12

Application of multivariate statistical analysis methods in optical biomedical diagnostics

© M.S. Mazing[1], M.Yu. Zanevskaya[1,2], A.Yu. Zaytseva[1]

[1] Institute of Analytical Instrument Making, Russian Academy of Sciences,
St. Petersburg, Russia
[2] St. Petersburg State University of Aerospace Instrumentation,
St. Petersburg, Russia

e-mail: mazmari@mail.ru

Received May 03, 2024
Revised June 06, 2024
Accepted October 30, 2024

A new methodological approach to the construction of multifunctional biomedical diagnostic devices to assess the critical state of the human body, the state of shock, has been developed. A wearable hardware and software system used for medical monitoring of the functional state of the human cardiovascular system based on optoelectronic sensors and analysis of the obtained multidimensional array of heterogeneous physiological data using the multivariate statistical analysis and machine learning techniques has been studied. The relationships between the spectral response of biological tissues and the functional state of a person, in particular, the state of shock, have been mathematically substantiated.

Keywords: Spectrophotometry, optical biomedical diagnostics, multivariate statistical analysis, method of principal components.

DOI: 10.61011/EOS.2024.11.60315.6614-24

The current development level of biomedical diagnostics, registration and analysis of the physiological state of the human body makes it possible to create a system of sensors that register individual indicators of physiological parameters in dynamics, which gives an idea of the onset of a critical state [1–3].

A state of shock — a physiological state of a sharp decrease in the volume of blood supply to tissues and centralisation of blood circulation. There is vasoconstriction, redirecting blood to the most important organs. Such a state can be detected by capillary blood circulation in the skin and changes in the optical characteristics of backscattered radiation in biological tissues [4,5].

Development of hardware and software system for medical monitoring of the functional state of the human cardiovascular system

The hardware and software system (HSS) of optical tissue oximetry has been developed, the physical principle of which is the difference of optical absorption properties of the main chromophores of biological tissue, in particular, physiological forms of haemoglobin protein. The forms of haemoglobin have different absorption capacity in a wide range of wavelengths, therefore it was decided to develop an optical system operating in the visible and near-infrared ranges. The optoelectronic module is represented by a chipset consisting of three spectral sensors AS72651, AS72652 and AS72653, each containing Gaussian interference filter technology. The individual Gaussian filters are integrated into standard silicon complementary metal–oxide–semiconductor (CMOS) technology and are presented in an LGA package with an integrated aperture that controls the flow of light to the photosensitive element array. Each optical channel records the optical intensity I (μW/cm^2). The diagram of the hardware and software system is shown in Fig. 1. Sensor AS72651 registers wavelengths 610/680/730/760/810/860 nm. The AS7265 detects wavelengths of 560/585/645/705/900/940 nm. The AS72653 detects wavelengths of 410/435/460/485/510/535 nm. Three SMD LEDs were selected as external radiation sources of the optoelectronic module: white, red and infrared.

The computational and data processing module performs general control of the system, displays the obtained measurements, and processes the obtained data array. The data received by the optoelectronic module were transmitted to a personal computer by means of a wireless personal network.

An experimental study with 14 male subjects was conducted using the developed HSS. During the study, a shock state was simulated experimentally under controlled conditions and conditions were created for short-term centralisation of blood circulation due to stress reaction of the body by means of cuff occlusion test on the upper extremities. The study was performed in the sitting position. The HSS was fixed on the forearm of the left hand in each subject. The research protocol was as follows: 1 — taking measurements at rest for one minute; 2 — taking measurements under conditions of short-term centralisation of blood circulation due to occlusion for 3 minutes. The

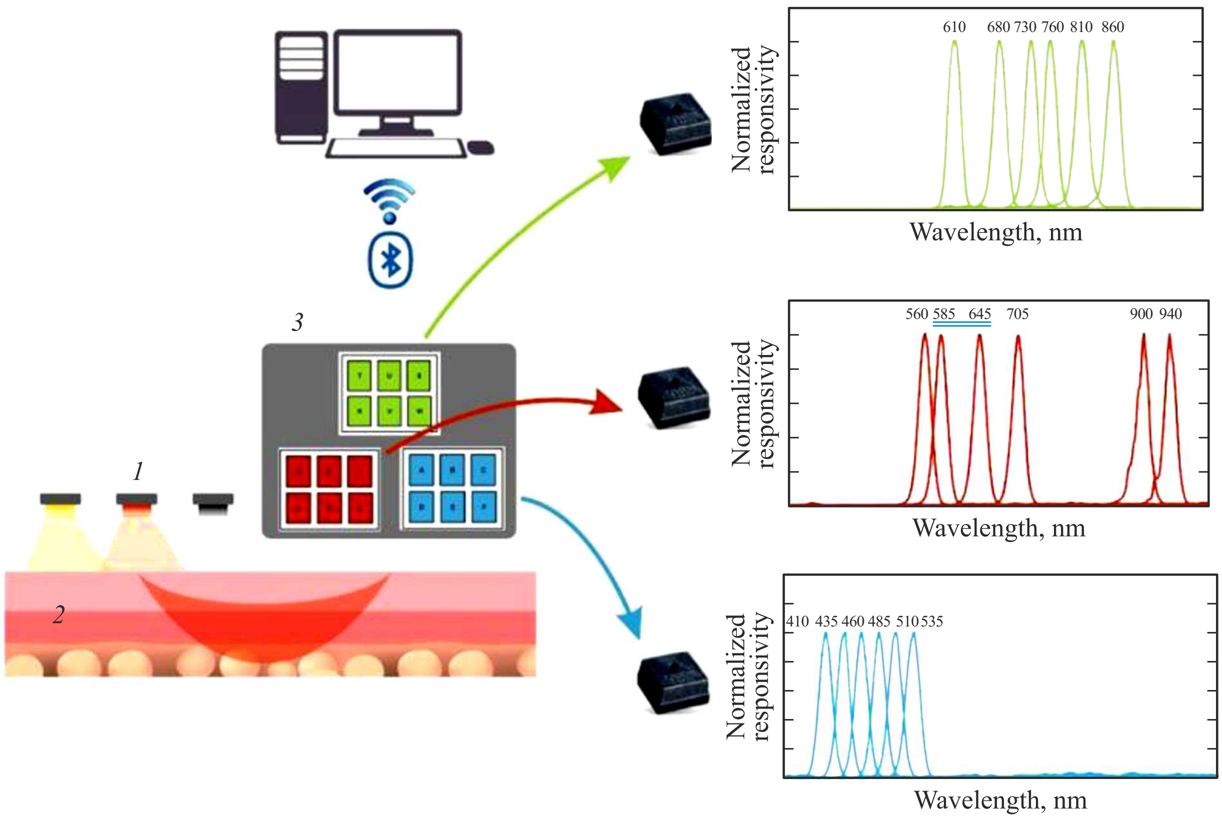

Figure 1. Functional diagram of the developed HSS: *1* — radiation sources; *2* — biological tissue; *3* — spectral sensors.

readings of each of the 18 optical channels of the HSS were obtained digitally throughout the experimental study and saved for subsequent analysis on a personal computer using specially developed software.

Research results

The obtained spectral responses at different stages of the experimental study were processed by methods of statistical multivariate analysis, in particular the principal component method (PCM), designed to reduce dimensionality and visualise the original spectral data [6]. Principal components are a generated set of new features $t(1), t(2), \ldots, t(p)$ each derived from a linear combination of the original (initial) features $x(1), x(2), \ldots, x(p)$, that were directly measured on the objects under study. PCM was applied to the spectral dataset, which was a matrix that consisted of 28 rows and 18 columns (readings from each of the 18 optical channels). The data were selected for presentation using the first two principal components, which explained 89.2% of the total variance of the original data. Figure 2 shows the distribution of the resulting data set in the plane formed by the principal components *1* and *2*.

Using the principal component method, it was found that the spectral responses obtained grouped into mathematical clusters according to the nature of the subject's physiological state. In Fig. 2, a clear ranking of rest/shock state can be traced along the axis x, which represents the first principal component (*Principal component 1*), with the greatest contribution to the differentiation of spectral responses of biological tissues made by wavelengths 645, 810, and 760 nm. The length of the vectors corresponds to the contribution of the optical channel reading at a certain wavelength to the subject's states, the direction indicates in which direction the increase in the reading of the given channel will shift the subjects on the given diagram. By analysing the lengths and directions of the vectors, optical channels (wavelengths) —indicators that contribute most to the shock state can be identified. An expression representing a linear combination of the weighted original variables with the corresponding „weights“ for the first principal component is presented below:

$$\begin{aligned} PC1 = &- 0.29\cdot 645\,\text{nm} - 0.28\cdot 810\,\text{nm} - 0.27\cdot 760\,\text{nm}\\ &-0.13\cdot 610\,\text{nm} - 0.12\cdot 730\,\text{nm} - 0.12\cdot 860\,\text{nm}\\ &-0.11\cdot 680\,\text{nm} - 0.09\cdot 410\,\text{nm} - 0.09\cdot 435\,\text{nm}\\ &-0.09\cdot 560\,\text{nm} - 0.06\cdot 510\,\text{nm} - 0.05\cdot 535\,\text{nm}\\ &-0.05\cdot 585\,\text{nm} - 0.05\cdot 940\,\text{nm} - 0.04\cdot 460\,\text{nm}\\ &-0.03\cdot 485\,\text{nm} - 0.1\cdot 705\,\text{nm} - 0.1\cdot 900\,nm \end{aligned}$$

Thus, it is found that the greatest contribution to the resting state/shock state differentiation is made by the

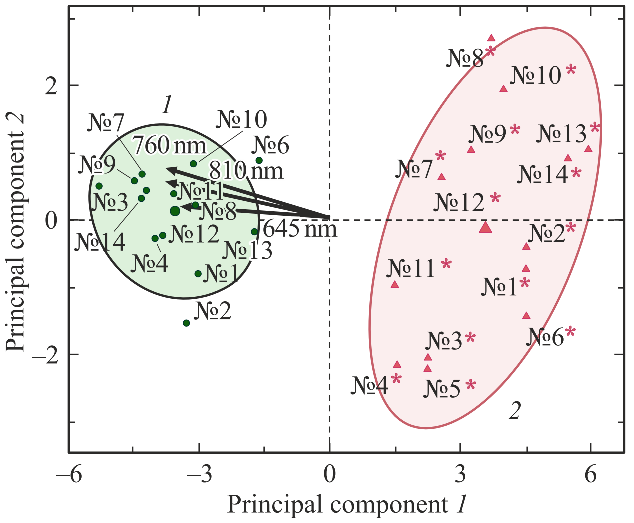

Figure 2. Distribution of the original data set in the plane formed by the two principal components into clusters: *1* — physiological response of biological tissues of subjects at rest; *2* — in the simulation of shock state. The vectors indicate the direction and magnitude of the initial features contribution to data differentiation.

responses of optical channels at wavelengths 645, 810, 760 nm.

Conclusion

A wearable hardware and software system used for medical monitoring of the functional state of the human cardiovascular system based on optoelectronic sensors has been developed. The methods of multivariate statistical analysis have been applied to analyse optical parameters of backscattered radiation of biological tissues in case of critical states of the human body. The shock state of the human body is experimentally simulated by applying functional load in the form of occlusion test of the upper extremities. The relationships between the spectral response of biological tissues and the functional state of a person, in particular, the state of shock, have been mathematically substantiated. The proposed system made it possible to objectively assess the presence of the shock state of the human body and the functional state of the body as a whole, which can be used in biomedical diagnostics to study the cardiovascular system functions in various critical conditions, to control the effectiveness of therapeutic and surgical interventions, as well as to optimise the recovery treatment.

Compliance with ethical standards

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Informed voluntary consent was obtained from each study participant.

Funding

The study was supported by a grant from the Russian Science Foundation (project No 24-21-00404).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] B. Kaur, S. Kumar, B.K. Kaushik. Biosensors, **13** (2), 181 (2023). DOI: 10.3390/bios13020181
[2] E. Vavrinsky, N.E. Esfahani, M. Hausner, A. Kuzma, V. Rezo, M. Donoval, H. Kosnacova. Biosensors, **12** (4), 217 (2022). DOI: 10.3390/bios12040217
[3] I.N. de Keijzer, D. Massari, M. Sahinovic, M. Flick, J.J. Vos, T.W. Scheeren. J. Clinical Monitoring and Computing, **36** (2), 291–299 (2022). DOI: 10.1007/s10877-022-00837-x
[4] J. Ali, J. Cody, Y. Maldonado, H. Ramakrishna. J. Cardiothoracic and Vascular Anesthesia, **36** (8), 2758–2766 (2022). DOI: 10.1053/j.jvca.2021.07.015
[5] A. Dunaev. J. Biomedical Photonics & Engineering, **9** (2), 020201 (2023). DOI: 10.18287/JBPE23.09.020201
[6] A. Maćkiewicz, W. Ratajczak. Computers & Geosciences, **19** (3), 303–342 (1993). DOI: 10.1016/0098-3004(93)90090-R

Translated by J.Savelyeva