG, while the negative result allows for the exclusion of DVT [34].

In recent years, there has been a growing interest in using PPG in the diagnosis of Chronic vein insufficiency (CVI). The advantage of this technique is its non-invasive nature and the simplicity of the test, but it also has its limitations. According to Abu-Halimah et al. [35], basic PPG can be a good tool confirming the presence or absence of a CVI, however, the quantitive results are not obtained, therefore PPG does not provide information about the severity of CVI or about results of surgical treatment. Similar conclusions were obtained by Calamati et al., who used the Light Reflection Rheography (LRR/D-PPG) technique, which is a modified form of basic PPG. According to these authors, LLR can be an objective diagnostic test for venous insufficiency and therefore suitable as screening for assessment of lower limb chronic venous insufficiency [36].

The use of PPG in the assessment of blood circulation in patients with diabetes

Diabetes is a disease that can cause complications for virtually any system. Particularly destructive are changes in macro- and microcirculation, which significantly reduce the quality of life of patients and increase their mortality [37]. Many studies have confirmed the utility of PPG as a simple test to assess peripheral circulation in patients without systemic diseases [38], but the use of this method in patients with diabetes and vascular complications may be significantly impeded.

The evaluation of diabetes-related changes in the vessels was taken up by Po-Chun Hsu et al. [39]. In their study, they included 94 patients (48 healthy) with the intention of investigating the validation of the introduction of non-invasive photoplethysmographic (PPG) waveform parameters in detecting diabetes-induced subtitling changes in arterial stiffness. In their study, the authors focused on two parameters — pulse wave velocity (PWVtoe) and Crest time ratio (CTR). The first of these parameters depends on how much time the pulse wave needs to get from the heart to the toe of the foot. The second parameter is described as the ratio of Crest time (CT) to Cycle time. CT is the time needed for the pulse wave to rise time from the lowest to the highest value, while the cycle time is the duration of one full pulse wave cycle. In their conclusions, the authors of the study indicate that this is the first study using countable parameters for the assessment of diabetes-related changes in the arterial circulation. In addition, researchers indicate that PPG may be a reliable tool for the assessment of disorders in the microcirculation in patients with type 2 diabetes. Moreover, one of the assessed parameters, CTR, made it possible to distinguish between patients with diabetes and healthy ones — this finding may highlight the better sensitivity to subtle arteriosclerosis compared to that of PWV and CT.

As other researchers have pointed out, also other data provided by PPG may be useful in assessing the vitality of the cardiovascular system in diabetics. Gen-Min Lin et al. [40] in their research they analyzed Multiscale Entropy (MSE) of PPG pulse amplitudes. They carried out their study on a group of 80 volunteers (36 healthy, 22 with well-controlled diabetes HbA1c $<8\%$ and 22 with poorly controlled blood glucose HbA1c $\geq 8\%$), each performing 1500 resting pulses amplitudes of bilateral index fingers. The authors of the study report that the MSE index for the dominant hand was significantly different between people with poorly and well-controlled diabetes, while the MSE index for the non-dominant hand allowed for the diagnosis of healthy people. In their conclusions, the authors suppose that the MSE of PPG pulse amplitudes can be used to assess microcirculation in people with type 2 diabetes [40].

Endothelial function assessment

Cardiovascular diseases are the most important cause of death worldwide [41]. The key pathophysiological factor in the development of many of them is vascular endothelial dysfunction, which precedes the development of atherosclerotic lesions [42]. For this reason, many scientists are interested in the ability to evaluate the function of the vascular endothelium, which would allow adequate response before the development of, for example, atherosclerosis.

Atherosclerosis is the basis for the development of many diseases of the cardiovascular system. It can lead to many complications, such as ischaemia of the myocardium, brain or limbs. Sometimes the vessel is narrowed rapidly, resulting in collapse and death of cells supplied with blood through a closed artery [43]. The basis for the development of atherosclerotic plaques is endothelial dysfunction, which may be reversible at an early stage, which is why many studies focus on the development of methods for the early detection of endothelial dysfunction [44].

PPG has been for some time considered an examination that can provide information about the endothelial function. This hypothesis was undertaken by Daoyuan Si et al. in a study comparing the ability to assess endothelial function with Brachial Flow-Mediated Dilation (FMD) and reactive hyperemia peripheral arterial volume (PAV) obtained with PPG. Currently, FMD is considered the main technique for testing the endothelial function [45]. FMD assessment is done indirectly by measuring changes in the diameter of the brachial artery before and after occlusion. Arterial occlusion is performed for 5 minutes and usually causes an uncomfortable numbness. When FMD procedures are performed, the brachial artery reacts with the widening of the diameter to respond to increased blood flow after occlusion. Damage to endothelial cell function decreases the ability of vasodilation by decreasing the widening of the diameter of the brachial artery observed during the FMD procedure [46]. Daoyuan's team examined 93 people (53 with coronary heart disease) and concluded that PAV may provide as accurate results as FMD, while being easier to perform. Moreover, the authors indicated that PAV has the potential to become a non-invasive method of early identification of patients at high risk of coronary artery disease [47].

One more study was conducted by Wu et al. In their work, they compared the sensitivity and specificity of endothelial vascular function assessment performed

with dilation index (DI) measured by the highly reproducible air pressure sensing system (APSS), which is considered to be just as accurate in determining endothelial function as FMD and endothelial function screening (EFS) device, that utilized PPG. The study involved 52 volunteers (age between 20 and 66) and showed satisfactory consistency between the EFS ratio and DI among the 52 testing subjects. Additionally, the comparison of the data acquired through APSS and the EFS device demonstrated an excellent correlation between the two sets. In their conclusions, the researchers emphasize that the EFS device can be considered as an effective tool for assessing endothelial function while being a convenient and economical solution. However, the authors point out that this technology requires further improvement to make it less sensitive to interference. One of the limitations of this study may also be that the results from the ESF were compared only with APSS, and not with FMD, which is considered the most reliable indicator of endothelial function [48].

CONCLUSION

The analysis of the latest research shows that the development of PPG techniques and devices can provide clinicians with new, accurate and cost-effective diagnostic tools. It turns out that this device can be used to monitor many key parameters and provide information necessary for planning further therapy. What is important, PPG enables patient monitoring in a continuous mode, and fast signalling of deterioration of patient parameters may be crucial for its survival.

The above article presents a multitude of areas in which PPG monitoring is attempted. Some of the applications focus on monitoring the patient during his stay in the hospital and some can be applied on an outpatient basis. One cannot forget about the usefulness of PPG as an aid in making clinical decisions regarding further therapy. PPG can provide important information to e.g. general and vascular surgeons, endocrinologists and cardiologists.

It is certain that the further development of the technique will enable the development of further applications for PPG, however, the time and clinical practice will show which of these applications will provide reliable data and improve treatment outcomes.

Conflict of interest

None.

References:

1. Thiele RH, Tucker-Schwartz JM, Lu Y, et al. Transcutaneous regional venous oximetry: a feasibility study. Anesth Analg. 2011; 112(6): 1353–1357, doi: 10.1213/ANE.0b013e3182166a26, indexed in Pubmed: 21613200.
2. Talke P, Stapelfeldt C. Effect of peripheral vasoconstriction on pulse oximetry. J Clin Monit Comput. 2006; 20(5): 305–309, doi: 10.1007/s10877-006-9022-3, indexed in Pubmed: 16841243.
3. Ishihara H, Sugo Y, Tsutsui M, et al. The ability of a new continuous cardiac output monitor to measure trends in cardiac output following implementation of a patient information calibration and an automated exclusion algorithm. J Clin Monit Comput. 2012; 26(6): 465–471, doi: 10.1007/s10877-012-9384-7, indexed in Pubmed: 22854918.
4. Ball TR, Tricinella AP, Kimbrough BA, et al. Accuracy of noninvasive estimated continuous cardiac output (esCCO) compared to thermodilution cardiac output: a pilot study in cardiac patients. J Cardiothorac Vasc Anesth. 2013; 27(6): 1128–1132, doi: 10.1053/j.jvca.2013.02.019, indexed in Pubmed: 23992653.
5. Alian AA, Shelley KH. Photoplethysmography. Best Pract Res Clin Anaesthesiol. 2014; 28(4): 395–406, doi: 10.1016/j.bpa.2014.08.006, indexed in Pubmed: 25480769.
6. Mannheimer PD. The light-tissue interaction of pulse oximetry. Anesth Analg. 2007; 105(6 Suppl): S10–S17, doi: 10.1213/01.ane.0000269522.84942.54, indexed in Pubmed: 18048891.
7. Kim JM, Arakawa K, Benson K, et al. Pulse oximetry and circulatory kinetics associated with pulse volume amplitude measured by photoelectric plethysmography. Anesthesia & Analgesia. 1986; 65(12): 1333???1339, doi: 10.1213/00000539-198612000-00015.
8. Moraes JL, Rocha MX, Vasconcelos GG, et al. Advances in photopletysmography signal analysis for biomedical applications. Sensors (Basel). 2018; 18(6), doi: 10.3390/s18061894, indexed in Pubmed: 29890749.
9. Bhattacharya J, Kanjilal PP, Muralidhar V. Analysis and characterization of photo-plethysmographic signal. IEEE Trans Biomed Eng. 2001; 48(1): 5–11, doi: 10.1109/10.900243, indexed in Pubmed: 11235591.
10. Gubbi SV, Amrutur B. Adaptive pulse width control and sampling for low power pulse oximetry. IEEE Trans Biomed Circuits Syst. 2015; 9(2): 272–283, doi: 10.1109/TBCAS.2014.2326712, indexed in Pubmed: 25014964.
11. Lee H, Chung H, Ko H, et al. Wearable multichannel photoplethysmography framework for heart rate monitoring during intensive exercise. IEEE Sensors Journal. 2018; 18(7): 2983–2993, doi: 10.1109/jsen.2018.2801385.
12. Zhao D, Sun Yu, Wan S, et al. SFST: A robust framework for heart rate monitoring from photoplethysmography signals during physical activities. Biomedical Signal Processing and Control. 2017; 33: 316–324, doi: 10.1016/j.bspc.2016.12.005.
13. Tremper K, Barker S. Pulse oximetry. Anesthesiology. 1989; 70(1): 98–108, doi: 10.1097/00000542-198901000-00019.
14. Bartels K, Thiele RH. Advances in photoplethysmography: beyond arterial oxygen saturation. Can J Anaesth. 2015; 62(12): 1313–1328, doi: 10.1007/s12630-015-0458-0, indexed in Pubmed: 26286382.
15. Bentham M, Stansby G, Allen J. Innovative multi-site photoplethysmography analysis for quantifying pulse amplitude and timing variability characteristics in peripheral arterial disease. Diseases. 2018; 6(3), doi: 10.3390/diseases6030081, indexed in Pubmed: 30227612.
16. Norgren L, Hiatt WR, Dormandy JA, et al. TASC II Working Group. Inter-society consensus for the management of peripheral arterial disease (TASC II). J Vasc Surg. 2007; 45 Suppl S: S5–67, doi: 10.1016/j.jvs.2006.12.037, indexed in Pubmed: 17223489.

17. Burns P, Gough S, Bradbury AW. Management of peripheral arterial disease in primary care. BMJ. 2003; 326(7389): 584–588, doi: 10.1136/bmj.326.7389.584, indexed in Pubmed: 12637405.
18. Hennion DR, Siano KA. Diagnosis and treatment of peripheral arterial disease. Am Fam Physician. 2013; 88(5): 306–310, indexed in Pubmed: 24010393.
19. Wilkes S, Stansby G, Sims A, et al. Peripheral arterial disease: diagnostic challenges and how photoplethysmography may help. Br J Gen Pract. 2015; 65(635): 323–324, doi: 10.3399/bjgp15X685489, indexed in Pubmed: 26009528.
20. Hodnett PA, Koktzoglou I, Davarpanah AH, et al. Evaluation of peripheral arterial disease with nonenhanced quiescent-interval single-shot MR angiography. Radiology. 2011; 260(1): 282–293, doi: 10.1148/radiol.11101336, indexed in Pubmed: 21502384.
21. Pollak AW, Norton PT, Kramer CM. Multimodality imaging of lower extremity peripheral arterial disease: current role and future directions. Circ Cardiovasc Imaging. 2012; 5(6): 797–807, doi: 10.1161/CIRCIMAGING.111.970814, indexed in Pubmed: 23169982.
22. Lazaro J, Bailon R, Laguna P, et al. Difference in pulse arrival time at forehead and at finger as a surrogate of pulse transit time. 2016 Computing in Cardiology Conference (CinC). 2016; 43: 269–272, doi: 10.22489/cinc.2016.079-432.
23. Høyer C, Nielsen NS, Jordansen MK, et al. Comparison of two methods based on photoplethysmography for the diagnosis of peripheral arterial disease. Scand J Clin Lab Invest. 2017; 77(8): 622–627, doi: 10.1080/00365513.2017.1390784, indexed in Pubmed: 29043840.
24. Stefanovska A. Physics of the human cardiovascular system. Contemporary Physics. 2010; 40(1): 31–55, doi: 10.1080/00107519981693.
25. Novo S, Coppola G, Milio G. Critical limb ischemia: definition and natural history. Curr Drug Targets Cardiovasc Haematol Disord. 2004; 4(3): 219–225, indexed in Pubmed: 15379613.
26. Pan X, You C, Chen G, et al. Skin perfusion pressure for the prediction of wound healing in critical limb ischemia: a meta-analysis. Arch Med Sci. 2018; 14(3): 481–487, doi: 10.5114/aoms.2016.62220, indexed in Pubmed: 29765431.
27. Yamada T, Ohta T, Ishibashi H, et al. Clinical reliability and utility of skin perfusion pressure measurement in ischemic limbs--comparison with other noninvasive diagnostic methods. J Vasc Surg. 2008; 47(2): 318–323, doi: 10.1016/j.jvs.2007.10.045, indexed in Pubmed: 18241755.
28. Holstein P, Nielsen PE, Lund P, et al. Skin perfusion pressure on the legs measured as the external pressure required for skin reddening after blanching: a photo-electric technique compared to isotope washout. Scand J Clin Lab Invest. 1980; 40(6): 535–543, indexed in Pubmed: 7444357.
29. Malvezzi L, Castronuovo J, Swayne L, et al. The correlation between three methods of skin perfusion pressure measurement: Radionuclide washout, laser Doppler flow, and photoplethysmography. Journal of Vascular Surgery. 1992; 15(5): 823–830, doi: 10.1016/0741-5214(92)90717-m.
30. Sullivan T. Basic data underlying clinical decision making in endovascular therapy. Annals of Vascular Surgery. 2009; 23(5): 553, doi: 10.1016/j.avsg.2009.08.001.
31. Sharif-Kashani B, Behzadnia N, Shahabi P, et al. Screening for deep vein thrombosis in asymptomatic high-risk patients: a comparison between digital photoplethysmography and venous ultrasonography. Angiology. 2009; 60(3): 301–307, doi: 10.1177/0003319708323494, indexed in Pubmed: 18854340.
32. Ho WK, Hankey GJ, Lee CH, et al. Venous thromboembolism: diagnosis and management of deep venous thrombosis. Med J Aust. 2005; 182(9): 476–481, indexed in Pubmed: 15865594.
33. Sissons GR. Investigation of suspected lower limb venous thrombosis. Ann R Coll Surg Engl. 1998; 80(1): 49–54, indexed in Pubmed: 9579128.
34. Ruangsetakit C, Nuntiwattana N, Hahtapornsawan S, et al. Digital photoplethysmography in the diagnosis of deep vein thrombosis in Thai patients. J Med Assoc Thai . 2017; 100(Suppl.): S155–S161.
35. Abu-Halimah S, Marston W. Plethysmographic techniques in the diagnosis of venous disease. Noninvasive Vascular Diagnosis. 2017: 525–533, doi: 10.1007/978-3-319-54760-2_39.
36. Calamanti C, Cenci A, Bernardini M, et al. A clinical decision support system for chronic venous insufficiency. Volume 9: 13th ASME/IEEE International Conference on Mechatronic and Embedded Systems and Applications. 2017, doi: 10.1115/detc2017-68016.
37. Vaidya V, Gangan N, Sheehan J. Impact of cardiovascular complications among patients with Type 2 diabetes mellitus: a systematic review. Expert Rev Pharmacoecon Outcomes Res. 2015; 15(3): 487–497, doi: 10.1586/14737167.2015.1024661, indexed in Pubmed: 25824591.
38. Korhonen I, Yli-Hankala A. Photoplethysmography and nociception. Acta Anaesthesiol Scand. 2009; 53(8): 975–985, doi: 10.1111/j.1399-6576.2009.02026.x, indexed in Pubmed: 19572939.
39. Hsu PC, Wu HT, Sun CK. Assessment of subtle changes in diabetes-associated arteriosclerosis using photoplethysmographic pulse wave from index finger. J Med Syst. 2018; 42(3): 43, doi: 10.1007/s10916-018-0901-1, indexed in Pubmed: 29368039.
40. Lin GM, Haryadi B, Yang CM, et al. Discrepancies between conventional multiscale entropy and modified short-time multiscale Entropy of Photoplethysmographic pulse signals in middle- and old-aged individuals with or without diabetes. Entropy. 2017; 19(3): 132, doi: 10.3390/e19030132.
41. Roth GA, Nguyen G, Forouzanfar MH, et al. Estimates of global and regional premature cardiovascular mortality in 2025. Circulation. 2015; 132(13): 1270–1282, doi: 10.1161/CIRCULATIONAHA.115.016021, indexed in Pubmed: 26408271.
42. Bonetti PO, Lerman LO, Lerman A. Endothelial dysfunction: a marker of atherosclerotic risk. Arterioscler Thromb Vasc Biol. 2003; 23(2): 168–175, indexed in Pubmed: 12588755.
43. Mozaffarian D, Benjamin EJ, Go AS, et al. Writing Group Members, American Heart Association Statistics Committee, Stroke Statistics Subcommittee. Heart Disease and Stroke Statistics-2016 Update: A Report From the American Heart Association. Circulation. 2016; 133(4): e38–360, doi: 10.1161/CIR.0000000000000350, indexed in Pubmed: 26673558.
44. Matsuzawa Y, Lerman A. Endothelial dysfunction and coronary artery disease: assessment, prognosis, and treatment. Coron Artery Dis. 2014; 25(8): 713–724, doi: 10.1097/MCA.0000000000000178, indexed in Pubmed: 25365643.
45. Corretti MC, Anderson TJ, Benjamin EJ, et al. International Brachial Artery Reactivity Task Force. Guidelines for the ultrasound assessment of endothelial-dependent flow-mediated vasodilation of the brachial artery: a report of the International Brachial Artery Reactivity Task Force. J Am Coll Cardiol. 2002; 39(2): 257–265, indexed in Pubmed: 11788217.
46. Zakaria H, Mengko T. Changes of Arterial stiffness during flow-mediated dilation procedure. 2015 4th International Conference on Instrumentation, Communications, Information Technology, and Biomedical Engineering (ICICI-BME). 2015, doi: 10.1109/icici-bme.2015.7401310.
47. Si D, Ni L, Wang Y, et al. A new method for the assessment of endothelial function with peripheral arterial volume. BMC Cardiovasc Disord. 2018; 18(1): 81, doi: 10.1186/s12872-018-0821-5, indexed in Pubmed: 29728052.
48. Wu HT, Lin BY, Yang CC, et al. Assessment of vascular health with photoplethysmographic waveforms from the fingertip. IEEE J Biomed Health Inform. 2017; 21(2): 382–386, doi: 10.1109/JBHI.2016.2515938, indexed in Pubmed: 26761908.