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Modeling and measurements of light transmission through human tissues

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Abstract. The paper presents selected results of studies connected with modeling of a biological object which could be used for simulation and measurements of the selected human tissues optical transmittance. The studies were performed for transilluminated homogeneous tissue layers as well as for objects consisted of different tissues. During simulations the software built with LabVIEW environment was used. Experimental verification of the model structure was made with spectrophotometry. The presented examples of modeling concern the transmittance spectra for two selected specific objects: the venous blood and muscle tissue analyzed in the wavelength range extending from 360 nm to 900 nm. The implemented model could be used in estimating the content and thickness of particular layers distinguished in a complex object and prediction of their transillumination efficiency.

Key words: biooptics, transillumination, light-tissue interaction, spectrophotometric measurements.

1. Introduction

Measurable effects of interaction between light and tissues may be utilized in biomedicine with emission, reflection or transmission mode, respectively. The latter is considered in the paper with focus on problems connected with measurements based on the analysis of influence of changes in optical pathway components on efficiency of light transmission through a slab of tissues. Transillumination is understood as the phenomenon of transmitting optical radiation with defined parameters by an object, which becomes the carrier of information on the characteristic size of the object [1–6]. In case of biological objects the optical properties of systemic liquids and other tissues are utilized. Transillumination as the method of examination by the passage of light through tissues or a body cavity is a diagnostic technique in the course of intensive development at the moment. It concentrates on development of effective transillumination of thick layers of tissues and on building efficient and stable algorithms representing and anatomic and functional properties. Numerous issues related to the measurement result interpretation still remain unsolved.

The most common example of transillumination is the observation of arterial blood pulsation allowing for measuring the blood pulse and blood oxygenation [7–10]. Pulse oximetry smartly joins rules of both in vivo spectrophotometry and photoplethysmography to monitor the arterial blood oxygen saturation. In 1985 Nellcor-100 was created in the USA – a model that became the synonym of the term pulse oximeter introduced at that time. The-state-of-the-art, taken here into account as the background, refers to the reported optical parameters of tissues when exposed to light of wavelengths included in the optical window in tissue spectrum [11–17]. Previous own authors' experience in one-dimensional modeling for transmission pulse oximetry [6, 17] has been adapted.

The transmission variant of light-tissue interaction is often more convenient and sensitive than the reflection variant. The finger-tips are the especially useful sites to place the optoelectronic sensors which are applied directly and very often in prolonged duration. The thickness of the object varies with each pulse, changing the light path length which effects are eliminated in estimating the oxygen saturation. Also, the input light intensity is negligible as a variable during measurements. However, there are always some artifacts, noises and interferences that can cause changes in the object parameters. The structure of a specialized algorithm, which has been proposed, makes possible creating a lot of free variants of reference standards, including changes in a number of layers and their biophysical compositions. Simulation of different changes in tissue composition allows predicting output results of occurring interactions.

The major aim of the work is to design such a model, which would sufficiently take into account the features and nature of biological objects. It would enable the reliable simulation of processes which could be a good alternative for time-consuming and very expensive physical phantoms. The application of the presented model may be helpful in evaluation of the content and thickness of particular layers and the transmittance factors carried by them to the resultant object transmittance. On the background of data reported in literature, the authors describe results collected by them during simulation and experimental spectrophotometric studies. This paper is organized as follows. In Section 2, the attributes of the model structure are presented. In Section 3, results of spectrophotometric measurements which were made on biological material taken from selected human tissues are discussed.

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Considering the measuring wavelength range, transmissions spectra of the samples of selected tissues were investigated.

2. The model structure

When biological object is exposed to selective transillumination, we can receive the selective optical response to particular wavelengths. This response includes information about optical parameters of the medium, however, other physical parameters of a given object also influence its output signal. The surface conditions, internal structure and size in the direction of transillumination are of great importance. The obtained information about optical properties for the defined wavelength is included in the object response as a resultant value of the intensity transmittance depending on different elements of the object structure. Real sets of biological tissues create inhomogeneous and irregular forms which may be substituted by virtual models based on an appropriate algorithm. In this paper the model of the object designed for tissue transillumination studies is presented. The model was used for transmittance simulation of selected tissues. Simulations were performed for the homogeneous object samples as well as samples consisted of different tissues. Presented algorithm enables to include any components into the model which can represent participation of significant or minor phenomena. It is possible to create virtual models and search for extreme interactions' effects as well as to evaluate efficiency of practical measurements. Experimental verification of this model was performed for the wavelength 660 nm and selected results are presented.

From the measurement point of view, especially convenient for effective transillumination are fingers, they are widely used in e.g. the objects in the transmission variants of pulse oximetry and photopletysmography [4, 7–10]. Of course like other human body parts the structure of fingers is also complex and there is heterogeneity in volume. The examples of finger cross-sections shown in Fig. 1 illustrate biophysical changes along a finger length.

The complicated object to be transilluminated may be virtually "reproduced" with the designed model based on the "sandwich" structure. This representation is performed with the division of a given object by virtual planes placed perpendicularly to transillumination direction (Fig. 2).

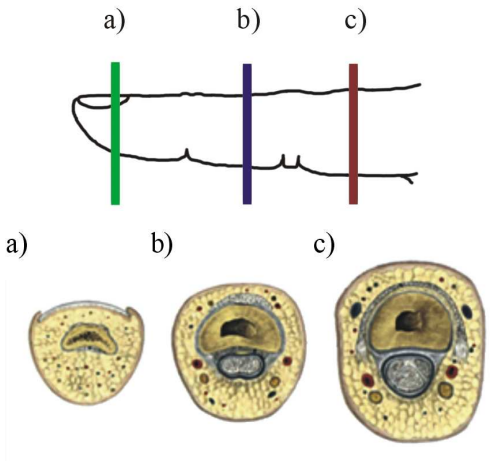


Fig. 1. Human finger cross-sections

One can receive in this case the object's layers of the thickness determined in the initial stage of model adaptation. The thickness of layers in assumed direction is described by x_n. Layers are made either by homogeneous tissues or several different tissues. Assuming respectively small x_n value, the modeled object could be divided into thin homogeneous layers made by the same kind of tissue such as: skin, muscle, bone, arterial and venous blood, blood vessels, fat and the set of tissues described as others [19]. Figures 3 and 4 present the example of the biological object division with planes in one direction and two directions respectively (see Fig. 1c). One by one, in following steps of plane division (i.e. steps of scanning), the sets of layers and corresponding optical parameters are obtained.

Taking into account the 3-D approach to the object modeling, it was assumed that the smallest component in the object structure is a single cube ($x = y = z$). Thus all layers were divided into numerous elementary cubes. Because investigation of such object transmission effects is very time-consuming, several applications supporting the modeling and estimation of effective transmittance have been prepared.

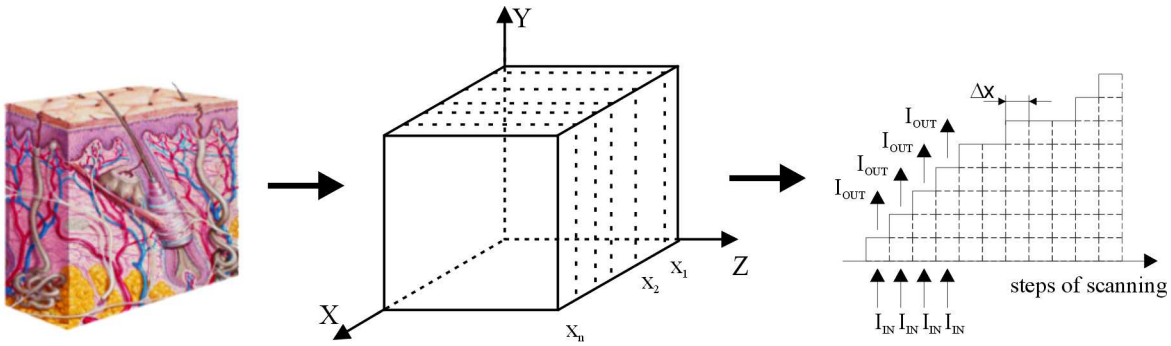


Fig. 2. General scheme of the model of biological object to be transilluminated with scanning steps in a given direction

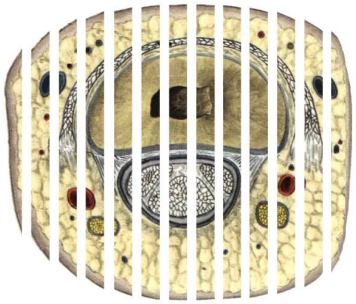


Fig. 3. Cross-section of the object by virtual planes in one direction x

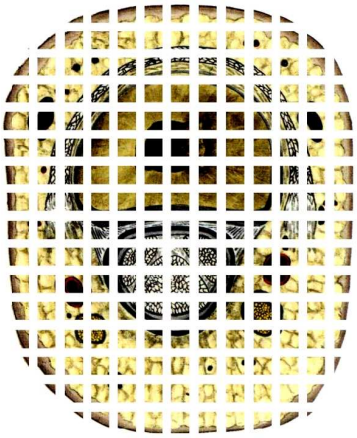


Fig. 4. Cross-section of the object by virtual planes in two directions x and y, respectively

Tissue cells content and optical parameters corresponding to selective light absorption and scattering contribute to light propagation through a set of cubes in whole object composition. The transmission of optical radiation through the absorbing and scattering object is determined by the values of two resultant quantities: the optical density (OD) and transmittance (T). For the optically linear object of thickness x, the total optical density is the sum of the absorbances A and scattering components OD_s of the total optical density, whereas the resultant transmittance is the product of factors T_a and T_s connected with the absorbing and scattering components of different layers, respectively. These relations are expressed generally in Eqs. 1 and 2.

$$OD = \sum_{j=1}^{k} A_j + \sum_{i=1}^{n} OD_{s_i} \tag{1}$$

$$T = \prod_{j=1}^{k} T_{a_j} \cdot \prod_{i=1}^{n} T_{s_i} \tag{2}$$

As was shown in Fig. 5, absorbing layers x_k and scattering layers x_n have been distinguished in the object and the related optical features are described by formulas (3) and (4).

$$OD = \sum_{j=1}^{k} a_j \cdot x_j + \sum_{i=1}^{n} s_i \cdot x_i \tag{3}$$

$$T = \prod_{j=1}^{k} 10^{-a_j \cdot x_j} \cdot \prod_{i=1}^{n} 10^{-s_i \cdot x_i} \tag{4}$$

where: a – absorption coefficient, s – scattering coefficient.

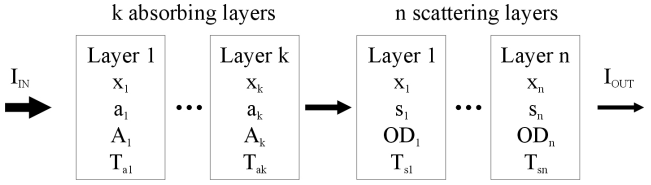


Fig. 5. Illustration of light transmission through the object consisting of absorbing and scattering layers

Finally the resultant optical density of the object of the thickness x, consisting of k absorbing layers and n scattering layers $\left(x = \sum_{j=1}^{k} x_j + \sum_{i=1}^{n} x_i\right)$ can be given as:

$$OD = \lg \frac{1}{\prod_{j=1}^{k} 10^{-a_j \cdot x_j} \cdot \prod_{i=1}^{n} 10^{-s_i \cdot x_i}}. \tag{5}$$

Estimating the effective values of parameters describing the absorption and scattering of a given object needs to consider some additional properties. There are several sources of optical heterogeneity of biological objects, including the anisotropy coefficient g. In the considered transmission variant of light-tissue interaction $0 \leq g \leq 1$ [11–15, 18]. The particular layers of the object may be generally described by components of the effective optical density OD_{ef} (Eq. 6) and factors of the effective transmittance T_{ef} (Eq. 7). The effective values of $OD_{s_{ef}}$ and $T_{s_{es}}$ will depend on the thickness x and coefficients s and g.

$$OD_{ef} = OD_a + OD_{s_{ef}}(x, s, g) \tag{6}$$

$$T_{ef} = T_a \cdot T_{s_{ef}}(x, s, g) \tag{7}$$

In process of modeling a human muscle tissue of 2 mm in thickness has been simplified to a model consisting of three components: the pure muscle layer, the blood vessel layer, and venous blood layer. It was assumed that the object thickness is constant while a given tissue content may change from 0% to 100%. According to such assumption, only a part of modeling results could arise in a real case. Figures 6–9 illustrate the process of modeling of particular tissues content in a complex object that was divided into 100 slices. We have considered 5151 configurations of the object. Figure 6 presents results of modeling of a given tissue content in a 3-layer object containing venous blood, blood vessels and muscle layers.

At each step of scanning a set of other thickness of particular layers is considered and the transmittance is determined. Any change in the object content reflects in transmittance changes at the successive steps of scanning (Fig. 7).

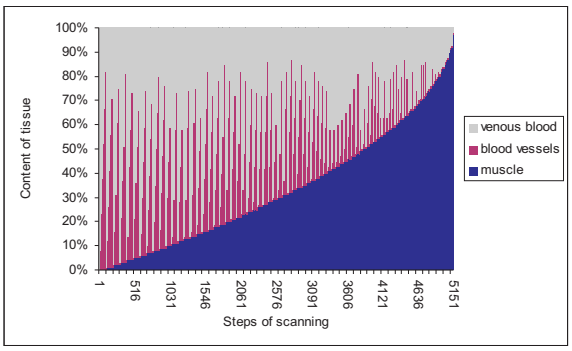


Fig. 6. Results of modeling of a given tissue content in a 3-layer object containing venous blood, blood vessels and muscle layers; the total object thickness is 2 mm

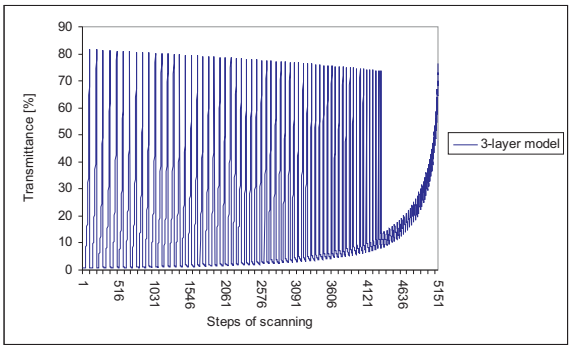


Fig. 7. Results of transmittance modeling for a 3-layer object containing venous blood, blood vessels and muscle layers; the total object thickness is 2 mm

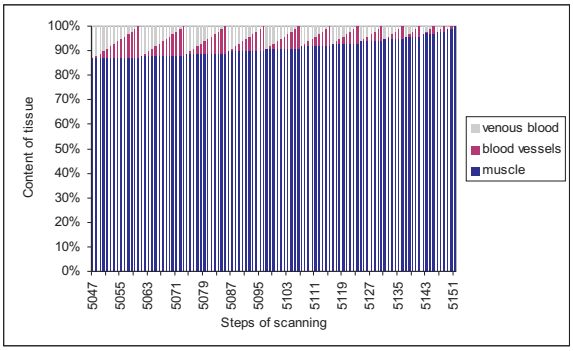


Fig. 8. Variants of the object structure evaluated in a selected stage of modeling

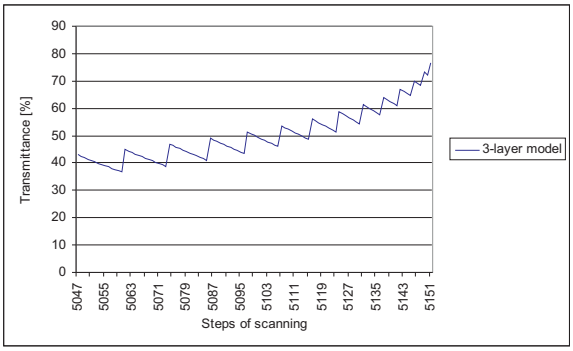


Fig. 9. Results of transmittance modeling for the predicted 105 variants of an object structure shown in Fig. 8

The evaluated content of 2 mm tissue components is as follows: the muscle tissue 1.75 mm while the blood and blood vessels 0.25 mm. This tissue set is reflected in the 3-layer object transmittance. If to limit the simulation results to the given range, we obtain ca. 105 variants of structure where the muscle content may alter between 1.75 mm to 2 mm. The latter means the "pure" muscle cells. The results concerning this simulation are presented in Fig. 8 and 9. The selected variants of the object structure correspond to the scanning steps from 5047 to 5151.

In Section 3 results of spectrophotometric measurements of the object transmittance are related to results of modeling.

3. Results of spectrophotometric measurements

To verify the designed object's model the measuring experiments on biological material taken from selected human tissues were performed. It was necessary to receive before an appropriate permission from the competent Bioethical Commission. The project of examinations was approved by the Bioethics Committee at the Poznan University of Medical Sciences, Poland. Biological material was taken by the medical specialists at this University: all tissue samples were collected from a dissected human corpse and initially prepared by the physician staff at the Division of Histopathology, Chair of Forensic Medicine. All samples were measured within few hours after a moment of sample taking. After measurements, whole biological material was transported back to the Division of Histopathology where was utilized in accordance with the law.

In vitro spectrophotometric experiments on the samples were made in the Laboratory of Optics at the Chair of Optical Spectroscopy, Faculty of Technical Physics, Poznan University of Technology, Poland. The Cary 400 spectrophotometer of high performance [20] was used in series of measurements (Fig. 10). The Cary series is certified to comply with the requirements of the EMC and LV directives of the EU.

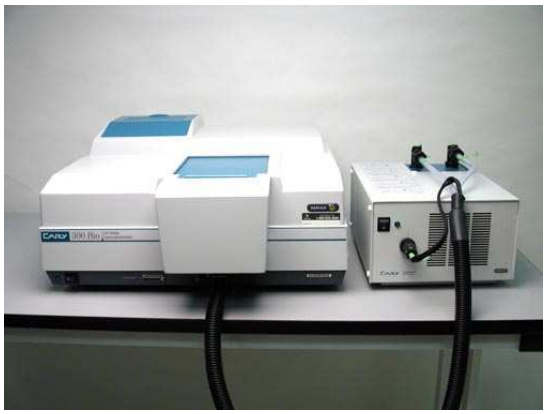
The Cary 400 is a research-grade instrument that represents the top-of-the line UV-VIS-NIR spectrophotometers. In its double beam design, the energy of the light source is divided into two so that one passes through the reference cell, and the other through the sample cell. The wavelength drive can change wavelengths at 16 000 nm/min in the UV-VIS and at 64 000 nm/min in the NIR. The sample compartment windows prevent back-reflection and thus incorrect results. The out-of-plane design of the monochromator reduces photometric noise and stray light, and produces very high resolution. The spectrophotometer is specified to measure up to 7 Abs with reference beam attenuation.

The light detector converts the arrival of not absorbed photons into an electrical signal. The optical design of the spectrophotometer ensures photometric stability, i.e. any absorbance change is due to the sample, not to drift in the instrument.

The measuring set was equipped with the professional software WinUV which has a modular design. All of the controls are contained within one window so they are easy

to find. By separating the software into modules specific for each application the level of complexity of each module is reduced. The users can control how the graphics look – from selecting the axes width to adding labels and pictures. The spectrum characteristics of the used glass accessories have been tested for the wavelengths 360 to 900 nm. The lowest value of this range was limited by violent increase of radiation absorption observed in used sodium glass. The upper value of the wavelength range depended on a measuring range of the spectrophotometer.

a)



b)

c)

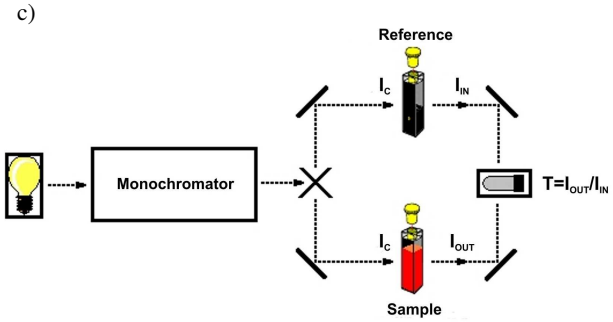


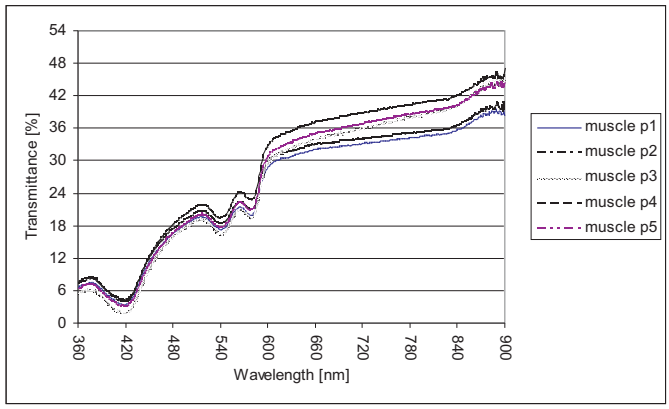
Fig. 10. Two views of the Varian Carry spectrophotometer (a) and (b), and a scheme illustrating its double-beam design (c) after Ref. 20

Considering the measuring wavelength range, transmissions spectra of the samples of selected tissues were investigated. A characteristic property of the real tissue is its heterogeneity and the differences in structure are followed by differences in the radiation transmission through a given sample. For example, investigating a real tissue sample assumed as "muscle tissue", a set that contains also remains of organic liquids and other tissues, is in fact the subject of measurements.

The analysis of obtained results has been made. Figure 11 presents the selected values obtained during measurements made on the muscle (Fig. 11a) and venous blood (Fig. 11b) samples.

Figure 11 presents two sets of experimental characteristics obtained for a given tissue at the changes in its position in relation to the measuring light flux. The results from measurements were compared with the transmittance values estimated with the software designed using the LabVIEW environment [21, 22]. Simulations were performed for 660 nm. This wavelength was taken as especially useful in sensing changes in the object structure because of a large difference in the extinction coefficients in the red region [7, 8].

a)



b)

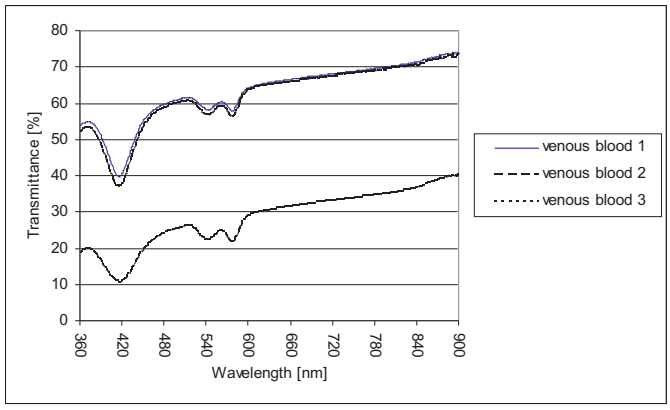


Fig. 11. Transmittance spectrum for muscle (a) and venous blood (b) evaluated at the wavelengths in the range 360 nm to 900 nm

The model is designed for a structure consisting of 1 to 8 tissues. The program makes possible modeling of: tissue content in the object, tissue transmittance for the object layers, and the resultant object transmittance. Figures 12–14 show three examples of the screenshots for the panels: Parameters of layers, Plot of transmittances, and Configuration of results.

Figure 12 presents the panel Parameters of layers in which: $Ft + Fw$ is the fraction of tissue and water, respectively, for the considered object model, Fw/Ft is relative water content in tissue, a, s, g mean selective values of the optical parameters for tissues while aw is the absorption coefficient for water at the wavelength 660 nm.

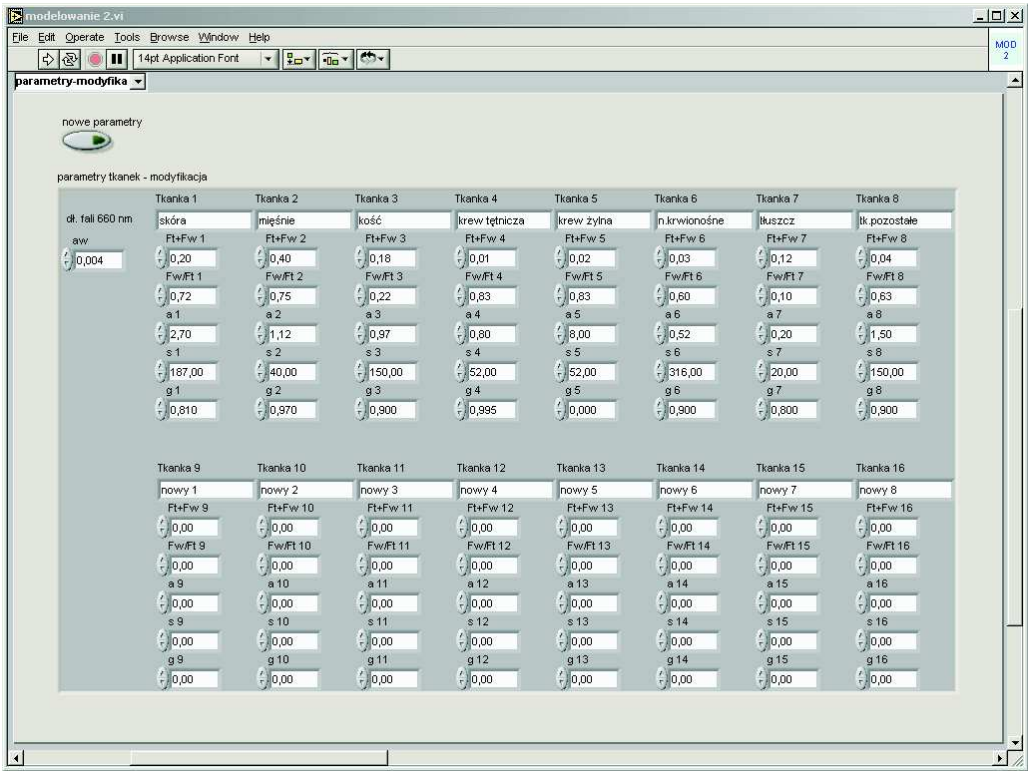


Fig. 12. Panel Parameters of layers

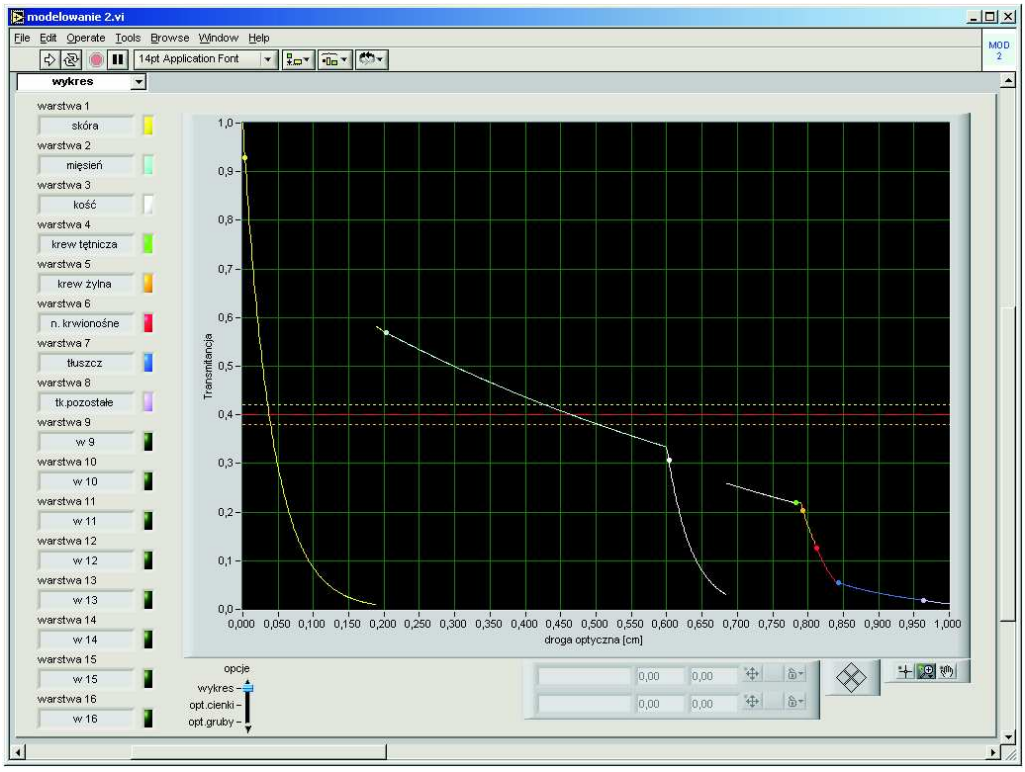


Fig. 13. Panel Plot of transmittances

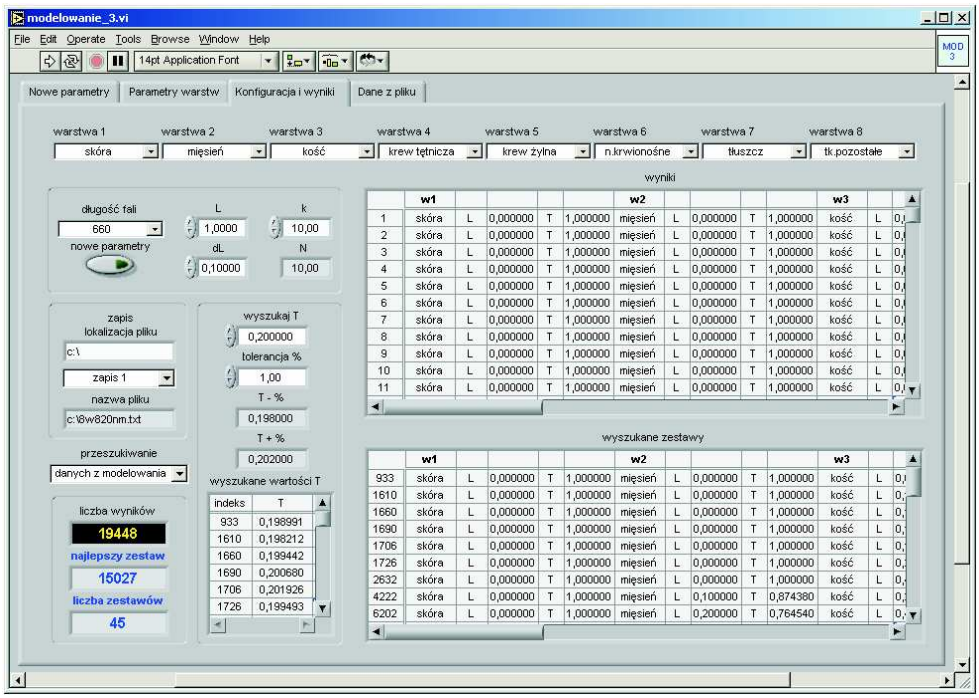


Fig. 14. Panel Configuration and results

We have considered 5151 configurations of the object which was divided into 100 slices. The transmittance differences observed could be caused by utilization of the average values of the optical parameters, changes in sample thickness and inaccuracy of measurement method. The average percentage transmittance obtained from the measurements made on the muscle tissue at the wavelength 660 nm equals approximately 33%. The 37% transmittance is the most close value from modeling for a 3-layer object reduced to 2-layer object when there is a lack of blood vessels. However, this variant had to be not considered for the reason that the muscle tissue is very rich in capillary vessels. The transmittance evaluated for the next tissue set of proper content proportions was 40%. Comparing the transmittance values obtained from measurements and simulation, the relative error equals 16%.

One of important purposes of presented simulation is evaluating the thickness of tissue at which discontinuity has to appear in the intensity transmittance versus this thickness. The point of transmittance discontinuity indicates a change in optical properties of a calculated layer, determining the intervals where a given transilluminated component of a tissue slab may be treated as optically thin or thick. The presented results may be useful in computer-aided generation of reference data for evaluation of light-tissue spatial transillumination.

4. Conclusions

Among the applied methods of tissue parameters measurement, a tendency to develop methods based on detection and analysis of natural and forced biooptical phenomena is significant. Under the noninvasive transillumination and illumination from underneath, it is possible to diagnose and monitor the parameters of tissues and organs examined. In the transmission variant of the light-object interaction the objective information on the quantity measured is obtained by means of optoelectronic sensor containing a source of the radiation penetrating the object and receiver of the radiation transmitted through. Representative examples of such examinations are e.g. detection of systemic fluids components (spectrophotometry, oximetry in vivo), localization by means of transillumination or illumination of veins, cysts, and neoplasms from underneath, transillumination with white light (instead of X-raying), imaging and monitoring of pulse wave (photoplethysmography), transmission variant of pulse oximetry. Simulation of different changes in tissue composition allows predicting results of occurring interactions in the considered transmission variant of light-tissue interaction. The structure of a specialized program which has been proposed makes possible creating a lot of free variants of object model, including changes in a number of layers and their biophysical structure. Currently the work on a program for improving modeling the transmittance of objects consisting of different tissue, which thickness into direction of light propagation can be changed, is in progress. Basing on preliminary results obtained which are promising, the long-terms plans of studies are connected with the expected possibility to identify several changes in features of biological objects exposed to selective transmission in the range of wavelength including visible and near infrared radiation. Modeling of effects of light-living tissues interaction may be useful in:

- improving methods of investigation of real objects in real conditions,
- performing virtual measurements, taking into account simulation of different probable situations, including pathological tissue compositions,

- increasing standardization effectiveness by developing non-living, substitute standards to calibrate pulse oximeters at extremely low levels of oxygen content, design of the virtual computer-assisted objects for simulation of real living compositions, and design of artificial objects offered as models of multi-component layers of real tissues, e.g., finger phantoms.

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