Mathematical modeling of change in color coordinates of superficial injuries of human soft tissues for forensic medicine

Chapter · February 2019
DOI: 10.1201/9780429057618-10

6 authors, including:

Serhii Kvaterniuk
Vinnytsia National Technical University

Vasyl Petruk
Vinnytsia National Technical University

Olena Kvaterniuk
Vinnytsia State Pedagogical University

Andrzej Kotyra
Lublin University of Technology

Mathematical modeling of change in color coordinates of superficial injuries of human soft tissues for forensic medicine

Sergey Kvaternyuk[a], Olena Kvaternyuk[b], Vasil Petruk[a], Olexander Mokanyuk[c], Andrzej Kotyra[d], Ainur Kozbakova[e]

[a]Vinnytsia National Technical Univ., Khmelnytske Shose, 95, Vinnytsia, 21021, Ukraine;
[b]Vinnytsia Humanitarian Pedagogical College, Nagirna street, 13, Vinnytsia, 21019, Ukraine;
[c]Vinnytsia National Medical University, str. Pirogov 56, Vinnytsia, 21018, Ukraine
[d]Lublin Univ. of Technology, Nadbystrzycka str., 38 D, Lublin, 20 – 618, Poland;
[e]Institute of Information and Computational Technologies, Str. Pushkeen, 125, Almaty, 050010, Kazakhstan

ABSTRACT

We proposed an empirical mathematical model that establishes the interrelation of a plurality of points in the color space of surface damages of human soft tissues and the time interval after their appearance, which allowed taking into account the variation over time of the concentrations of hemoglobin degradation products in them that affect the color of surface lesions and establish the time interval after their occurrence. A mathematical model is developed for changing the color coordinates of surface damages of human soft tissues from the time interval after their appearance, taking into account the changes in the concentrations of the products of destruction of hemoglobin. The inverse optical problem of determining the time interval after the occurrence of superficial injuries as a result of trauma by blunt objects according to the color coordinates and the relative sizes of zones of different color of damage is solved, which can be used for digital colorimetry in forensic medical examination.

Keywords: color, measurement, colorimetry, tissue characterization, optical diagnostics for medicine

1. INTRODUCTION

For the investigation of surface damage to biological tissues in forensic medicine, it is important to quickly determine and document the degree of damage, as well as an analysis of its specific features. Measurement of the optical parameters of the human skin allows us to obtain objective information about the spatial distribution of various biological chromophores in it and its structure used to study various types of pathologies in forensic problems. The condition of superficial pathologies of biotissues essentially influences their color, therefore the analysis and classification of superficial pathologies of biotissues by color are especially important for forensic medical examination. The relevance of the topic is due to the need to increase the reliability of establishing the time interval after the occurrence of superficial injuries of human soft tissues with blunt objects in accordance with the problems of forensic medicine, taking into account their optical and physical parameters by improving the method of colorimetry. The object of research is the process of establishing the time interval after the occurrence of superficial damages of human soft tissues with blunt objects for the tasks of forensic medicine. Recently, the method of digital colorimetry is often used for express diagnostics of pathological biological tissues. The development of the method of digital colorimetry corresponds to the main trends of modern medical research, which include the automation and computerization of measurements. The use of digital cameras, flatbed scanners and computer programs for processing color digital images has made it possible for a fast, objective and automated method of obtaining colorimetric parameters. The advantages of digital colorimetry as an analytical method consist in increasing the sensitivity and selectivity of the determination of various substances, in the possibility of studying the concentration of certain pigments in biological tissues, and also in constructing calibration test scales for visual determination of components in express methods of analysis.

When the optical radiation interacts with the biotissue, different phenomena may occur and processes, in particular, reflection, refraction, absorption, scattering, which depend on the state and structure of the biotissue [1-3]. Optical characteristics of biotissues carry important information on the quantitative content and spatial distribution of various biological components of the tissue, which gives the potential for studying the state of the tissue [4-6].

Among optical methods of biological tissues in vivo in conditions currently the most developed methods of reflection spectroscopy and fluorescence spectroscopy. Although the method of reflection spectroscopy, based on the measurement of the spectrum of diffuse backscattered radiation by biological tissue, has been used for a long time, the latest advances in optoelectronics and computer technologies have given it new opportunities and made it possible to transform the spectroscopy of biotissue reflection into a popular and popular method of investigation [3, 7]. Most of the published works on in vivo spectroscopy of biotissue reflection are devoted to the study of skin tissue, is, on the one hand, the most accessible human biotissue, and on the other hand - one of the most complex biological structures [8]. One of the most important problems of modern medical research is the development of methods for visualizing the heterogeneous structure of biological tissues. Among the currently known methods of visualization, optical methods are among the most attractive, primarily due to their non-invasiveness, the potential for achieving high spatial capacity, and the possibility of carrying out multifunctional monitoring of the investigated medium. Visual examination of the surface of the tissue is widely and successfully used to study its condition, the main emphasis in such reviews is directed to the analysis of changes in color of the tissue caused by various factors. The main emphasis in such reviews is aimed at analyzing the change in color of the tissue and the classification of morphological manifestations. In particular, a visual examination of cutaneous morphology is the basis of clinical dermatology. Obviously, visual inspection is an extremely subjective process, and its results are highly dependent on the experience and qualifications of the physician. The desire for an objective assessment of the changes that occur in biological tissues encourages physicians to increasingly use hardware research methods in their practice. In recent years, there has been a significant increase in interest in this method of biological tissue research, as a method of digital imaging, based on the computer processing of experimentally obtained images of the surface of biological tissues. The digital imaging method has found various applications in dermatology [9], but all these applications are based on a simple RGB analysis of the surface image of the tissue, which limits the possibilities of the method. The issue of visualization, documentation, monitoring, measurement and classification of morphological manifestations of various processes in biological tissues is a field of use of the digital visualization method based on computer processing of experimentally obtained images of its surface. For applied problems of forensic examination, it is actual to analyze the concentration of pigments in the surface layer of pathologically damaged biotissues by measuring the color coordinates of digital image elements based on the digital colorimetry method. Analysis of digital images using a variety of color bars is widely used in medical research. The objectivity of evaluating the perception of the color of the biotissue and the features of its surface and subsurface structures is based on the physical principles of the formation and evaluation of the color of the tissue, embodied in colorimetric methods of measuring color and computer methods for digital visualization of the surface of biological tissues [10]. The use of color coordinates and other color characteristics of objects, in conditions of measurement, ensuring the reliability and reproducibility of research, allows you to quickly obtain information for applied forensic problems [11, 12]. Studies on the characteristics of color as an integral parameter makes it possible to assess the state of the object of investigation is particularly relevant. Definition of integral indicators is most expedient for the analysis of complex heterogeneous biological environments of different origin. Traditionally, the method of colorimetry is based on reflection spectroscopy. The color of the skin is determined by the spectral composition of radiation diffusely reflected by the skin. In this case, spectral measurements are conducted averaged over a certain area of the investigated object, which makes it difficult to determine the spatial localization of its pathological regions. Modern video colorimeters allow to investigate the distribution of color parameters on the surface of the object of investigation, it allows to determine its state and physical parameters [13-17]. However, video colorimetry is characterized by large errors in measuring the coordinates of the color of objects, in comparison with the spectrophotometric method, since it is more difficult to provide stable research conditions and constant lighting characteristics in such devices [18-19]. Modern colorimeters are successfully used as biomedical devices [20], while the colorimeters that measure the color characteristics of the light reflected by the skin of certain spectral intervals corresponding to the absorption regions of the main chromophores interest, and accordingly, they allow obtaining information on their quantitative content in biological tissues. However, existing instruments of this class are based on approximate models of skin tissue, expressed in rather crude quantitative estimates of the chromophores content in biological tissue. An alternative method for studying biotissues is the multispectral imaging method, based on a unique combination of spatial and spectral measurements and is widely used at present [21-25]. Different objects become visible in different spectral bands, giving the possibility to obtain the type and region of localization of the content of certain chromophores and changes in the functional structure within the biotissue. One of the advantages of optical methods for studying biological media is the possibility of obtaining information about the medium by analyzing the polarization characteristics of the radiation scattered by the medium. Here it is necessary to note measurements of the polarization of scattered light in the study of coherent backscattering, as well as studies of the effect of the particle size of the medium on the polarization of forward scattered radiation [26-29].

2. MATHEMATICAL MODEL OF THE EFFECT OF MORPHO-FUNCTIONAL CHANGES IN SURFACE DAMAGE ON THE COLOR COORDINATES

Concentrations of hemoglobin degradation products in the biotissues of surface damage depend on the time interval after their occurrence. The coordinates of the color of the surface damage depend on the concentration of the products of destruction of hemoglobin. Therefore, the coordinates of the color of the surface damage also depend on the time interval after the occurrence. In [30, 33], using the theory of radiation transfer for a multilayer model of the skin tissue of the human skin, the dependence of the color coordinates on the concentrations of hemoglobin degradation products associated with the time interval after the onset was calculated, which made it possible to determine the dependence of the color coordinates in the time interval after the appearance of lesions. In solving the inverse problem, namely, setting the time interval after occurrence based on the coordinates of the color of the surface damage, it is possible to calculate the color coordinates characteristic for each of the intervals for setting the time interval and use them to create a scale of color samples. This will, on the basis of determining the element closest in color to the surface damage from the scale of the color samples, set the time interval after its occurrence.

However, if differences in the concentration of hemoglobin degradation products are taken into account, even within one surface damage, then the image of the surface damage will always be several zones of different colors. For example, in Fig. 1. the image of a superficial injury on the background of intact skin is divided into zones of different colors $N_1 - N_4$, and the intact skin has a color N_0.

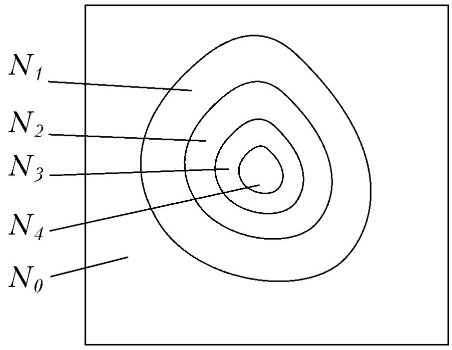

Fig. 1. Color zones of superficial damage of soft tissues as a result of trauma by a blunt object

With a change in the time interval after the occurrence of damage, zones of certain colors decrease and others increase, which will create a certain ratio between the relative sizes of these zones characteristic for a certain time range of the time interval after the occurrence of surface damages. Based on the ratio of the relative sizes of the zones of surface damage of different colors, it becomes possible to determine the interval of time after its occurrence. In order to determine the functional dependence that will allow us to set the time interval after the occurrence of damage, we will carry out a study of the coordinates of the color of the surface lesions for a group of 128 patients. In this case, the coordinates of the color of the surface damages are determined using the digital imaging method using a Nikon D3100 digital camera and also calibration based on the color coordinate measurements using an industrial colorimeter WF-32 (Shenzhen VTT Technology Co., Ltd., China). The results of measurements of the dependence of the color coordinates in the RGB coordinate system from the time interval after the appearance of the damage are shown in Fig. 2.

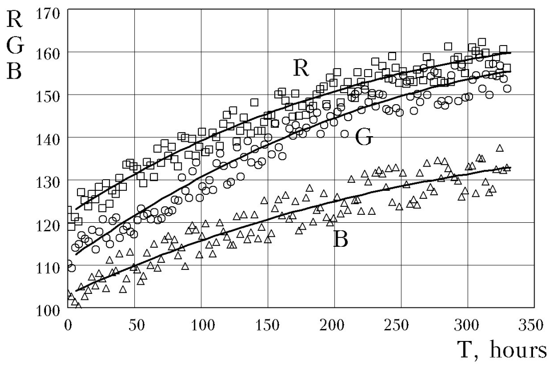

Fig. 2. Dependences of the coordinates of the color of surface damages in the RGB coordinate system from the time interval after the occurrence of damage

Using regression with the help of third-order polynomials, we determine the functional dependencies of the color coordinates in the RGB system of surface damage with the change in the time interval after the injury with a blunt object, and we obtain an empirical model:

$$\begin{cases} R = 121{,}776 + 0{,}204T - 3{,}388 \cdot 10^{-4} T^2 + 2{,}067 \cdot 10^{-7} T^3, \\ G = 111{,}042 + 0{,}224T - 3{,}073 \cdot 10^{-4} T^2 + 1{,}056 \cdot 10^{-7} T^3, \\ B = 102{,}937 + 0{,}146T - 2{,}029 \cdot 10^{-4} T^2 + 1{,}033 \cdot 10^{-7} T^3, \end{cases}$$

where R, G, B – coordinates of the color of surface damages in the RGB system; T – the time interval after the appearance of the injury by a blunt object.

The International Commission on Illumination (CIE) recommends using the LAB coordinate system to compare the color coordinates of different objects and determine the color difference. In order to change from the color coordinates in the RGB system to the color coordinates in the LAB system, you must first go to the coordinates in the XYZ system.

To change from the coordinates of the surface damage color in the RGB coordinate system to the XYZ coordinate system, it is necessary to use the formulas [31]. This takes into account the 8-bit representation of each color coordinate, which corresponds to a 24-bit total color depth of RGB images. The coefficients in the formulas are given for the case of a standard D_{65} type lighting source, a standardized illuminator/observer geometry (D/0°) and a given aperture of photodetector (10°). We calculate the coordinates of the color of the surface damages in the XYZ coordinate system, depending on the time interval after the occurrence of damage based on the color coordinates in the RGB system (Fig. 3).

Using regression with the help of third-order polynomials, we determine the functional dependencies of the color coordinates in the XYZ coordinate system of surface damage with a change in the time interval after the occurrence of trauma by a blunt object:

$$\begin{cases} X = 16{,}033 + 0{,}064T - 5{,}781 \cdot 10^{-5} T^2 - 1{,}518 \cdot 10^{-8} T^3, \\ Y = 16{,}567 + 0{,}063T - 5{,}644 \cdot 10^{-6} T^2 - 1{,}333 \cdot 10^{-7} T^3, \\ Z = 15{,}392 + 0{,}04T + 1{,}835 \cdot 10^{-5} T^2 - 1{,}057 \cdot 10^{-7} T^3, \end{cases}$$

where X, Y, Z – the coordinates of the color of surface damages in the XYZ system; T – the time interval after the occurrence of trauma by a blunt object.

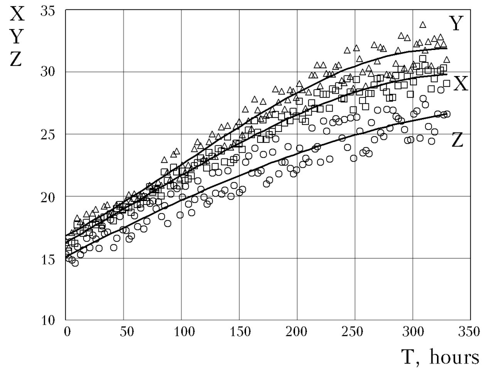

Fig. 3. Dependences of the coordinates of the color of surface damages in the XYZ coordinate system from the time interval after the occurrence of damage

Based on the color coordinates in the standard XYZ colorimetric system, it is possible to investigate the state of the skin tissue for forensic tasks. It is also possible, with the help of correction factors, to take into account the spectral characteristics of the light source, as well as the geometry of the illuminator / observer and the aperture of the photodetector.

In the color space (L^*, a^*, b^*), each color corresponds to a point whose position is determined by three independent coordinates: lightness – L^* and two chromatic coordinates – a^* and b^* associated with the X, Y, Z color coordinates. We calculate the coordinates of the color of the surface damages in the LAB coordinate system, depending on the time interval after the occurrence of damage based on the coordinates of the color of the surface damages in the XYZ system according to the formulas [31, 32] (Fig. 4).

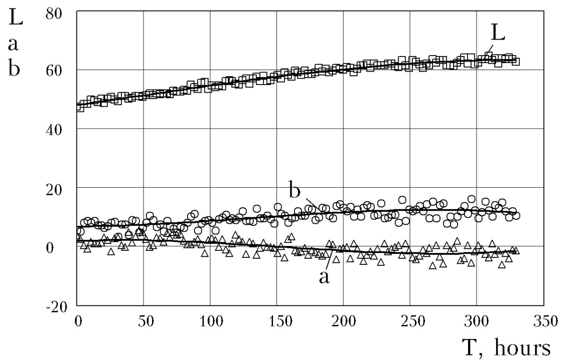

Fig. 4. Dependences of the coordinates of the color of surface damages in (L^*, a^*, b^*) coordinate system from the time interval after the occurrence of damage

Using regression with the help of third-order polynomials, we determine the functional dependencies of the color coordinates in the LAB coordinate system of surface damage with a change in the time interval after the occurrence after injury by a blunt object:

$$\begin{cases} a = -1,951 - 0,029T + 2,297 \cdot 10^{-5} T^2 + 2,295 \cdot 10^{-8} T^3, \\ b = 3,041 + 0,035T - 6,042 \cdot 10^{-5} T^2 + 2,366 \cdot 10^{-8} T^3, \\ L = 47,6 + 0,085T - 1,307 \cdot 10^{-4} T^2 + 6,513 \cdot 10^{-8} T^3, \end{cases}$$

where a, b, L – the coordinates of the color of surface damages in the LAB system; T – the time interval after the occurrence of trauma by a blunt object.

3. DETERMINATION OF THE TIME INTERVAL AFTER OCCURRENCE OF SURFACE DAMAGES BY COLOR PARAMETERS

On the basis of the obtained color coordinate dependencies in the LAB coordinate system of the pathological tissue of surface damage from the time change after injury a blunt object for the forensic medical tasks it is necessary to determine the time interval after the occurrence of superficial injuries in one of the time intervals: less than 1 hour, from 1 to 3 hours, from 3 to 6 hours, from 6 to 12 hours, from 12 to 24 hours, from 24 to 48 hours, from 48 to 72 hours, from 72 to 96 hours and more than 96 hours. Let us determine the arithmetic mean of the color coordinates in the LAB system $\overline{L}$, $\overline{a}$, $\overline{b}$ and their average deviation σ_L, σ_a, σ_b for each of the intervals of the time interval after the occurrence of surface damages. Based on the results of the calculation, it becomes possible to develop a rule for establishing the time interval after the occurrence of superficial damages of human soft tissues with blunt objects according to the color coordinates:

$$T=\begin{cases}0<T\le 1, \ \textit{if}\ (-1{,}980<a\le -1{,}951)\wedge(3{,}041<b\le 3{,}075)\wedge(47{,}600<L\le 47{,}685);\\ 1<T\le 3, \ \textit{if}\ (-2{,}037<a\le -1{,}980)\wedge(3{,}075<b\le 3{,}144)\wedge(47{,}685<L\le 47{,}855);\\ 3<T\le 6, \ \textit{if}\ (-2{,}122<a\le -2{,}037)\wedge(3{,}144<b\le 3{,}247)\wedge(47{,}855<L\le 48{,}108);\\ 6<T\le 12, \ \textit{if}\ (-2{,}292<a\le -2{,}122)\wedge(3{,}247<b\le 3{,}450)\wedge(48{,}108<L\le 48{,}606);\\ 12<T\le 24, \ \textit{if}\ (-2{,}627<a\le -2{,}292)\wedge(3{,}450<b\le 3{,}841)\wedge(48{,}606<L\le 49{,}575);\\ 24<T\le 48, \ \textit{if}\ (-3{,}275<a\le -2{,}627)\wedge(3{,}841<b\le 4{,}574)\wedge(49{,}575<L\le 51{,}404);\\ 48<T\le 72, \ \textit{if}\ (-3{,}893<a\le -3{,}275)\wedge(4{,}574<b\le 5{,}242)\wedge(51{,}404<L\le 53{,}094);\\ 72<T\le 96, \ \textit{if}\ (-4{,}478<a\le -3{,}893)\wedge(5{,}242<b\le 5{,}846)\wedge(53{,}094<L\le 54{,}650);\\ 96<T, \ \textit{if}\ (a\le -4{,}478)\wedge(5{,}846<b)\wedge(54{,}650<L).\end{cases}$$

The developed rule for establishing the time interval after occurrence of superficial damages of human soft tissues with blunt objects is based on the average characteristics of biological tissues that do not take into account the individual characteristics of recipients. In this case, the color coordinates at the boundaries of the time-slots are unclear. In fact, the rule of establishing the time interval after the occurrence of superficial damage to tissues formalizes a subjective visual method for determining the time interval after the appearance of lesions, which is used by forensic experts in their work with a scale of color samples. The time interval after the occurrence of damage is determined by the color of the element of the scale, which is closest to the color of the surface damage and is typical for a certain time interval after the occurrence. Calculate the probability density functions of the color coordinates, characteristic for each of the time intervals after the occurrence of damage using the law of normal distribution (Gaussian function). In Fig. 5 shows the probability density functions for the color coordinate L_i calculated for each of the time interval after occurrence of surface damages.

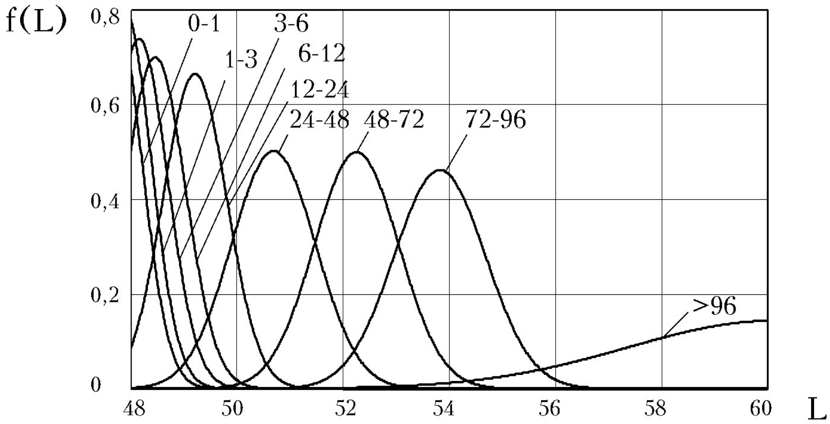

Fig. 5. Probability density functions for the color coordinate L_i of each of the time intervals after the occurrence of surface damages

However, as shown in Fig. 1, the image of surface damage has several zones of different colors. If for color segmentation of images of surface damages, use a scale of color samples with surface damage colors characteristic of the corresponding time intervals after the occurrence of damage, then taking into account the normal law of distribution of the probability density function of the color coordinates of surface damages, the dependence of the relative sizes of zones of different colors on the intervals of time after damage $f_{bruise\ i}(T)$, will also correspond to the Gaussian function. In this case, the functional dependence for establishing the time interval after the occurrence of surface damage, or in other words, the time interval after the occurrence of surface damage to the j-th interval, can be written as follows:

$$f_j(T) = \sum_{i=1}^{i\_max} \frac{k_i}{100} \cdot f_{bruise\ i}(T) = \sum_{i=1}^{i\_max} k_i \cdot a_i \cdot \exp\left(\frac{-(T-b_i)}{2 \cdot c_i^2}\right).$$

where k_i – weights for the i-th color of the color sample scale.

For each interval of the time interval after the occurrence of surface damage, the membership function corresponding to the given interval must have a maximum value determining the rule for establishing the time interval after the occurrence of surface damages:

$$T = \begin{cases} 0 < T \le 1,\ \textit{if}\ f_0(T) = \max\left(f_j(T)\right); \\ 1 < T \le 3,\ \textit{if}\ f_1(T) = \max\left(f_j(T)\right); \\ 3 < T \le 6,\ \textit{if}\ f_2(T) = \max\left(f_j(T)\right); \\ 6 < T \le 12,\ \textit{if}\ f_3(T) = \max\left(f_j(T)\right); \\ 12 < T \le 24,\ \textit{if}\ f_4(T) = \max\left(f_j(T)\right); \\ 24 < T \le 48,\ \textit{if}\ f_6(T) = \max\left(f_j(T)\right); \\ 48 < T \le 72,\ \textit{if}\ f_7(T) = \max\left(f_j(T)\right); \\ 72 < T \le 96,\ \textit{if}\ f_2(T) = \max\left(f_j(T)\right); \\ 96 < T,\ f_8(T) = \max\left(f_j(T)\right). \end{cases}$$

In this case, the time interval after the occurrence of surface damage is determined by the function of the time interval after the occurrence of damage to a certain interval, which will assume the maximum value.

5. CONCLUSION

Since the coordinates of the color of the surface damages of biological tissues associated with the concentrations of hemoglobin degradation products, which vary from the time interval after the occurrence of surface damage, it becomes possible to determine the dependence of the color coordinates of the surface damage on the time interval after the occurrence of surface damages. For this purpose, using the CIE recommendations and using a standard light source D_{65}, the coordinates of the color of the surface damages of the tissues in the RGB, XYZ and LAB systems are calculated, depending on the time interval after the occurrence of damage. The proposed approach for the diagnosis of pathological skin tissue in forensic medical examination can be used in other areas of biomedical diagnostics, in particular, in the diagnosis of oncological tumors [34–36].

With the use of regression, the functional dependencies of the color coordinates of the surface damage of the biotissue in the LAB system were calculated from the time interval after the appearance of the lesions, and the inverse problem of finding the dependence of the time interval after the appearance of damage on the color coordinates was solved. In this case, the rules for establishing the time interval after the occurrence of damage are compiled on the basis of the color coordinates in the LAB system that are characteristic for the given interval. The developed rules for determining the time interval after the occurrence of damage is the basis for improving the method for establishing the time interval after the occurrence of damage and developing the appropriate hardware [37, 38] and software with using fuzzy logic or a neural network to support the adoption of a diagnostic solution [39, 40].

REFERENCES

[1] Khlebtsov N. G., Maksimova I. L., Tuchin V. V. et al. Introduction to light scattering by biological objects. Handbook of optical biomedical diagnostics. ed.: V.V. Tuchin. – Bellingham, WA: SPIE Press, 2002. – p. 31–167.

[2] Van Gemert M. J. C., Acques S. L., Sterenborg H. J. C. M., Star W. M. Skin optics. *IEEE Trans. Biomed. Eng.*, **36(12)**, 1146–1154 (1989).

[3] Bashkatov A. N. et al. Optical properties of human skin, subcutaneous and mucous tissues in the wavelength range from 400 to 2000nm. *J. Phys. D: Appl. Phys.*, **38**, 2543–2555 (2005).

[4] Yudovsky D., Pilon L. Retrieving skin properties from in vivo spectral reflectance measurements. *J. Biophotonics*., **4(5)**, 305–314 (2011).

[5] Johns M., Giller C. A., Liu H. Determination of hemoglobin oxygen saturation from turbid media using reflectance spectroscopy with small source-detector separation. *Appl. Spectroscopy*., **55(12)**, 1686–1694 (2001).

[6] Bargo P. R. et al. In vivo determination of optical properties of normal and tumor tissue with white light reflectance and an empirical light transport model during endoscopy. *J. Biomed. Opt*., **10(3)**, 034018-1–15 (2005).

[7] Pacholczyk B., Fabiańska A., Kusińska R. et al. Analysis of cancer tissues by means of spectroscopic methods. *Contemp. Oncol. (Pozn).*, **16 (4)**, 290–294 (2012).

[8] Odland G. F. Structure of the Skin in: Goldsmith LA. (Ed.), Physiology, Biochemistry and Molecular Biology of the Skin, Oxford University Press, Oxford, 3–62 (1991).

[9] Kenet R. D. Digital imaging in dermatology. *Clinics in Dermatology*, **13(4)**, 381–392 (1995).

[10] Khomyakov M. U. Skin detection on color images. *Computer optics*, **35(3)**, 373–379 (2011).

[11] Miyake Y., Tsumura N., Takeya M., Inagawa R. Applications of color image processing based on spectral information [Electronic resource] Document Identification Number: DIN01022805. Digital Color Imaging in Biomedicine, 15–32, 2001.02.28. URL: http://biocolor.umin.ac.jp/book200102/din01022805.pdf.

[12] Grossman S. E., Johnston A., Vanezis P., Perrett D. Can we assess the age of bruises? An attempt to develop an objective technique. *Medicine, Science and the Law*, **51**, 170–176 (2011).

[13] De Lasarte M., Vilaseca M., Pujol J. et al. Development of a perceptual colorimeter based on a conventional CCD camera with more than three color channels. *Proceedings of the 10th Congress of the International Colour Association (AIC'05)*, 1247–1250 (2005).

[14] Boher P., Leroux T., Collomb-Patton V. et al. New Imaging Optics for video-colorimetry. Proceedings of the IMID 2013 DIGEST, 1185 (2013).

[15] Nakano K., Aoki Y., Satoh R. et al. Non-contact measurement of pulse wave velocity using RGB cameras. *Proc. SPIE*, **9715**, 971515 (2016).

[16] Palacios-Ortega N., Prieto D. V. Evaluation between methods for the color measurement in holograms by using a CMOS-RGB camera and a spectrometer. *Proc. SPIE*, **8785**, 878568 (2013).

[17] Balsamo A., Chimienti A., Grattioni P. et al. An Active Vision System for 3D Surface Color Measurements. *Proc. ISCC/CIE Exp. Symp.*, 67–72 (2006).

[18] Boher P., Leroux T., Collomb Patton V. et al. Color accuracy of an imaging system using color filters. *Journal of Information Display*, **13(1)**, 7–16 (2012).

[19] Tien W.-H., Kartes P., Yamasaki T. et al. A color-coded backlighted defocusing digital particle image velocimetry system. *Experiments in Fluids*, **44(6),** 1015–1026 (2008).

[20] Duteil L., Ortonne J. P. Colorimetric assessment of the effects of azelaic acid on light-induced skin pigmentation. *Photodermatol. Photoimmunol Photomed.,* **9 (2)**, 67–71 (1992).

[21] Wessman C. A., Aber J. D., Peterson D. L. et al. Remote sensing of canopy chemistry and nitrogen cycling in temperate forest ecosystems. *Nature*, **335(6186)**, 154–156 (1988).

[22] Hardeberg J. Y., Schmitt F., Brettel H. Multispectral color image capture using a liquid crystal tunable filter. *Opt. Eng.* **41(10)**, 2532–2548 (2002).

[23] Huang W., Zhang B., Li J. et al. Early detection of bruises on apples using near-infrared hyperspectral image. *Proc. SPIE*, **8761**, 87610P (2013).

[24] Huang W., Zhao C., Wang Q. et al. Development of a multi-spectral imaging system for the detection of bruises on apples. *Proc. SPIE*. **8721**, 872105 (2013).

[25] Kabakeris T., Intreß J., Geyer M. et. al. Detection of postharvest quality loss in broccoli by means of non-colorimetric reflection spectroscopy and hyperspectral imaging. Computers and Electronics in Agriculture, **118**, 322-331 (2015).

[26] Keane P.A., Patel P.J., Liakopoulos S. et al. Evaluation of age-related macular degeneration with optical coherence tomography. *Survey of ophthalmology*, **5 (57)**, 389-414 (2012).

[27] Ahlers C., Götzinger E., Pircher M. et al. Imaging of the retinal pigment epithelium in age-related macular degeneration using polarization sensitive optical coherence tomography. *Invest. Ophthalmol. Vis. Sci*., **51**, 2149-2157 (2010).

[28] Kang H., Darling C.L., Fried D. et al. Nondestructive monitoring of the repair of enamel artificial lesions by an acidic remineralization model using polarization-sensitive optical coherence tomography. *Dental Mat.*, **28(5)**, 488–494 (2012).

[29] Baumann B., Götzinger E., Pircher M. et al. Segmentation and quantification of retinal lesions in agerelated macular degeneration using polarization-sensitive optical coherence tomography. *J. Biomed. Opt*. **15(6)**, 61704 (2010).

[30] Petruk V. G., Kvaternyuk S. M., Kvaternyuk O.E. et al. Method for determining the color coordinates of normal and pathological tissues. *Visnyk of Vinnytsia Politechnical Institute*, **4**, 25–30 (2015).

[31] Useful Color Equations. – http://www.brucelindbloom.com/index.html?Equations.html.

[32] ISO 7724-1: 1984 Paints and varnishes – Colorimetry – Part 1: Principals. Committee: ISO/TC 35/SC 9, Edition: 1, Publication date: 1984-09-01. – 12 p.

[33] Pteruk V., Mokanyuk O., Kvaternyuk O. et al. Changes of color coordinates of biological tissue with superficial skin damage due to mechanical trauma. *Proc. SPIE*, **9816**, 98161I (2015).

[34] Petruk V.G., Kvaternyuk S.M., Bolyuh D.B. et al. Research of the spectral diffuse reflectance of melanoma in vivo. *Proc. SPIE*, **8698**, 86980F (2012).

[35] Petruk V. G., Ivanov A. P., Kvaternyuk S. M., Barun V. V. Spectrophotometric Method for Differentiation of Human Skin Melanoma. II. Diagnostic Characteristics. *Journal of Applied Spectroscopy*, **83(2)**, 261–270 (2016).

[36] Petruk V. G., Ivanov A. P., Kvaternyuk S. M., Barun V. V. Spectrophotometric Method for Differentiation of Human Skin Melanoma. I. Optical Diffuse Reflection Coefficient. *Journal of Applied Spectroscopy*, **83(1)**, 85–92 (2016).

[37] Petruk V., Kvaternyuk O., Kvaternyuk S. et al. Methods and means of measuring control and diagnostics of biological tissues in vivo based on measurements of color coordinates and multispectral image. *Proc. SPIE*, **9816**, 98161H (2015).

[38] Petruk V., Kvaternyuk S., Kvaternyuk O. et al. Multispectral method and means for determining the distance of the shot on the basis of the study of gunshot injuries of the skin tissues. *Przeglad elektrotechniczny*, **93(3)**, 129–132 (2017).

[39] Petruk V., Kvaternyuk S., Kvaternyuk O. et al. Assessment of the validity of the diagnosis of damage of tissues by multispectral method using neural network. *Przeglad elektrotechniczny*, **93(5)**, 106-109 (2017).

[40] Rotshtein A., Shtovba S., Chernovolik G., Petruk V. Processing of optical information for medical decision making support systems by intelligent techniques. *Proc. SPIE*, **4425** (2001).