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Specific features of diffuse reflection of human face skin for laser and non-laser sources of visible and near-IR light

L.E. Dolotov, Yu.P. Sinichkin, V.V. Tuchin, G.B. Al'tshuler, I.V. Yaroslavsky

***Abstract*. The specific features of diffuse reflection from different areas of human face skin for laser and non-laser sources of visible and near-IR light have been investigated to localise the closed-eye (eyelid) region. In the visible spectral range the reflection from the eyelid skin surface can be differentiated by measuring the slope of the spectral dependence of the effective optical density of skin in the wavelength range from 650 to 700 nm. In the near-IR spectral range the reflectances of the skin surface at certain wavelengths, normalised to the forehead skin reflectance, can be used as a criterion for differentiating the eyelid skin. In this case, a maximum discrimination is obtained when measuring the skin reflectances at laser wavelengths of 1310 and 1470 nm, which correspond to the spectral ranges of maximum and minimum water absorption.**

Keywords: *reflection spectroscopy, face skin, water, IR LEDs, IR lasers.*

1. Introduction

Currently, the methods of optical diagnostics and phototherapy are widely used to diagnose and treat skin diseases [1, 2]. In particular, light is widely applied in the diagnostics and monitoring of the state of face skin to determine its aging [3 – 6], in cosmetic and other medical procedures (in particular, photothermal therapy [7 – 9]), and laser ablation of skin surface [10 – 12]. In the latter case it is very important to estimate the penetration depth of light into skin, because an insufficient treatment depth reduces the treatment efficiency, whereas an excessive depth is very likely to cause various minor effects: erythemas, pigmentation, cicatrisation, etc.

To apply efficiently the methods of optical diagnostics and phototherapy, one needs information about the structure and optical properties of biological tissue. Reflection spectroscopy is an informative *in vivo* diagnostic method for analysing the state of biological tissues. The spectral composition of light diffusively reflected by a biological tissue is formed as a result of light scattering and absorption in the region of light beam propagation in the tissue, due to which the light diffusively reflected by skin carries information about the epidermis and dermis structures, the number of blood vessels and the degree of their filling with blood, the spatial distribution of chromophores in skin and their concentration, and the intensity of the metabolic processes occurring in skin [13, 14]. The light penetration depth into skin tissue, especially in the red and near-IR spectral ranges, is fairly large (up to few millimeters); therefore, the formation of diffuse reflection spectrum may involve the biological tissues lying under skin, for example, bone tissues in the forehead region, muscular tissue in the cheek region, and iris and sclera of eye in the eyelid region. The involvement of hypodermic tissues may change both the absorbing and scattering properties of a medium, as a result of which the spectral composition of light emerging from the skin and forming a diffuse reflection spectrum changes. In this context, a comparison of the skin reflectance at different wavelengths may yield not only important information about the melanin content in the epidermal layer or the presence of surface or deep-lying blood vessels, but also some data about the skin cover thickness, the proximity of bone or muscular tissues, the state of hypoderma (fatty tissue), and the content of water and lipids in the biological tissue.

Thus, the study of the effect of hypodermic tissues on the diffuse reflection spectrum of skin is of certain interest. In this paper, we report the results of studying the possibility of differentiating areas of human face skin (in particular, the eyelid area) based on the spectral measurements of diffusively reflected light in the visible and near-IR spectral ranges. The comparative study of the optical parameters of the skin of face parts with different localisation and sufficiently large probe depth, up to lower lying tissues, is promising for monitoring the state of laser-corrected face skin (for example, in rejuvenascence or treating post-burn and other damages), in both pre- and post-operational periods.

2. Formation of the diffuse reflection spectrum of skin

Typical diffuse reflection spectra of skin tissues of different types [15], obtained by the integrating-sphere method, are

L.E. Dolotov, Yu.P. Sinichkin N.G. Chernyshevsky National Research State University, ul. Astrakhanskaya 83, 410012 Saratov, Russia; e-mail: ldolotov@yandex.ru, yusin49@gmail.com;
V.V. Tuchin N.G. Chernyshevsky National Research State University, ul. Astrakhanskaya 83, 410012 Saratov, Russia; Institute of Precise Mechanics and Control, Russian Academy of Sciences, ul. Rabochaya 24, 410028 Saratov, Russia; e-mail: tuchinvv@mail.ru;
G.B. Al'tshuler, I.V. Yaroslavsky Palomar Medical Technologies Inc., 15 Network Drive, Burlington, MA, 01803 USA

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shown in Fig. 1. Different contributions of skin layers to light absorption and scattering are characteristic of forming the skin reflection spectrum. In the visible spectral range the main components of skin that determine its absorbing and scattering properties are epidermis and dermis. In the short-wavelength spectral range strong absorption of epidermal melanin and dermal blood vessels determines a fairly small penetration depth (0.5 – 1.5 mm at the 1/e level [16]) of light into the skin tissue and, correspondingly, the low reflectance; in this case, the reflection spectrum exhibits characteristic absorption bands of hemoglobin. An increase in the wavelength (i.e., decrease in the melanin and hemoglobin absorption) leads, correspondingly, to an increase in both the light penetration depth in biological tissues (to 2.5 – 3 mm) and the skin reflectance (the skin spectrum is formed with participation of hypodermis, along with epidermis and dermis). In the near-IR spectral range the melanin and hemoglobin absorption hardly affects the skin reflection spectrum (one can see from Fig. 1 that in the range above 900 nm the reflection spectra of skin of different types of almost coincide), and the dominant chromophores are water and lipids [13].

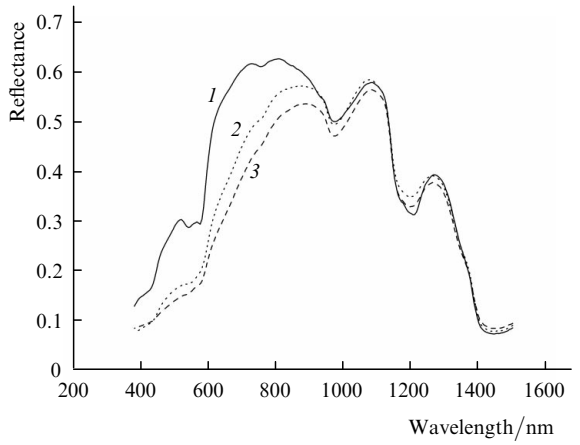

Figure 1. Diffuse reflection spectra of the forearm skin of volunteers with skin of types (*1*) III and (*2*, *3*) VI.

3. Differentiation of different areas of human face skin by diffuse reflection spectra in the visible spectral range

Different areas of the face skin surface were illuminated by a collimated white light beam 6 mm in diameter, using a fibre optic sensor. The light diffusively reflected from skin was collected by an optical fibre (with a diameter of 400 μm and numerical aperture of 0.2) at an angle of 22°; the light reflected by the skin was detected from an area 15 mm in diameter. An enlarged detection area in comparison with the illuminated area is a necessary condition for minimising spectral distortions when measuring the skin reflectance in the red and near-IR spectral ranges, where strong scattering and weak absorption of skin lead to an increase in the skin surface area from which the light diffusively scattered by tissue emerges.

As a probe radiation source we used a 20-W HL-2000 halogen lamp, and the spectrum of reflected light was recorded with a USB4000 spectrometer (Ocean Optics™, USA). The reflection spectra measured in the range of 400 – 900 nm were normalised to the $BaSO_4$ reflection spectra.

We investigated the diffuse reflection spectra of skin tissue in different parts of the face for four 20-to-40 year-old volunteers, with skin of types II and III. Figure 2 shows the skin reflection spectra for one of the volunteers, with selected ranges of 470 – 515, 585 – 630, and 650 – 700 nm, which were used to discriminate different face areas. The slope of the spectral dependence of the effective optical density $OD(\lambda)$ of skin tissue in the selected wavelength ranges was chosen as a discrimination criterion:

$$P = 10^5 \frac{\Delta OD}{\Delta \lambda}. \quad (1)$$

In expression (1) the OD value is related to the diffuse reflectance R_d through the simple relation [13]

$$OD = -\lg R_d, \quad (2)$$

and the large proportionality factor (10^5) was chosen because of the small slope of the dependences $OD(\lambda)$.

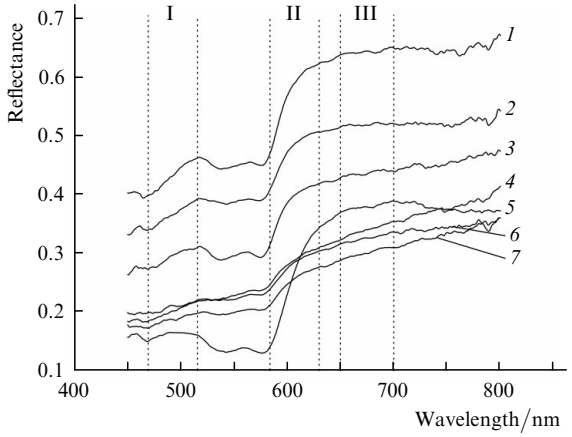

Figure 2. Reflection spectra of skin in different parts of human face: (*1*) cheek, (*2*) forehead, (*3*) area above the upper lip, (*4*) right part of eyelid, (*5*) lip, (*6*) left part of eyelid, and (*7*) central part of eyelid. The vertical lines indicate the spectral ranges chosen to discriminate facial parts.

Figure 3 shows the results of the parameter P (averaged over all volunteers) measured for different parts of face (forehead, cheek, lip, and the area above the lip), as well as the results of three measurements of P of the skin in the left, right, and central parts of eyelid (hereinafter the left part of eyelid is considered to be the area closer to the bridge of the nose). Spectral region I (470 – 515 nm, Fig. 3a) exhibits some discrimination of the eyelid skin; however, the reliability of the results is lower due to the large spread of values. In this range both blood and other chromophores (for example, melanin and bilirubin) affect the reflection spectra [13].

In spectral range II (585 – 630 nm, Fig. 3b) the slope of the reflection spectrum is determined by the presence of the edge of hemoglobin absorption band. A large slope provides large values of the discrimination criterion. Against the background of large P values variations in the reflection spectra manifest themselves weaker than in other spectral

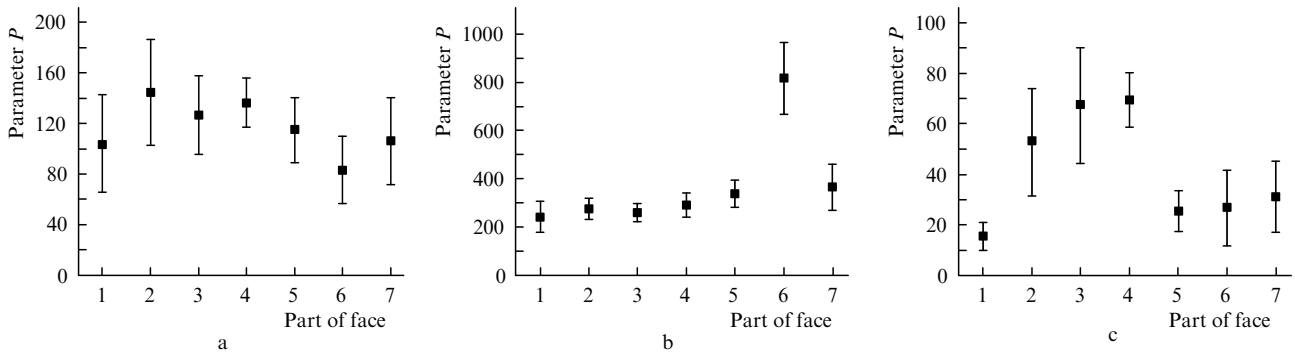

Figure 3. Values of the parameter P in the spectral ranges of (a) 470 – 515, (b) 585 – 630, and (c) 650 – 700 nm for different parts of face: (1) forehead, (2) right part of eyelid, (3) central part of eyelid, (4) left part of eyelid, (5) cheek, (6) lip, and (7) area above the upper lip.

ranges, as is evidenced by the spread in the parameter values.

The largest discrimination of the eyelid area is obtained in spectral range III (650 – 700 nm, Fig. 3c). The means and variances of the parameter P are listed in Table 1. According to these data, the P value for eyelid skin steadily exceeds those for other areas of face skin surface. Based on this circumstance, one can use the parameter introduced to discriminate the eyelid skin for volunteers with skin of types II and III. In the spectral range under consideration the parameter P is similar to the melanin pigmentation index of skin [13, 17]. The value of the melanin index in the eyelid region can be explained as follows: there is the eye iris under the eyelid, whose colour is formed with direct participation of melanin [18]. However, as can be seen in Fig. 1, it is unreasonable to use this parameter as a discrimination criterion for highly pigmented skin. The effect of melanin on the skin reflection spectrum is insignificant in the range above 1 μm (see Fig. 1); therefore, we chose specifically this spectral range to determine the discrimination criterion for face skin areas.

Table 1. Means and variances of the parameter P for different parts of face.

Part of face	Mean	Variance
Forehead	15.62	5.51
Eyelid (left part)	52.66	21.00
Eyelid (right part)	67.04	22.67
Eyelid (centre)	69.34	10.70
Cheek	25.39	7.99
Lip	26.82	14.93
Area above the upper lip	31.03	13.95

4. Differentiation of areas of human face skin by diffuse IR reflection spectra

4.1 Measurements on a Lambda 950 spectrophotometer

The measurements of diffuse reflection spectra of skin in three parts of face (forehead, cheek, and eyeball closed by eyelid) were performed on a Lambda 950 spectrophotometer (PerkinElmer®, USA), with an R400-7-VIS/NIR fibreoptic sensor (Ocean Optics™, USA) introduced into one of the spectrophotometer channels. The sensor was Y-shaped and had a tip with seven optical fibres 400 μm in diameter at the common end. Six optical fibres, forming a circle 500 μm in radius, served to supply light, and the central optical fibre was used to collect the light reflected from the skin. Each spectrum was measured for about 2 – 3 min, as a result of which *in vivo* spectral measurements were somewhat hindered. Therefore, special holders were designed to fix the sensor tip (in particular, glasses with a sensor tip attached were used to fix the sensor on the eyelid).

Five volunteers took part in the measurements (24-to-59 year old men with skin of types II and III). Typical diffuse reflection spectra from different face skin areas for one of the volunteers are shown in Fig. 4. It can be seen that, first, the reflection spectrum of eyelid skin is below the others and, second, the reflection spectrum of skin is significantly affected by water absorption in the spectral range under consideration. Ranges of maximum water absorption and ranges where this absorption is minimum can be selected in the reflection spectra. The regions of maximum water absorption correspond to wavelengths of 1187 ± 5, 1447 ± 6, and 1925 ± 6 nm [19, 20], and the regions of minimum absorption correspond to wavelengths of 1089 ± 6, 1270 ± 1, and 1654 ± 6 nm. Note that absorption of hypodermic fat at 1165 and 1210 nm contributes to the 1187-nm absorption [21].

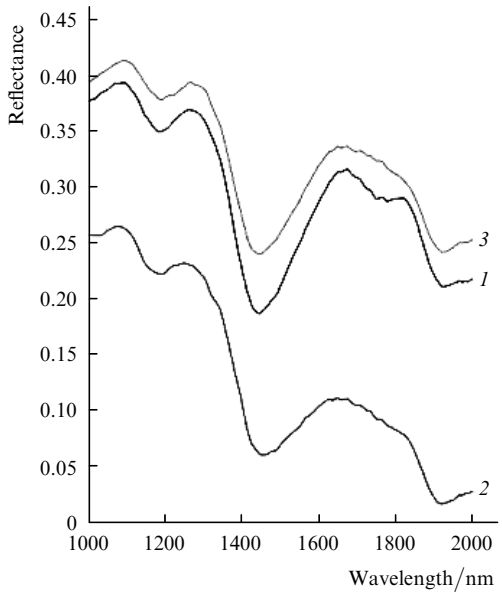

Figure 4. Reflection spectra of skin for different parts of face: (*1*) forehead, (*2*) eyelid, and (*3*) cheek.

The use of reflectance as a discrimination criterion for a corresponding face skin area is not efficient. This can be seen in Fig. 5, which shows the measured reflectances of three areas of skin surface (forehead, eyelid, and cheek) at four wavelengths for all volunteers. It is much more efficient to use the ratios of skin reflectances measured in different parts of face as a criterion. Figure 6 shows the wavelength dependences of the ratios of eyelid/forehead, eyelid/cheek, and cheek/forehead skin reflectances for one volunteer. Note that the behaviour of the spectral dependences of the eyelid/forehead and eyelid/cheek reflectance ratios is opposite to that of the cheek/forehead reflectance ratio.

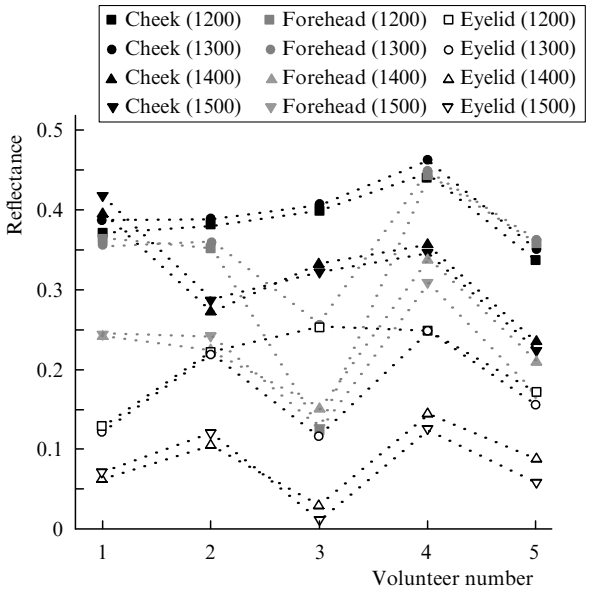

Figure 5. Reflectances of the face skin surface for five volunteers, measured at different wavelengths (in nanometers).

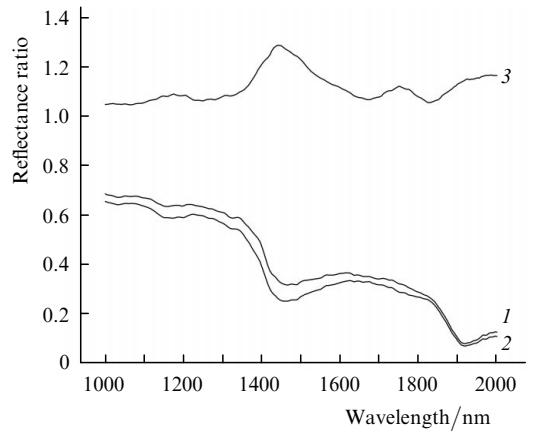

Figure 6. Wavelength dependences of the ratios of skin reflectances measured for different parts of face (one volunteer): (*1*) eyelid/forehead, (*2*) eyelid/cheek, and (*3*) cheek/forehead.

Concerning the eyeball region, we found it possible to use the eyeball skin reflectance at a certain wavelength, normalised to the forehead skin reflectance, as a differentiation criterion. It can be seen in Fig. 7 that the normalised skin reflectance in the eyeball region is always below unity, whereas for the cheek region it always exceeds unity.

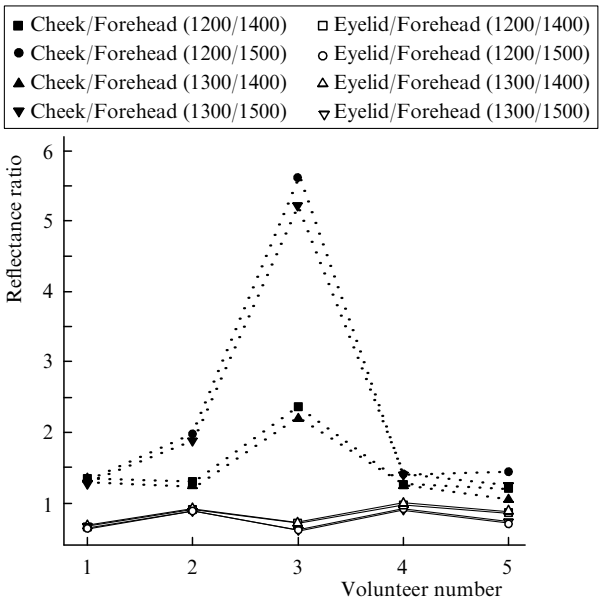

Figure 7. Reflectances of the cheek and eyelid skin for five volunteers, measured at different wavelengths (in nanometers) and normalised to the forehead skin reflectance.

4.2 Measurements at fixed wavelengths by IR LEDs ($\lambda = 1200$, 1300, and 1450 nm)

An L1200\1300\1450-35B2 LED (Epitex, Japan) with radiation wavelengths of 1200, 1300, and 1450 nm was used as a radiation source. A collimating 74-VIS lens (Ocean Optics^{TM}, USA) was applied to guide the LED radiation into illuminating fibres of the above-described R400-7-VIS/NIR fibreoptic sensor. The detecting fibre of the sensor was connected through an SMA 905 connecter with a PDA10CS photodetector (ThorLabs, Germany). The signal was recorded by a GDM-8135 digital voltmeter (GW Instek, Taiwan).

Four volunteers took part in the measurements. Figure 8 shows the averaged reflectances of the forehead, eyelid, and cheek skin, measured at wavelengths of 1200, 1300, and 1450 nm. It can be seen that the differentiation of skin areas is minimum at $\lambda = 1300$ nm and maximum at $\lambda = 1450$ nm. Apparently, the differentiation became possible due to the absorption in water, which is present in the biological tissue; this absorption is minimal at a wavelength of 1300 nm and maximal at 1450 nm.

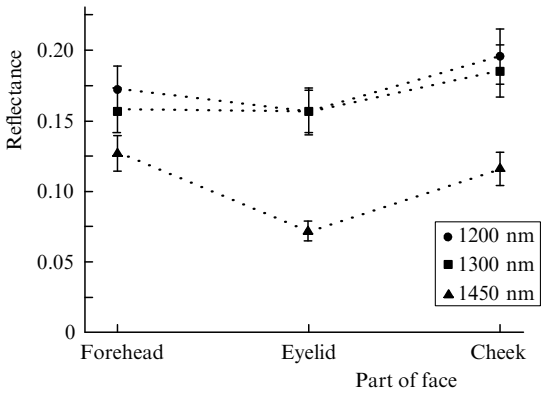

Figure 8. Reflectances of the forehead, eyelid, and cheek skin, measured at different wavelengths.

Eyelid is one of the thinnest regions of human skin. The epidermis and dermis thicknesses are about 0.04 and 0.3 mm, respectively, which is much smaller than the thickness of the skin in other facial areas [14]. Therefore, the formation of the skin reflection spectrum is significantly affected by the processes of light absorption and scattering in eye sclera and iris. It was established in [22] that, although on the whole one can suggest similarity of the structures of eye sclera and bloodless dermis and proximity of their optical characteristics, it is also necessary to take into account some differences in the structure and texture of these biological tissues, specifically: the presence of elastin fibres in the dermis (which differ from collagen fibres in the size and degree of hydration), and the high dispersivity of scatterers in the skin dermis, which leads to differences in the scattering characteristics of the eye sclera and skin dermis. The refractive indices of direct scatterers in these tissues may also differ [22], which may result in different reflectances of the eyelid skin and the skin in other parts of face.

As a differentiation parameter for eyelid skin, one can use the skin reflectance measured at the water absorption wavelength and normalised to the skin reflectance at a wavelength corresponding to minimum water absorption (Fig. 9).

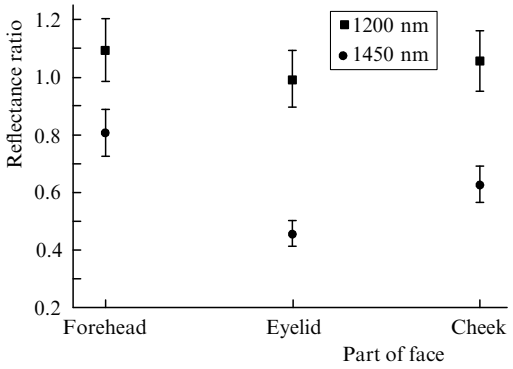

Figure 9. Reflectances of the forehead, eyelid, and cheek skin, measured at wavelengths of 1200 and 1450 nm (water absorption bands) and normalised to the skin reflectance at a wavelength of 1300 nm, corresponding to minimum water absorption.

4.3 Two-wave measurements using 1310- and 1470-nm lasers

The light sources were an S1FC1310 laser (ThorLabs, Germany) (wavelength 1310 nm, power 2.1 mW) and a laser module (1470 nm, 2 W). The laser emitters had fibre outputs to provide optical communication between the lasers and fibre optic sensor. In addition, the air isolation between the laser fibre and fibre optic sensor played the role of attenuator for the 1470-nm radiation of the laser module; therefore, measurements were performed with radiation attenuated to 10–15 mW. The radiation reflected by skin was recorded using the above-described sensor, PDA10CS photodetector, and GDM-8135 digital voltmeter.

The measurements of the skin reflectance in different facial areas were performed for eight volunteers, five measurements near a chosen skin area at two wavelengths for each volunteer. The measurements results were averaged. As an example Fig. 10 shows the mean reflectances of different parts of face (forehead, temple, cheek-bone, cheek, right eyelid, and left eyelid) at wavelengths of 1310 nm and 1470 nm, as well as the confidence interval, calculated by the standard technique. These results are in agreement with the above-reported ones. First, the skin reflectance at $\lambda =$ 1470 nm is lower than at $\lambda = 1310$ nm; this regularity reflects the character of the spectrum in the wavelength range of 1000–1500 nm. Second, the eyelid skin reflectance at both wavelengths is below the corresponding values for other facial areas.

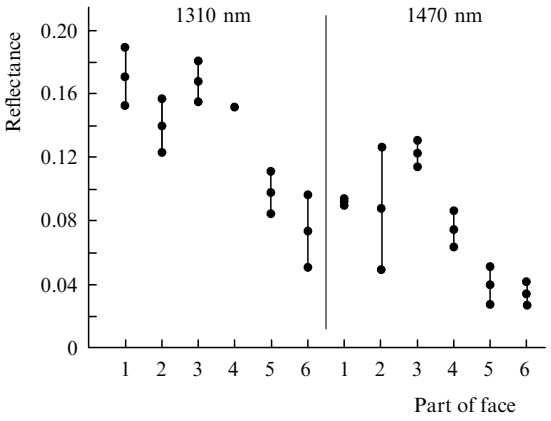

Figure 10. Reflectances of skin in different parts of volunteer face, measured at two wavelengths: (1) forehead, (2) temple, (3) cheek-bone, (4) cheek, (5) right eyelid, and (6) left eyelid.

5. Conclusions

In the visible spectral range the eyelid skin surface can be discriminated by determining the melanin index (content). Its values for the eyelid skin exceed those for other parts of face for volunteers with skin of types II and III.

Concerning the differentiation in the eyeball area, it turned out possible to use the skin reflectances at certain wavelengths (normalised to the forehead skin reflectance) as a differentiation criterion: the ratio of the normalised skin reflectance in eyeball (eyelid) area is always smaller than unity, whereas this parameter for cheeks always exceeds unity.

The eyelid skin can also be differentiated from other facial skin areas by comparing the skin reflectances in the near-IR spectral range at wavelengths corresponding to the presence and absence of absorption in water. The skin reflectances in the eyelid area, measured at a wavelength corresponding to absorption in water and normalised to the skin reflectance at the wavelength at which the water absorption is minimum, are much lower than those for other parts of face. This can be explained by the large light penetration depth into tissues (in particular, the eyeball tissue) with high water content.

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