Monte Carlo modeling of eye iris color

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ABSTRACT

Based on the presented two-layer eye iris model, the iris diffuse reflectance has been calculated by Monte Carlo technique in the spectral range 400-800 nm. The diffuse reflectance spectra have been recalculated in *L*a*b** color coordinate system. Obtained results demonstrated that the iris color coordinates (*hue* and *chroma*) can be used for estimation of melanin content in the range of small melanin concentrations, i.e. for estimation of melanin content in blue and green eyes.

Keywords: iris, melanin content, glaucoma, Monte Carlo technique, digital image analysis

1. INTRODUCTION

Knowledge of tissue optical properties is important for development of theoretical models describing the light propagation within tissues (including a human eye iris). These models can be used when designing laser therapy and diagnostic techniques or interpretation of the data of spectrophotometric measurements. There are numerous papers describing the methods of determining optical properties of many types of tissues.[1]

Recently some diagnostic criteria of dystrophic, degenerative and inflammatory diseases of an eye iris have been based on descriptive, relative and, in many respects, subjective criteria to which the discoloration of an iris of the eye is also refered.[2-7] Now the eye iris classification is based on the data of iridochromoscopy, iridochromophotography, and biomicroscopy in polarized light.[2-8] Objective criteria of inflammatory and degenerative changes can be obtained from the data of the fluorescent angiography. Unfortunately, the method is invasive and cannot be applied to all patients.

For definition of chromatic characteristics human tissues the method of colorimetry is widely used. It is based on the analysis of spectral composition of diffusely reflected light. This method has found wide application in biology and medicine. Chromophores contained in the human tissues change a spectral distribution of diffusely reflected white light and consequently change the tissue color. Thus, connection between concentration of tissue chromophores and the tissue color parameters is very interesting. Development of the digital visualization techniques allowing to obtain object color images with the high spatial resolution, enables to visualize its pigmental composition and the pigment spatial distribution by computer processing of the objects image.

2. STRUCTURE AND PROPERTIES OF THE HUMAN EYE IRIS

Fig. 1 shows the transverse (horizontal) section of an eyeball. The eye iris is forefront of choroid of the eye. The iris has the form of a plate with slightly elliptical shape. Peripheral edge of the iris (its root) is merged with the ciliary body and the trabecular meshwork. The iris is 12-12.5 mm in diameter with a circumference of 36-37 mm.[4,9,10] The forefront surface of the iris can be divided into two zones: the pupil zone (1-2 mm wide) and the ciliary zone (3-4 mm wide). The separation line corresponds to plexus of small arteries, which form small arterial iris circle. The distance between the

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separation line and edge of eye pupil is about 1.5 mm.[9] Iris thickness is not everywhere equal. The thickness has maximal value (up to 480-550 μm) in the area of the small arterial circle, and minimal value was observed in ciliary zone - up to 350 μm.[11] Eye pupil has also very different size. For children the pupil diameter is minimal (up to 2 mm), in the young age the pupil diameter is maximal (about 4 mm), and in the old age the pupil diameter decreases again.

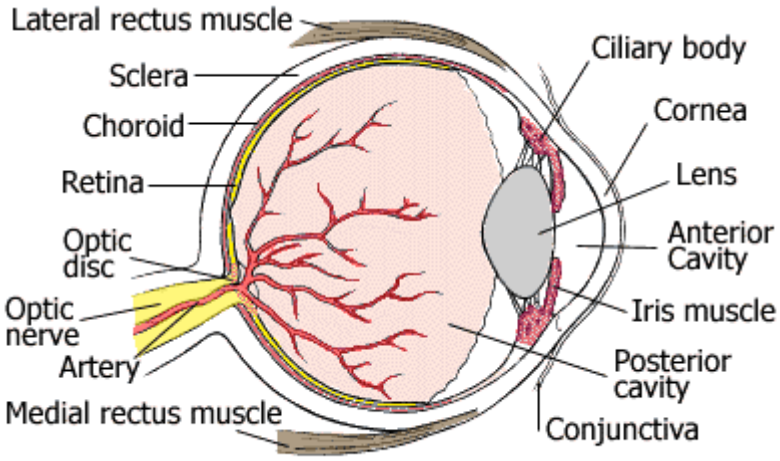


Fig. 1. The transverse (horizontal) section of eyeball

Structurally, the iris contains two different layers. The iris thin innermost layer is called the iris pigment epithelium (IPE) and consists of a compact array of opaque cells. The outermost layer refers to the iris stroma, which contains more loosely arranged cells including melanocytes that synthesize the pigment.[4-6,12,13] The iris structure is illustrated in figure 2. According to electronic microscopy, basic cellular elements of the stoma layer are fibroblasts, melanocytes and a network of collagen fibrils.[4-6,12] Diameter of collagen fibrils in iris stroma is 60 nm and its axial periodicity is 50-60 nm.[5] Size of the iris melanocytes is about 100 μm and the cells are filled with very small melanin particles.[5,11-13] Structurally, the stroma can be subdivided in two sublayers: the mesodermal upper and deep sublayers. In the upper sublayer of stroma (in ciliary zone) melanocyte conglomerations form the pigmentary spots, so-called nevuses.[4-6,12]

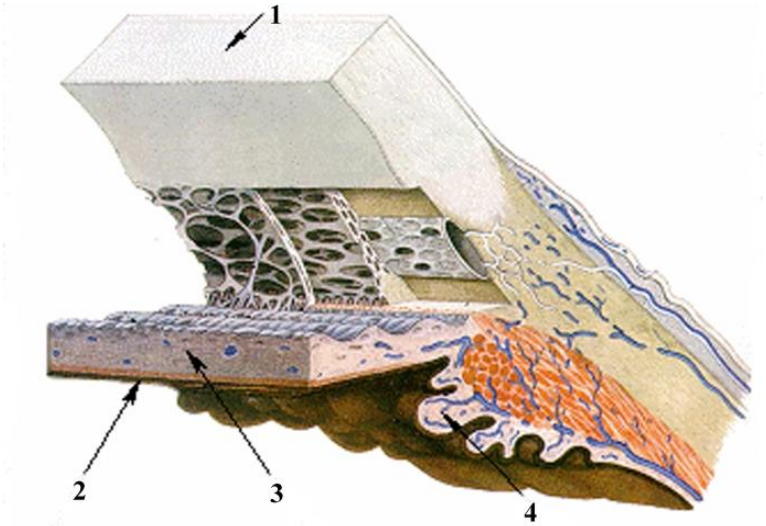


Fig. 2. The eye iris structure: 1 - the cornea; 2 - the iris pigment epithelium (IPE); 3 - the iris stroma; 4 - the ciliary body

Iris vessels are localized within the iris stroma. The vessels include large vessels (arterioles and venules) and capillaries.[6] In the depth of the iris stroma, near the iris root (in area of the eye trabecular meshwork), iris arteries and venues form

large arterial circle of the iris. From this circle, radial vessels with a diameter smaller than the diameter of the vessels of the large arterial circle go to the eye pupil.[9] Size of the large iris vessels (arterioles) is 50-100 μm. Precapillaries have diameter 14-16 μm, and capillaries - 3-12 μm. Diameter of venules is 12-100 μm.[14] Unfortunately, blood content in eye iris has been investigated not enough, however, for choroid the volume fraction of blood are known. Hammer and Schweitzer[15] found the volume fraction as 20%, Delori and Pflibsen[16] estimated the fraction as 50%, and Preece and Claridge[17] reported that the choroid blood volume fraction ranged from 50 to 80%. Since iris is forefront of the eye choroid it is necessary to expect, that blood content in the iris can be taken from approximately 30 to 70%.

From the iris structure, there are three principal elements that contribute to its color.[18] One is the pigment in the IPE, which is black in irises of all colors. Another is the melanin content in the iris stroma, which is the primary cause of color variations among different irises.[17] Brown irises have a large amount of melanin, which absorb much of the incoming light especially at short wavelengths. For blue irises which have low melanin content in the stroma, long-wavelength light penetrates the stroma and is absorbed in the IPE, while the short-wavelength undergoes Rayleigh scattering and reflection. Green and hazel irises are products of moderate amounts of melanin. Thus, the spectrum of iris colors basically results from varying amounts of the stroma melanin. However, blood of the stromal vessels also contributes in forming iris color, especially in short-wavelength spectral range. The third structural component that influences color is the cellular density of the iris stroma. For example, in an area of low density, little light is reflected by the semi-transparent stroma, so it shows the black color of the IPE, and, on the contrary, in an area of high density light does not penetrate IPE and is backreflected by the iris stroma.

Melanin synthesis occurs in special organoids - melanosomes, and then a transformation into enzymatic-inert pigmentary granules takes place. In accordance to its chemical composition the pigment is a combination of sulfur-containing pheomelanin and sulfur-free eumelanin, and the content of the pheomelanin produced by melanocytes at early and mature cells age is dominating (up to 99%). At cells ageing there is eumelanin contents dominating.[19-23] Melaninous granules in the residual bodies laying in the stroma's back part are identical in size and form the pigment granules of the pigmentary epithelium covering the iris back surface. It should be noted that melanin's granules size enclosed in the residual bodies located in forefront of iris stroma is equal to melanin granules size in melanocytes.[4-6] In Fig. 3 the extinction coefficient spectra[24] of pheomelanin and eumelanin are presented.

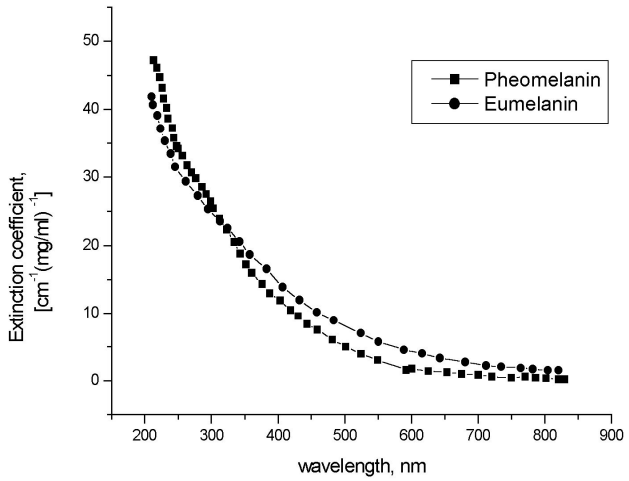


Fig. 3. Extinction coefficient spectra of melanins[24]

Since structure and function of iris pigment epithelium are very similar to structure and function of retinal pigment epithelium we can assume that optical properties of these tissues are also very similar. Hammer et al.[25] measured the optical properties of retinal pigment epithelium earlier and we have used the data in our calculation. Figs. 4 and 5 show the optical properties of retinal pigment epithelium obtained by digitization of the data presented by Hammer et al.[25]

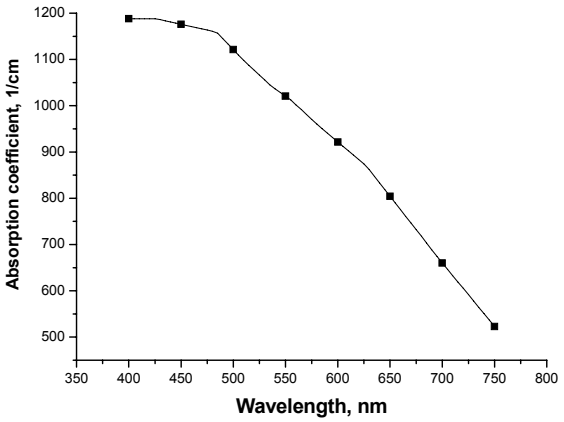


Fig. 4. The absorption properties of retinal pigment epithelium[25]

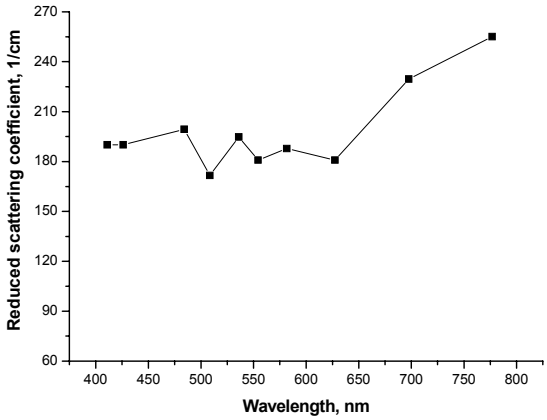


Fig. 5. The scattering properties of retinal pigment epithelium[25]

3. MATERIALS AND METHODS

For estimation of scattering properties of iris stroma, the reflectance measurements of rabbit's vitiligo irises with different blood content have been performed. The reflectance measurements were performed using commercially available optical multichannel spectrometer LESA-6med (BioSpec, Russia). Fig. 6 shows a scheme of the experimental setup.

As a light source a 250 W xenon arc lamp with filtering of the radiation in the spectral range from 400 to 700 nm has been used in the measurements. Light was delivered to the iris and collected from the tissue using the originally designed optical probe, which consists of two optical fibers. Both fibers have 400 mm in core diameter and a numerical aperture of 0.2. The fibers have been enclosed in aluminum jacket (8-mm outer diameter) to provide a fixed distance between the fibers and the tissue surface. The central fiber has been placed in perpendicular to iris surface delivering incident light to the surface. Distance between the delivering fiber and iris surface is 12 mm. Diameter of the illuminated spot is about 5 mm. The collecting fiber is mounted at angle of 20° regarding to central fiber. Distance between tip of collecting fiber and iris surface is 20 mm and, in this geometry, light has been collected from area with diameter about 8 mm. The spectrometer was calibrated using white slab $BaSO_4$ with a smooth surface.

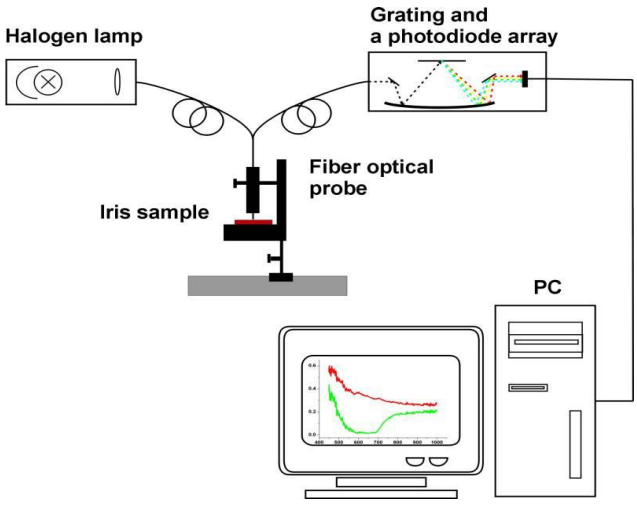


Fig. 6. Experimental setup for in vitro measurements

For processing the experimental data the inverse Monte Carlo technique has been used. The technique takes into account both the measurements geometry and blood influence on the measured reflectance spectra. In this study we used Monte Carlo algorithm developed by L. Wang and presented in Ref. 26. Blood optical properties have been calculated earlier.[27] Inverse problem has been solved by minimization the target function $\left(F\left(\mu_a,\mu_s'\right)=\left(R_{\exp}-R_{\text{calc}}\left(\mu_a,\mu_s'\right)\right)\Big/R_{\exp}\right)^2$ using the Levenberg-Marquardt nonlinear least-squares-fitting algorithm described in detail by Press *et al*. [28] Iteration procedure repeats until experimental and calculated data are matched. During the procedure the optical properties of bloodless vitiligo iris stroma have been estimated, and the result is presented in Figs. 7 and 8.

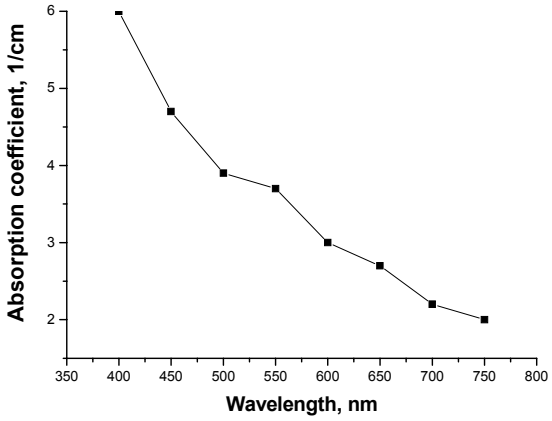


Fig. 7. The absorption properties of bloodless vitiligo iris stroma

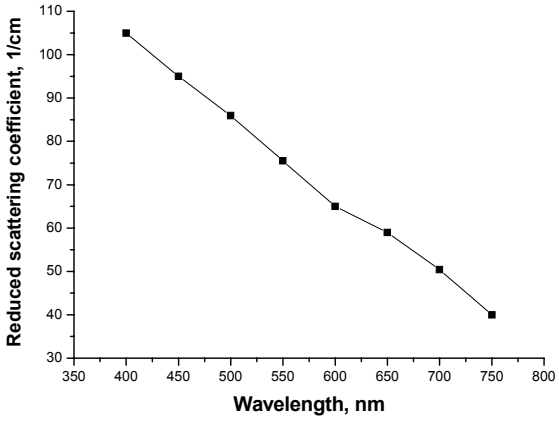


Fig. 8. The scattering properties of bloodless vitiligo iris stroma

Based on the presented in Section 2 two-layer iris model and using experimental data presented in Figs. 3-5, 7 and 8, the iris diffuse reflectance has been calculated by Monte Carlo technique in the spectral range 400-800 nm. Calculation of the reflection spectrum of an iris was performed in the assumption, that iris represents a homogeneous scattering flat layer (with thickness 450 μm) with uniformly distributed absorbing component such as melanin. As absorption component pheomelanin has been taken. Absorption properties have been calculated as summa absorption coefficient of vitiligo samples (see Fig. 7) and absorption coefficient of pheomelanin at different concentrations. Absorption coefficient of pheomelanin (see Fig. 3) at concentration of 1 mg/ml has been taken as a reference-point and denoted as μ^0_a. Since the main scattering component of iris stroma is collagen fibrils with diameter about 60 μm then the iris scattering has been modeled with the approximate relation $\mu_s = A/\lambda^4$, where A is parameter dependent on volume fraction of the fibril, and λ is wavelength in nm. In these calculations we varied parameter A in the range $(50\div200)\times10^{11}$. In this case scattering coefficient of iris stroma has values in the range 50÷200 cm^{-1} that correspond to values of scattering coefficient of real biological tissues. Anisotropy factor has been calculated as 0.2.

The spectrum has been recalculated in XYZ color coordinates with the relations

$$X=\sum_{380\text{ nm}}^{780\text{ nm}} R_d(\lambda_i)I_c(\lambda_i)\bar{x}(\lambda_i)\Delta\lambda$$

$$Y=\sum_{380\text{ nm}}^{780\text{ nm}} R_d(\lambda_i)I_c(\lambda_i)\bar{y}(\lambda_i)\Delta\lambda$$

$$Z = \sum_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} R_d(\lambda_i) I_c(\lambda_i) \bar{z}(\lambda_i) \Delta\lambda$$

where $R(\lambda)$ is the iris reflectance, and $\bar{x}(\lambda_i), \bar{y}(\lambda_i), \bar{z}(\lambda_i)$ are specific color coordinates, $R_d(\lambda)$ is spectrum of light source, $\Delta\lambda$= 5 nm, $I_c(\lambda)$ - spectrum of standard source of white light radiation incident on a object surface. The color coordinate Z determines brightness of diffusely reflected white color light (in percentage terms to brightness of white color light, diffusely reflected from standard reflecting object (type $BaSO_4$), accepted as 100 %). The XYZ color coordinates defined the x and y color coordinates:

$$x = \frac{X}{X+Y+Z},$$

$$y = \frac{Y}{X+Y+Z},$$

which determines a reflected white light chromaticity in the point on the color diagram (x, y).

In turn, knowledge of the x, y coordinates allows to calculate color coordinates in $L^*a^*b^*$ color coordinate system. In the system color is represented in the form of a vector in space where parameters L^*, a^* and b^* form the Cartesian system of coordinates (Fig. 9):

$$L^* = 116\left(\frac{Y}{Y_0}\right)^{1/3} - 16;$$

$$a^* = 500\left[\left(\frac{X}{X_0}\right)^{1/3} - \left(\frac{Y}{Y_0}\right)^{1/3}\right];$$

$$b^* = 200\left[\left(\frac{Y}{Y_0}\right)^{1/3} - \left(\frac{Z}{Z_0}\right)^{1/3}\right].$$

Here X_0, Y_0, Z_0 - color coordinates of a standard white color source (X_0 = 490,342; Y_0 = 500; Z_0 = 591,098). The relations were applicable at $X/X_0 > 0.008856$, $Y/Y_0 > 0.008856$, $Z/Z_0 > 0.008856$.

The parameter L^* defines brightness, and the parameters a^* and b^* are coordinates of chromaticity (a^* varies from green color to red, b^* - from dark blue to yellow). They define primary colour *(hue)* and its saturation *(chroma)*:

$$Hue = \arctan\left[\frac{b^*}{a^*}\right],$$

$$Chroma = \sqrt{(a^*)^2 + (b^*)^2}.$$

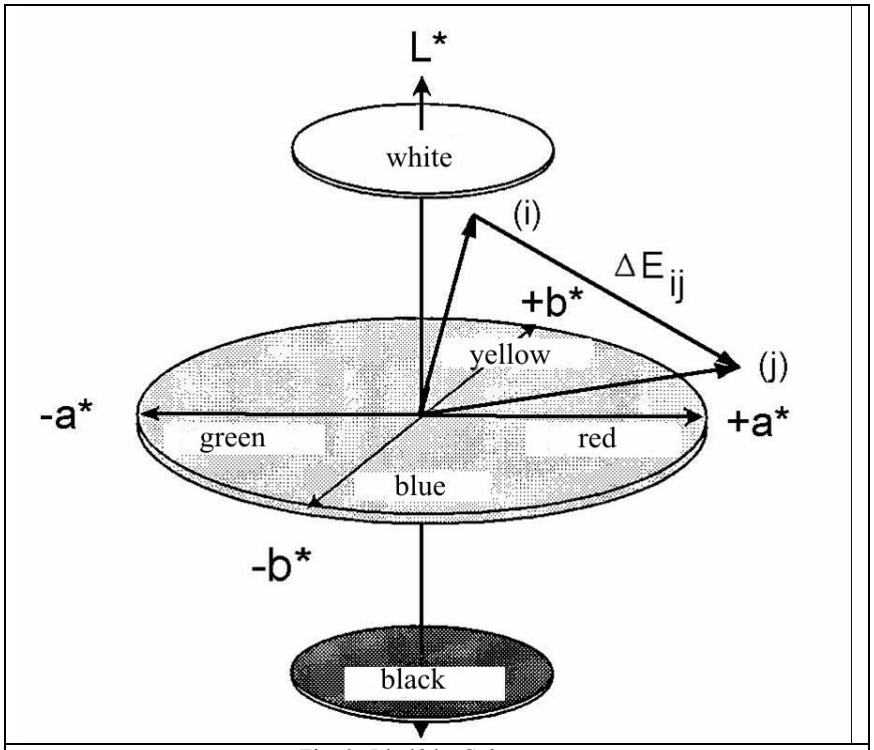
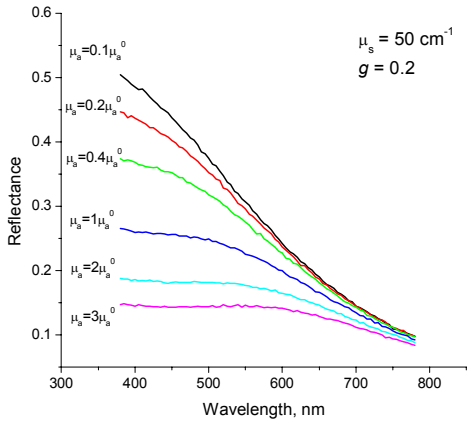


Fig. 9. *L*a*b** - Color space

4. RESULTS AND DISCUSSION

Fig. 10(a,b) presents reflectance spectra of the iris of human eye calculated for different melanin concentrations. μ^0_a is absorption coefficient of melanin with concentration 1 mg/ml.



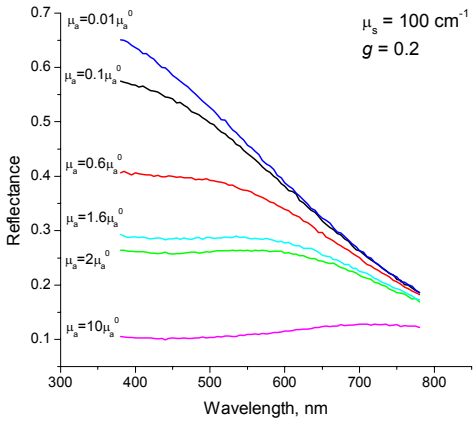


Fig. 10a. The reflectance spectra of the iris of human eye calculated for different melanin concentrations

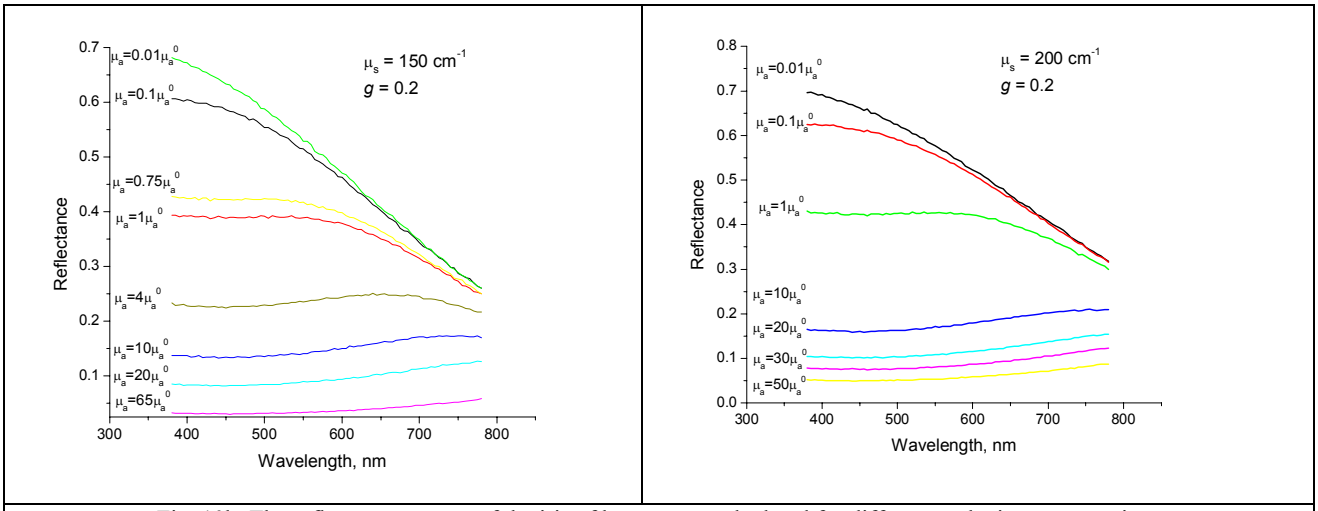


Fig. 10b. The reflectance spectra of the iris of human eye calculated for different melanin concentrations

In Figs. 10a and 10b one can easily see that changes of absorption coefficient (i.e. increasing of melanin concentration) lead to significant decreasing of reflection spectra in visible spectral range and the effect is especially seen in short wavelength spectral range. Figs. 11 and 12 show the results presented in (*x, y*) and (*a**, *b**) color coordinates, respectively.

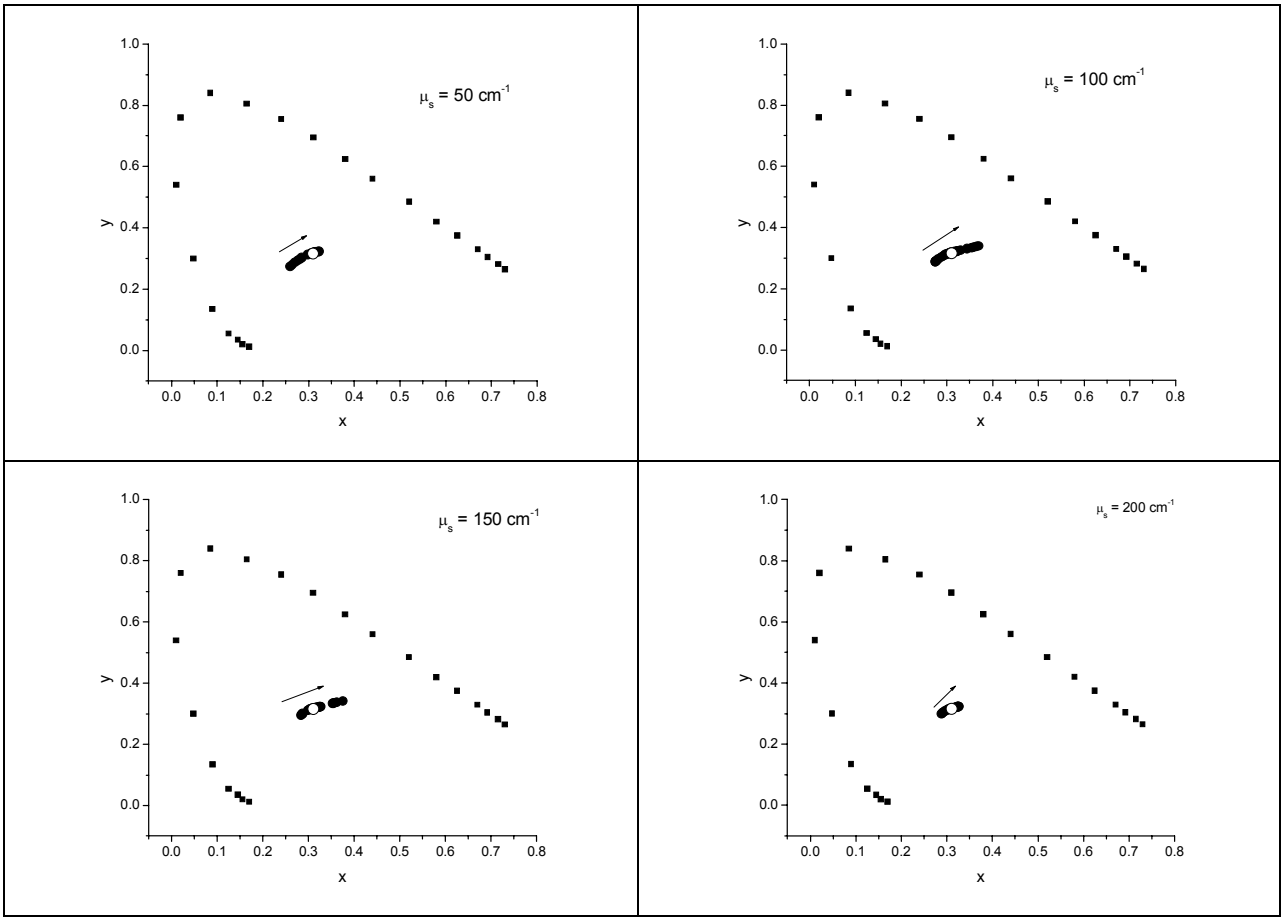


Fig. 11. The color coordinates of the reflectance spectra of the iris of human eye calculated for different melanin concentrations

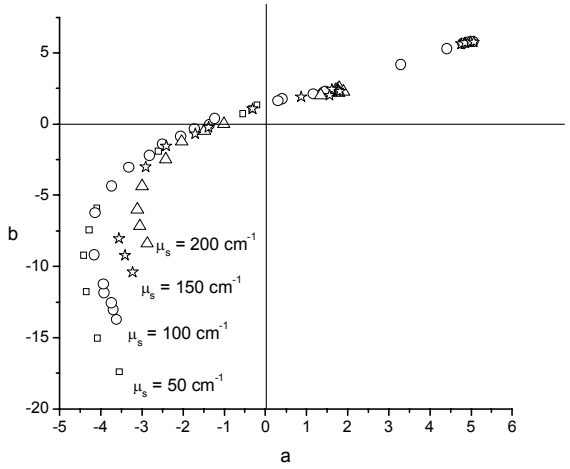


Fig. 12. The color coordinates of the calculated reflectance spectra of the iris of human eye

Influence of iris optical properties (scattering and absorption) on the iris quantitative color characteristics (main colour (*hue*) and its saturation (*chroma*)) are presented in Figs. 13 and 14.

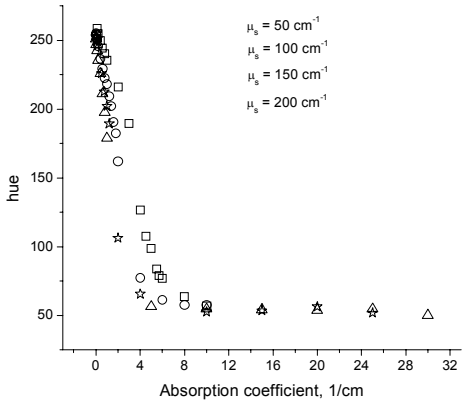


Fig. 13. Dependence of iris *hue* from μ_a.

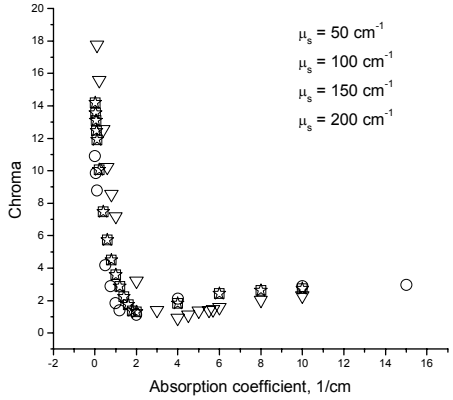


Fig. 14. Dependence of iris *chroma* from μ_a.

Hue and *chroma* dependencies on iris absorption coefficient have similar behavior. Curves consist of two branches. One branch corresponds to range of small melanin concentration where color of iris is green-blue. The second branch corresponds to greater melanin concentrations when iris color is observed as brown.

In the range of large melanin concentrations (i.e. for brown eyes) an increase in melanin concentration caused linear increase in color saturation *(chroma)* of the eye iris. Good linear correlation between melanin concentration and color characteristics (*hue* and *chroma*) for blue irises (i.e. in the range of small melanin concentration) is observed too. It is very interesting that the dependencies are not dependent on iris scattering characteristics (see Figs. 13, 14). Thus, we can conclude that the characteristics (*hue* and *chroma*) of iris color can be used for estimation of melanin contents in iris of human eye.

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