Front. Optoelectron. 2017, 10(3): 287–291
DOI 10.1007/s12200-017-0723-7

RESEARCH ARTICLE

Influence of pulse waves on the transmission of near-infrared radiation in outer-head tissue layers

Jerzy PLUCIŃSKI (✉)[1], Andrzej FRYDRYCHOWSKI[2]

1 Department of Metrology and Optoelectronics, Faculty of Electronics, Telecommunication and Informatics, Gdańsk University of Technology, ul. G. Narutowcza 11/12, 80-233 Gdańsk, Poland
2 Department of Human Physiology, Faculty of Health Sciences with Subfaculty of Nursing and Institute of Maritime and Tropical Medicine, Medical University of Gdańsk, ul. Tuwima 15, 80-210 Gdańsk, Poland

Abstract In this study, we investigate the effect of pulse waves on the transmission of near-infrared radiation in the outer tissue layers of the human head. This effect is important in using optical radiation to monitor brain conditions based on measuring the transmission changes in the near-infrared radiation between the source and the detector, placed on the surface of the scalp. This is because the signal related to the changes in the width of the subarachnoid space (SAS) due to the pulse wave is modified. These latter changes can be used, for instance, in detecting cerebral edema and in evaluating cerebral oxygenation. The research was performed by modeling the propagation of near-infrared radiation in the tissue layers using a Monte-Carlo method. The main objective of this study was to assess the extent to which the changes in the transmission of near-infrared radiation correspond to the changes in the optical parameters of the tissues of the head and in the width of the subarachnoid layer.

Keywords infrared radiation, transmission, human head, tissue, Monte-Carlo method

1 Introduction

The optical methods used for brain diagnosis, such as detecting cerebral edema [1,2] and cerebral oxygenation [3–5], are based on measuring the optical radiation transmitted by the outer tissue layers of the head. Because of the transmission properties of the tissues of the head, near-infrared radiation is used. This radiation, transmitted through the layers of the head tissues, can be modulated in amplitude because of the changes in the pulse or oxidation state of the tissues. The transmission can also be altered by changing the position of the brain within the skull (due to head tilt) or volume changes in the brain due to cerebral edema. The main problem in brain diagnosis based on the transmission of near-infrared radiation is extracting the modulation component due to the factor of interest (e.g., edema). Generally, some factors were neglected by assuming that the near-infrared radiation intensity can be modulated either solely through changing the tissue transmission properties (such a case is most commonly found in cerebral oximetry [6]), or because of the variation in the width of the subarachnoid layer (such a case is most common in detecting cerebral edema [1,7]). In quantitative research, both the modulation factors may play important roles. To investigate and verify the same, a Monte-Carlo method was used to test how the changes in the transmission correspond to the change in the width of the subarachnoid space (SAS) due to the cyclic change in the volume of the brain. In addition, the extent to which the changes in the transmission correspond to the changes in the blood volume in the blood vessels was investigated.

Received April 5, 2017; accepted June 5, 2017

E-mail: pluc@eti.pg.gda.pl

2 Influence of the pulse wave on the volume of brain and its optical parameters

Under the influence of blood pressure from the heart, the volume of the blood inside the blood vessels within the skull changes cyclically (Fig. 1). Because the skull can be assumed inextensible and the blood and other tissues of the head can be assumed incompressible, the change in the blood volume results in a cyclic change in the brain volume consistent with the heart rate. These changes are possible because the brain inside the skull is surrounded by a cerebrospinal fluid, which is displaced into the spinal canal when the intracranial volume increases (cerebral blood is

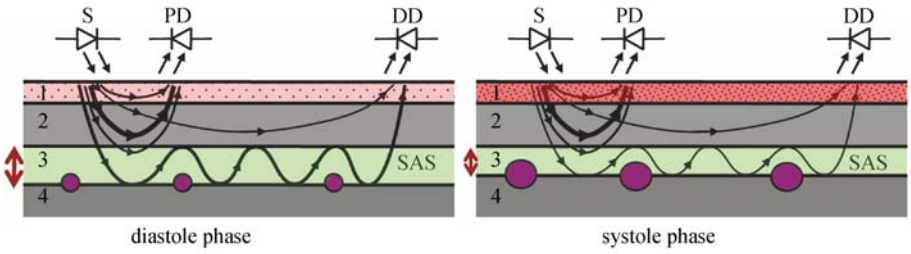

Fig. 1 Simplified diagram illustrating the effects of the pulse wave during particular phases of cardiac cycle on the width of the SAS, cerebral arteries and arterioles (indicated by different radii of the wheels), amount of blood in the skin (indicated by dot density), and the transmission of near-infrared radiation in the outer-head tissue layers, where 1, 2, 3, and 4 represent the skin, skull bone, SAS, and surface of the brain covered with cerebral arteries and arterioles (indicated by circles), respectively. S denotes the near-infrared source, PD denotes the proximal detector (used to compensate for a changes of skin absorption), and DD denotes the distal detector (used to detect near-infrared radiation propagating in the SAS or in the brain) [1]

excised). Available imaging methods employed in medical diagnostics are incapable of accurately determining the extent of the effect of added blood volume on the intracranial pulmonary vessels in changing the cyclic width of the SAS. Hence, indirect methods were employed to perform this measurement. For example, Sakai et al. [8] estimated the variation in the width of the SAS due to the cyclic change in the hemoglobin in gray matter. The results show that the cyclic variation in the width of the SAS was only 4 μm. By assuming this slight change and based on modeling the optical-radiation transmission in head tissues, Firbank et al. showed that the change in the near-infrared transmission between the source and the detector placed at a distance of up to 50 mm is largely due to the cyclic change in the brain absorption under the volume of blood added to the intracranial pulmonary vessels rather than the cyclic variation in the width of the SAS [9]. Given the current advancements, the assumed value of 4 μm is too small because it accounts for changes in the volume of the brain resulting from the changes in the volume of the blood only in the gray matter. The volume of the blood in the vessels lying deeper inside the skull was neglected.

In this study, the change in the width of the SAS was estimated based on the amount of the cerebrospinal fluid displaced into the spinal canal at the beginning of each heart cycle, which is approximately 1 mL (at the end of the cycle, the same volume of blood returns to the tissues inside the skull) [10,11]. This value is due to the difference in the blood-flow velocity in the arteries and veins within the skull during the cycle. Because the tissues inside the skull are incompressible, the same volume of blood at the beginning of each cycle must increase the amount of blood contained within the skull. Assuming that the human brain has an average volume of approximately 1500 cm^3, the increase in the size of the brain can be approximately calculated at the beginning of the pulse wave, and thus, the decrease in the width of the SAS. Assuming that the position of the brain remains constant during the heart cycle and that the change in its dimension is uniform in all directions, the heart rate changes the width of the subarachnoid layer by 15 μm (average difference between the highest and lowest widths of the subarachnoid layer). This value was assumed in simulating the near-infrared transmission in the following part of the work. Assuming this value causes a significant increase in the proportion of the width of the SAS with respect to the change in the near-infrared transmission in the outer-head tissue layers compared to that assumed in the study by Firbank et al. [9]. Moreover, the study conducted by Greitz et al. using magnetic-resonance-phase imaging in adult volunteers indicated a greater variation in the width of the SAS under the effect of the pulse wave, i.e., 10 μm [12]. In the simulations presented in this study, the change in the brain-absorption coefficient was assumed the same as that used by Firbank et al. [9], i.e., a change of 1/84 due to the cyclic-hemoglobin variation in the gray matter.

3 Numerical modeling of transmission of near-infrared radiation in outer-head tissue layers

In the numerical calculation of the transmission of near-infrared radiation in the outer-head tissue layers, it was assumed, for simplicity, that the individual outer-brain tissues form layers of fixed width (except for the SAS layer) and fixed optical parameters (excluding the brain) (see Fig. 2). The circumstantial changes in the skin parameters were neglected, as they can be easily compensated while measuring the near-infrared radiation transmitted by the brain or SAS if an additional detector is placed near the radiation source [1].

The calculations were performed using an average bone thickness of 5 mm (bone thickness varies from person-to-person and is generally in the range of 3.5–12 mm [13]). It was assumed that in the initial phase of the pulse wave, the parameters of the individual outer layers of the head are the same, as given in Table 1 (the values given in the table

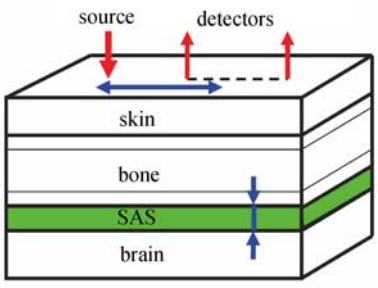

Fig. 2 Model of the outer-head tissue layers used in calculating the near-infrared transmission between the near-infrared radiation source and the detectors placed on the head surface

Table 1 Optical parameters of tissues of the head used for numerical modeling [14]

tissue	thickness /mm	absorption coefficient /mm^{-1}	reduced scattering coefficient /mm^{-1}
skin	3	0.013	1.7
bone – external compact lamina	1	0.0242	0.88
bone – spongious layer	2.5	0.01627	0.59268
bone – internal compact lamina	1.5	0.0242	0.88
SAS	0–3.5	0.001	0.001
brain	10	0.037	2.0

correspond to a wavelength of λ = 870 nm, i.e., the wavelength used by the authors in the clinical tests [1]). Next, it was assumed that the width of the SAS decreases by 10 μm and the absorption coefficient of the gray mater increases by 1/84 (i.e., from 0.037 to 0.03744 mm^{-1}) under the effect of the pulse wave.

The calculations were conducted for four different widths of the SAS (0, 0.3, 1, and 3.5 mm). A modified Monte-Carlo method was used wherein the computations can be conducted for several values of the SAS-layer width simultaneously. This method was described in detail in another study [14]. In the simulating the near-infrared transmission in the outer-head tissue layers, 10^9 photons were used. This number was chosen by a tradeoff between the accuracy of the calculations and the calculation time. The calculations were made on a quad-core Intel processor i7-3770K (working at 4500 MHz) using multi-threaded computing. The calculation time was 32 h and 56 min. In Fig. 3, the calculated relative changes in the power incident on the detector due to the pulse wave are presented as a function of its distance from the source. The relative power-change parameter was calculated as the ratio of the power change corresponding to $(1- P_s/P_d)\times 100\%$, where P_s is the power in the systole phase and P_d is the power in the diastole phase. Figure 3 shows the effects of the reduction in the width of the SAS and the increase in the brain-absorption coefficient on the power received by the detector.

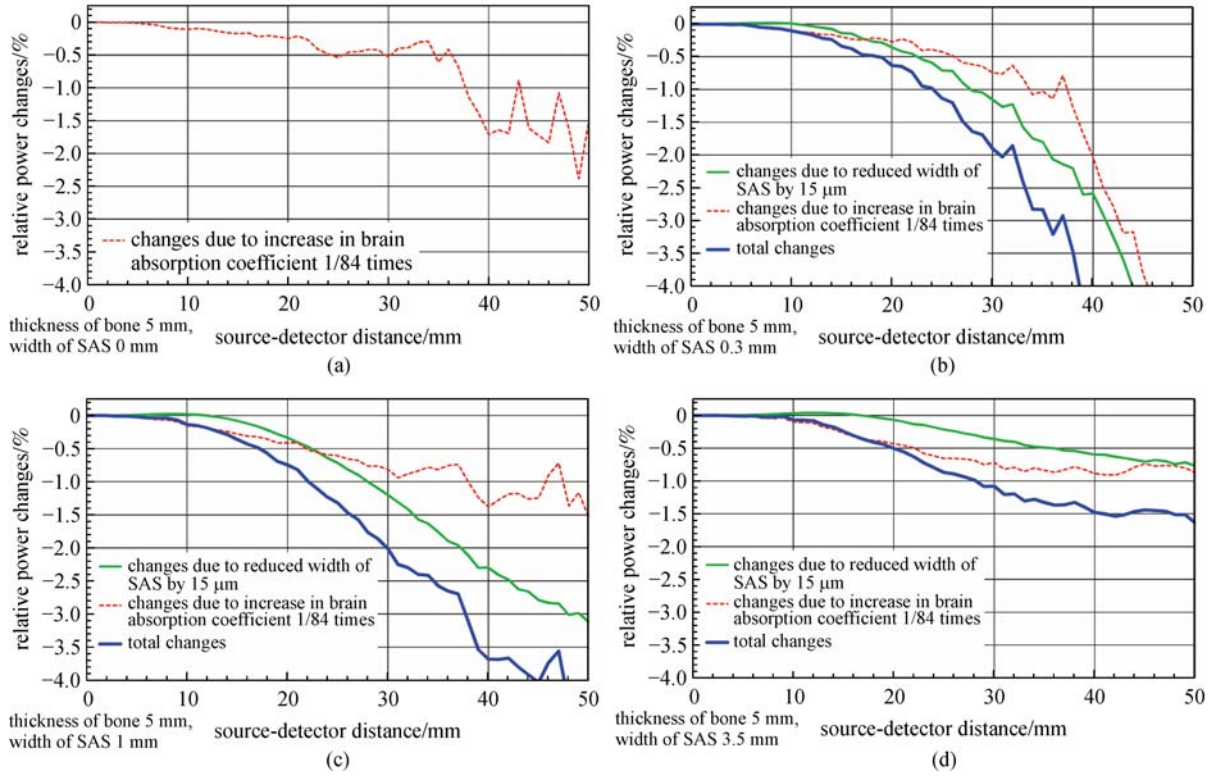

Fig. 3 Changes in relative power due to the pulse wave received by the detector as a function of its distance from the near-infrared radiation source for different widths of the SAS (i.e., for (a) 0, (b) 0.3, (c) 1, and (d) 3.5 mm)

The modeling results, presented in Fig. 3, show that the relative power changes due to the pulse wave received by the detector are in the order of a few percent. These changes increase with the increase in the distance between the source and the detector. The reduction in the width of the SAS and the increase in the brain-absorption coefficient, which contribute to the changes in the relative power recorded by the detector, depend on this distance. At short distances (i.e., for distances less than 17, 23, or 50 mm, the widths of the SAS are equal to 0.3, 1, or 3.5 mm, respectively), the influence of the increase in the brain-absorption coefficient is greater than that of the reduction in the width of the SAS on the changes in the relative power received by the detector. The situation is the opposite for longer distances. Studies have shown that even when the width of the SAS is equal to zero, there is a small (1%) modulation of near-infrared transmission, which should be considered in the optical diagnostics of cerebral edema. The results, shown in Fig. 3, indicate that the calculation results of the relative power of the detector for distances greater than 35 mm between the source and the detector have significant variance, despite using 10^9 photons in the simulations. To significantly reduce this variance, more number of photons are required (one-two orders of magnitude) in the computation. This would require a multi-week calculation for the typical PCs or computing clusters.

4 Conclusions

The preliminary research shows that the changes in the width of the SAS and in the absorption coefficient of the brain due to the pulse wave have comparable contribution to the transmission of near-infrared radiation in the outer-head tissue layers. The contributions of these factors depend on the width of the SAS, the distance between the source and the detector, and probably the thickness of the bone (preliminary tests performed on near-infrared transmission for a bone thickness of 10 mm help in confirming this assumption). In a further research, a study cycle for different values of the bone thickness will be conducted. Moreover, the authors plan to observe the changes in the near-infrared transmission occurring at different degrees of cerebral edema and with changes in the cerebral vascular width when vascular active drugs are administered during the research on patients in clinical settings.

Acknowledgements This study was supported by DS Programs of the Faculty of Electronics, Telecommunications and Informatics of the Gdańsk University of Technology.

References

1. Frydrychowski A F, Pluciński J. New aspects in assessment of changes in width of subarachnoid space with near-infrared transillumination-backscattering sounding, part 2: clinical verification in the patient. Journal of Biomedical Optics, 2007, 12(4): 044016
2. Frydrychowski A F, Kaczmarek J W, Juzwa W, Rojewski M, Pluciński J, Gumiński W, Kwiatkowski C, Lass P, Bandurski T. Near-InfraRed Transillumination (NIR-TI) a new non-invasive tool for exploration of intracranial homeostasis and monitoring of its impairments. Biocybernetics and Biomedical Engineering, 1999, 19 (2): 99–108
3. Tobias J D. Cerebral oxygenation monitoring: near-infrared spectroscopy. Expert Review of Medical Devices, 2006, 3(2): 235–243
4. Murkin J M, Arango M. Near-infrared spectroscopy as an index of brain and tissue oxygenation. British Journal of Anaesthesia, 2009, 103(suppl_1): i3–i13
5. Milej D, Janusek D, Gerega A, Wojtkiewicz S, Sawosz P, Treszczanowicz J, Weigl W, Liebert A. Optimization of the method for assessment of brain perfusion in humans using contrast-enhanced reflectometry: multidistance time-resolved measurements. Journal of Biomedical Optics, 2015, 20(10): 106013
6. Kacprzak M, Liebert A, Staszkiewicz W, Gabrusiewicz A, Sawosz P, Madycki G, Maniewski R. Application of a time-resolved optical brain imager for monitoring cerebral oxygenation during carotid surgery. Journal of Biomedical Optics, 2012, 17(1): 016002
7. Pluciński J, Frydrychowski A F. Verification with numeric modelling of optical measurement of changes in the width of the subarachnoid space. Biocybernetics and Biomedical Engineering, 1999, 19(4): 111–126
8. Sakai F, Nakazawa K, Tazaki Y, Ishii K, Hino H, Igarashi H, Kanda T. Regional cerebral blood volume and hematocrit measured in normal human volunteers by single-photon emission computed tomography. Journal of Cerebral Blood Flow and Metabolism, 1985, 5(2): 207–213
9. Firbank M, Okada E, Delpy D T. A theoretical study of the signal contribution of regions of the adult head to near-infrared spectroscopy studies of visual evoked responses. NeuroImage, 1998, 8(1): 69–78
10. Ruskin K J, Rosenbaum S H, Rampil I J. Fundamentals of Neuroanesthesia – A Physiologic Approach to Clinical Practice. Oxford: Oxford University Press, 2014
11. Alperin N, Mazda M, Lichtor T, Lee S H. From cerebrospinal fluid pulsation to noninvasive intracranial compliance and pressure measured by MRI flow studies. Current Medical Imaging Reviews, 2006, 2(1): 117–129
12. Greitz D, Wirestam R, Franck A, Nordell B, Thomsen C, Ståhlberg F. Pulsatile brain movement and associated hydrodynamics studied by magnetic resonance phase imaging. Neuroradiology, 1992, 34 (5): 370–380
13. Pluciński J, Frydrychowski A F, Kaczmarek J, Juzwa W. Theoretical foundations for noninvasive measurement of variations in the width of the subarachnoid space. Journal of Biomedical Optics, 2000, 5(3): 291–299
14. Pluciński J, Frydrychowski A F. New aspects in assessment of changes in width of subarachnoid space with near-infrared transillumination/backscattering sounding, part 1: Monte Carlo numerical modeling. Journal of Biomedical Optics, 2007, 12(4): 044015

Jerzy Pluciński received the M.Sc. degree in electronics at the Faculty of Electronics, the Gdańsk University of Technology, Poland in 1984, and then in 1994, obtained his Ph.D. degree in optoelectronics (summa cum laude). In 2010, he obtained Habilitated Doctor degree (summa cum laude) at the same university. In years 1991 and 1992, he took two one-month internships at the Universität Karlsruhe, Germany, in 1993 – an one-month internship at the Université de Strasbourg, France, and in 1996 – a six-month postdoc internship at the Measurement and Sensor Laboratory in Kajaani, University of Oulu, Finland. In years from 1997 to 2003, he worked for 21 months at the Optoelectronics and Measurement Techniques Laboratory, the University of Oulu, Finland. He has research interests in optoelectronics and photonics, optics of highly-scattering materials, optical coherence tomography, low-coherence interferometry, optical fiber sensors, and laser technics. He is the author or co-author of over 150 scientific papers, the author of 1 monography, 1 academic handbook, and 2 chapters in 2 international academic handbooks. Now he is Professor at the Gdańsk University of Technology. He directs there the Optoelectronics Team at the Department of Metrology and Optoelectronics at the Faculty of Electronics, Telecommunications and Informatics.

Andrzej Frydrychowski completed his medical studies at the Medical Faculty, the Medical Academy in Gdańsk, Poland in 1973. He received the Ph.D. degree in medical science at the same unit in 1980, based on the dissertation: "Attempting to objectify the phenomenon of pain in experimental studies on cats". He graduated habilitated doctor in 2007, based on the assessment of general scientific achievements and the presented habilitation thesis: "Measurement of transluminal translucency with reverse scatter (NIR-T.BSS): a new, non-invasive method for examining changes in the width of the subarachnoid space and parameters of intracranial artery". From completing medical studies and obtaining the medical diploma in 1973 to May 2007, he worked continuously at the Chair and Department of Physiology of the Medical Academy in Gdańsk. For one year, he worked at the Department of Nuclear Medicine of the same unit. On October 2008, he was assigned the duties of the Head of the newly established Department of Human Physiology at the Faculty of Health Sciences of the Medical University of Gdańsk. He is the author or co-author of about 150 scientific papers. Now he is Professor at the Medical University of Gdańsk.