EYE TISSUE TRANSMISSION FOR NEAR- AND MID-INFRARED LASER RADIATION

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Abstract: Comparison of the eye tissue transmission for six laser radiations from visible up to mid-infrared region was done. The attenuation of the alexandrite (visible 0.75 µm), and Nd:YAP (near infrared 1.08 µm) laser radiations was found to be minimal – a retina reachs ~ 46% energy of these lasers entering the eye. On the other side the radiations of 1.54 µm (Er:glass), 1.66 µm (Er:YAP), and 2.01 µm (Tm:YAG) lasers are absorbed by the primary segments of the eye and no impact is appeared on the retina. The absorption values measured for 1.34 µm (Nd:YAP) was recorded to be between the curves obtained for two group of radiation wavelengths mentioned above. On retina, only 0.5% of cornea radiation was found. In this case the anterior parts of the eye are not affected so hard as in the case of eye safe radiation application.

Introduction

Since the first laser was constructed by Maiman in 1960 the application list of laser instruments constantly expanding. It includes such area as technology (welding, cutting, drilling), medicine treatments, measurement of distances, detection of objects, guidance of objects, electronics industry, cleaning, entertainment, etc.

Many of the lasers which are being used for these applications are capable of injuring individuals who may be inadvertently exposed by either direct intrabeam exposures, reflected exposures or by beams directed by conduits such as fiber or hollow waveguide optics. On the other hand, the laser radiations are used for the therapy of many eye diseases. These entire events follow from the interaction of the laser radiation with the eye tissues.

To understand of the proceed mechanisms we must awake that the interaction processes can be divided into primary and secondary effects. The primary processes include the reflection, absorption, transmission, and scattering of the radiation strongly dependent on the wavelength. Among these processes, the spectral absorption play the distinguished role in the biophysical interaction depending mainly on the penetration depth of the radiation into the tissue. Water being the main tissue component also in eye structures (as it is in all human body), the decisive role in the penetration is done by the absorption of the particular wavelength radiation by the water molecules presented there. Therefore, most of the eye structures (cornea, lens, vitreous humor) follow the absorption coefficient of water and they are transparent for the radiation from visible up to near infrared (Fig. 1.)

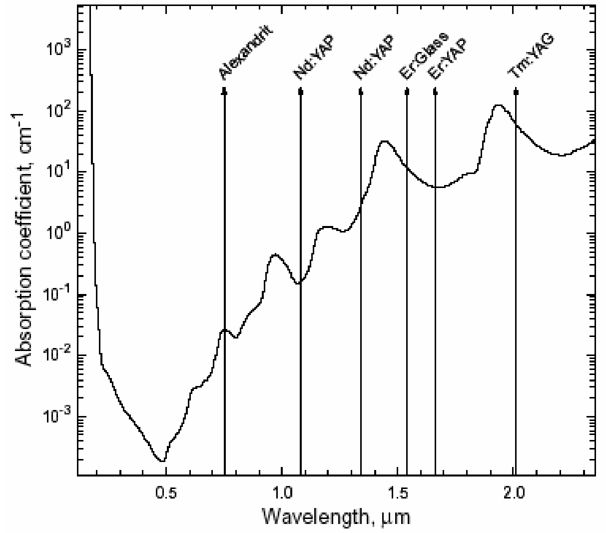

Figure 1: Water absorption and examined laser wavelengths [5].

On the other hand, the retina, in which melanin, haemoglobin and yellow pigment are presented, absorbs light from the visible part of the spectrum, and iris, where melanin pigment exists absorbs specific color of light. As concern of the applications, the radiation of which the wavelength coincides with the water absorption peak, is useful for the immediate ablation processes. An applicability of the particular laser varies by the necessary quantity of energy dose and thermal damage of the irradiated tissue surroundings. As secondary effects we must count the dependence of interacting intensity on the interaction duration determined by working regime of the laser system used. Following these allocations a photochemical and temperature interaction, the photoablation, plasma induced ablation, and photodisruption influence the results of the treatment or eye injury (Fig. 2). Inside the

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last processes, acoustic phenomena, multi-photon absorption, Raman and Brillouin scattering, are involved.

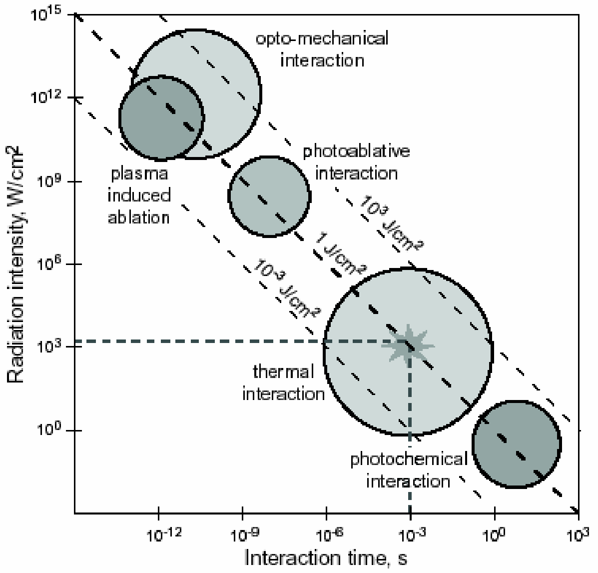

Figure 2: Laser radiation – tissue interaction. Thermal interaction for free-running laser radiation [5].

The spectral region beyond 1.4 µm has often been referred to as the "eye-safe" region because the incident energy is absorbed by the outer ocular media (cornea, aqueous humor, lens, vitreous humor), and retina stay no impacted. The transmission of the human eye in the visible and near infrared region can be found in literature.

In our work we concentrated on the detailed experimental in vitro penetration investigation of the laser radiation which wavelength is from the so called "eye safe" region, e.i. from the part of spectrum around the wavelength of 1.5 µm. For the comparison we checked the region of wavelengths from 0.75 µm up to 2.01 µm. On the graph of the water absorption this region includes the maximum peaks in the vicinity of 1.4 µm and 1.9 µm (Fig. 1). Unlike the reference [7] where the continuous radiation 1.3 µm compared with the visible 0.5 µm was used for our investigation of the interaction we used the pulsed lasers working in the free running regime with the length of pulse around 100 µs. With the interacting intensity ~ 0.3 - 1.4 kW/cm^2 (fluence 0.3 - 1.4 J/cm^2) we must count that the coming interaction falls into the thermal region and the absorption of the energy in particular eye segments results in heating the individual segments of the eye (Fig. 2). The goal of the study is the detailed ascertainment of the radiation influence in the anterior segment of the eye.

Experimental setup

Sources of laser radiation

As radiation sources alexandrite (0.75 µm), Nd:YAP (1.08 and 1.34 µm), Er:glass (1.54 µm), Er:YAP (1.66 µm), and Tm:YAG (2.01 µm) laser systems were used. Particular systems were working in free-running regime. The laser systems were composed from the laser crystal placed along with the xenon flashlamp into pumping elliptical silver coated or diffuse ceramic cavity. The laser resonators were formed by mirrors suited for the generated wavelength. The lengths of all resonators were about 35-40 cm. Generated pulse length was ~ 100 µs. For the particular experiments the output of all lasers was adjust on the level of interaction energy ~ 20 - 100 mJ. The diameter of the output beam spot was 3 mm. Data of all laser systems components are summarized in Table 1.

Table 1: Data of all laser systems components. (λ – generated laser radiation wavelength, Crystal dimension – diameter x length, M_{rear} material – rear mirror material, R_{OC} – output coupler reflexivity, Res. length – length of laser resonator)

Laser	λ, µm	Crystal dim., mm	M_{rear} material	R_{OC}, %	Res. length, cm
Alexandrite	0.75	6 × 110	diel.	75	40
Nd:YAP	1.08	7 × 120	diel.	60	36
Nd:YAP	1.34	7 × 120	diel.	60	36
Er:glass	1.54	4 × 80	copper	42	30
Er:YAP	1.66	6 × 100	diel.	90	32
Tm:YAG	2.01	5 × 79	copper	74	31

Measuring instruments

For measurement of the output laser energy and through the eye transmitted radiation, a computer-operated two channel Molectron JD2000 Joulemeter/Ratiometer with Molectron detectors (J25, 8.59 V/J and ED 200LA, 1.28 V/J) were used. The post operation record was made by the microscope Nicon SMZ-2T, Mitsubishi CCD color video camera (CCD-100), and PC computer. The histological evaluation was carried out by the scanning electron microscope – JEOL (JSM 6400).

Experiment arrangement and tissue preparation during the experiment

For the interaction investigation the human eye tissues (*in vitro*) were used. Up to the experiment the eyes were stored in a saline solution. The experimental arrangement is illustrated in Fig. 3. Chosen radiation was directed vertically into the eye by a proper mirror (M) with reflectivity R = 100% under the angle of 45°. To determine the value of the energy falling into the eye, the part of the laser beam was declined before the mirror (M) by the beam splitter (BS) and this energy was measured by Molectron detector (D1). The eye was placed on a special holder (EH) which allows the passage of the radiation into the eye. Above the eye, the Molectron detector (D2) was placed to find out the transmitted energy. After the calibration measurement (without the eye tissue), the above mentioned arrangement allows us to have the value of the transmitted energy in every single laser shot.

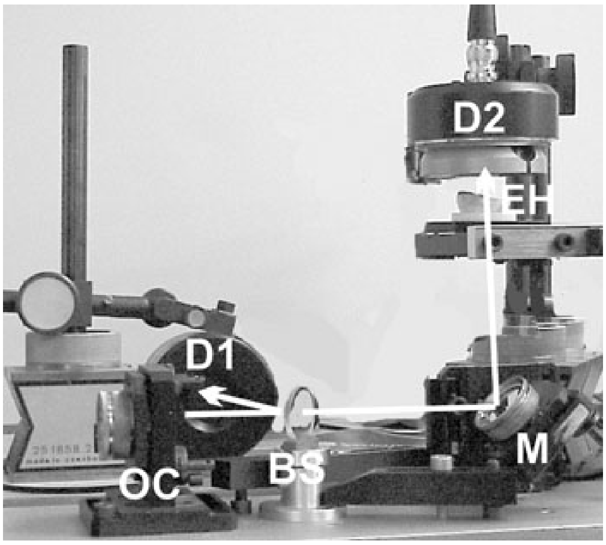

Figure 3: Experimental setup. OC – output coupler of the laser resonator, BS – beam splitter, M – mirror with the reflectivity R = 100% under the angle of 45°, D1 and D2 – energy detectors, EH – eye holder.

The measurement was divided into 5 steps – the transmission of following tissues was measured:

1. cornea, aqueous humor – anterior chamber fluid, lens, and vitreous humor
2. cornea, aqueous humor, and lens
3. cornea, and aqueous humor
4. cornea itself
5. lens itself

Ad 1. In the first measurement the value of the energy reaching the retina after the straight laser irradiation was measured. Therefore the posterior segment of the eye was cut and the energy passing the cornea, aqueous humor, lens, and vitreous humor were measured for five various input energies from 20 mJ up to 100 mJ (step 20 mJ). Every measurement was repeated 20 times for the particular energy value. The obtained data was automatically recorded via Molectron Joulemeter to the computer.

Ad 2. The vitreous humor was removed and the energy after its pass through the cornea, aqueous humor, and lens was measured. In the following step the lens was removed.

Ad 3. The transmission of the cornea and aqueous humor was recorded.

Ad 4. The cornea transmission was investigated.

Ad 5. At the end the transmission of the eye lens were measured.

This procedure was repeated three-times for all compared six wavelengths from 0.75 μm up to 2.01 μm.

Eye tissue analysis

The eye samples were immediately photographed after the laser treatment. The Nicon SMZ-2T microscope and the Mitsubishi CCD colour video camera (CCD-100), and PC computer were used for the notation of the interaction changes. After the whole treatment the samples were stored in formaldehyde solution.

Results

The resulted values of the particular eye tissues transmission were obtained as mean values of measured interaction energy data (from 20 mJ to 100 mJ, 20 measurements of each) successively for all wavelengths. The repetition rate of the laser was low (1 Hz) therefore it can be supposed that the temperature of the tissue was not significantly changed during the measurement. As substantial, the reflection of the coming radiation on the tissue boundary was taken into account. As it is seen from the procedure of radiation application, this correction is needed in data analysis for transmission measurement of cornea and lens itself (*Ad 4*, and *Ad 5*). The index of refraction for cornea and lens are n = 1.376 and n = 1.386, respectively, for wavelength 500 nm [6]. Supposing that these values do not vary significantly with the wavelength, we used these values for the recalculation of the cornea and lens input radiation energy. The measured raw data of the cornea transmission in dependence on the laser radiation wavelength (together with the calculated transmission curve of water layer with corresponding thickness) are shown in Fig. 4.

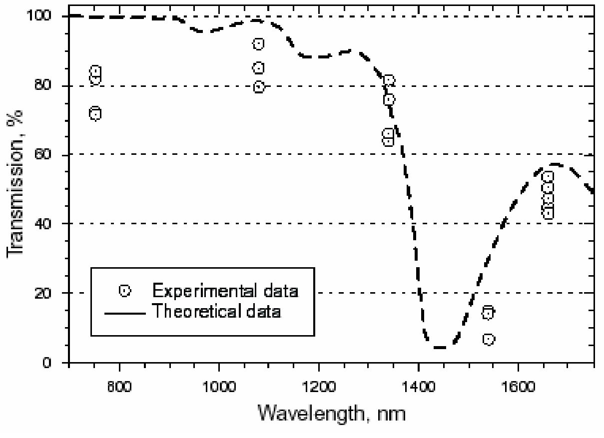

Figure 4: Transmission of human cornea for different wavelengths, experimental and theoretical data (calculated transmission of 1 mm thick water layer)

From the measured depth of eye structures provided in every measurement and measured transmission, the absorbed energy and absorption coefficients were calculated. The whole set of corrected values of the particular eye tissue structures for all investigated wavelengths are shown in (Table 2, 3) and illustrated in Figure 5.

Table 2: Transmission values of particular eye tissues for all investigated wavelengths (λ - laser radiation wavelength, T – eye tissue transmission value).

λ [μm]	cornea T [%]	aqueous T [%]	lens T [%]	vitreous T [%]	eye T [%]
0.75	81.5	68.5	81.6	100.0	45.6
1.08	89.9	89.6	59.4	95.5	45.7
1.34	75.6	57.6	33.1	3.2	0.5
1.54	15.3	6.7	0.6	0.0	0.0
1.66	49.8	24.4	8.6	2.0	0.2
2.01	5.4	50.7	0.0	0.0	0.0

Table 3: Absorption coefficients of particular eye tissues for all investigated wavelengths (λ - laser radiation wavelength, α – eye tissue absorption coefficient).

λ [μm]	cornea α [cm^{-1}]	aqueous α [cm^{-1}]	lens α [cm^{-1}]	vitreous α [cm^{-1}]
0.75	2.0	1.9	0.4	0
1.08	1.1	0.6	1.0	0
1.34	2.8	2.8	2.2	2.1
1.54	18.8	13.5	10.2	-
1.66	7.0	7.1	4.9	2.5
2.01	29.2	3.4	-	-

Discussion

The main goal of this study was the detailed investigation of the six radiation absorption measurements in the individual segments of the human eye provided in the same experimental conditions and interacting laser radiation parameters. Unlike the conditions done in [7] where continuous exposure was used for rabbit eye, in our case we used pulsed irradiation with the higher intensity but lower fluence. From the histograms done in Fig. 5 it is seen that the attenuation of the alexandrite (visible 0.75 μm), and Nd:YAP (near infrared 1.08 μm) laser radiations was found to be minimal (in comparison with the other investigated wavelengths) – a retina reached 46% radiation energy entering the eye. Nevertheless, it is necessary to awake that 54% of this radiation is absorbed by the anterior structures of the eye. The radiation is absorbed in lens mainly, while the alexandrite laser radiation is attenuated by cornea and aqueous humor. The reason could be in higher scattering contribution done by shorter alexandrite laser wavelength, and also by the absorption parameters of cornea tissue structures (see Fig. 1).

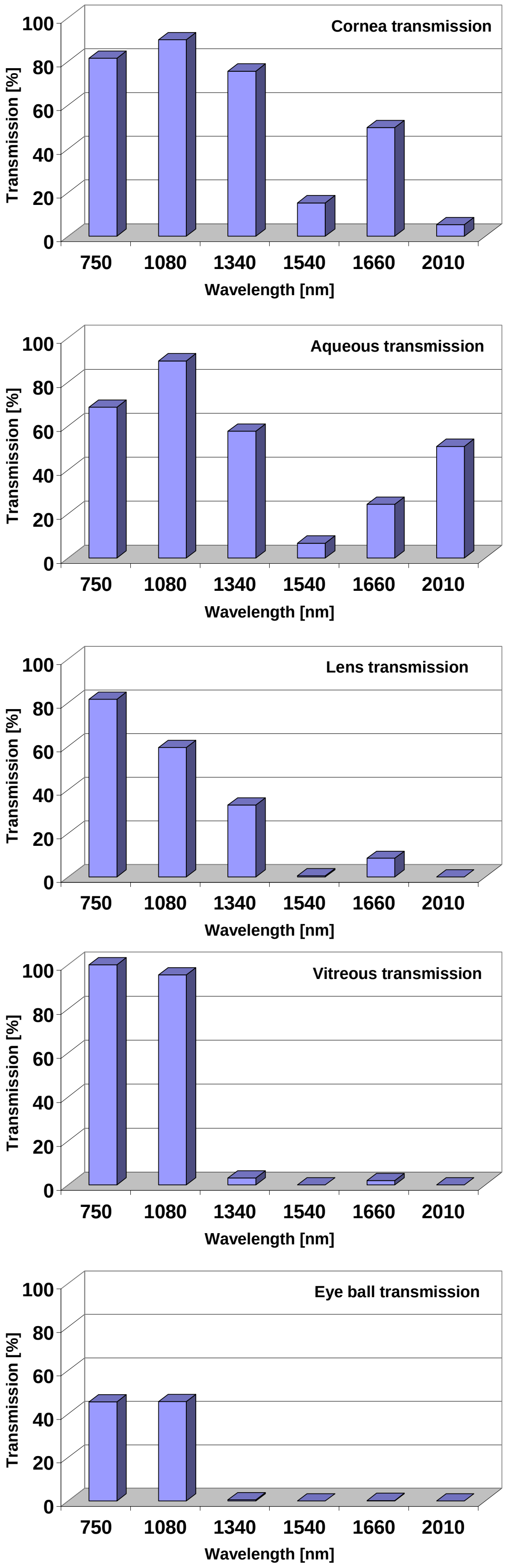

Figure 5: Transmission of human eye segments for all investigated wavelengths.

On the other side, the radiation with the wavelengths in the "eye safe" region (the vicinity of 1.5 µm – 1.54 µm (Er:glass), 1.66 µm (Er:YAP)), and also 2.01 µm (Tm:YAG) radiation are mainly absorbed by the primary segments of the eye, and no impact appeared on the retina (up to the interaction energy 100 mJ incident into the eye). The anterior eye parts are more loaded than in the previous case. The attenuation of 1.66 µm radiation is done by the cornea tissue and aqueous humor, mainly. Small part (10.6 %) of the energy is absorbed by the lens. The radiation 1.54 µm and 2.01 µm are attenuated before reaching the eye lens. The difference between these two radiations is in the depth of the absorption in the cornea tissue. Due to the local absorption maximum of 2.01 µm radiation in water, this radiation is absorbed more in cornea tissue. The absorption values measured for 1.34 µm (Nd:YAP) was recorded to be between the values obtained for two groups of radiation wavelengths mentioned above. On retina, only 0.5% of cornea radiation was found. In this case the anterior parts of the eye (the cornea and lens) are not affected so hard as in the case of eye safe radiation application. The essential part of the energy is transformed into the heat in aqueous and vitreous humor.

Similar results were obtained in our previous study [8], where only two laser radiation wavelengths were investigated.

Conclusions

Comparison of the eye tissue transmission for six laser wavelengths from near-middle infrared was done. From the step by step transmission measurement of the human eye globe layers (*in vitro*) was recognized that the value of the absorbed energy in particular segments was various for monitoring wavelengths yielding substantial fluence differences on the retina and anterior segments mainly.

Acknowledgements

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