Effects of femtosecond laser radiation on the skin

P Yu Rogov, V G Bespalov
ITMO University, Optics and Photonics Department, 49 Kronverksky Pr.
St. Petersburg, Russia

E-mail: RogovPU@niuitmo.ru

Abstract. A mathematical model of linear and nonlinear processes is presented occurring under the influence of femtosecond laser radiation on the skin. There was held an analysis and the numerical solution of an equation system describing the dynamics of the electron and phonon subsystems were received. The results can be used to determine the maximum permissible levels of energy generated by femtosecond laser systems and the establishment of Russian laser safety standards for femtosecond laser systems.

1. Introduction
Currently femtosecond laser systems (FLS) are used in scientific applications and in medical technology [1, 2]. However, despite the rapid development of femtosecond technologies and their usage in biology and medicine, currently in the Russian Federation there are no standards for safe levels of energy intense femtosecond laser pulses. It should be noted that the mechanism of interaction of intense femtosecond laser radiation with matter is significantly different from the mechanism of interaction of pulses of longer duration since the exposure time is less than the time required for excitation of the phonon subsystem [3]. In addition, the power density that occurs when using the FLS results in a variety of non-linear processes, such as self-focusing, two- and three-photon absorption, multiphoton ionization and in high energy density leads to an optical breakdown [4]. Particularly relevant the process is when femtosecond radiation affects the biological tissue, as an intense femtosecond pulses can be a significant danger to the skin, eyes and other organs [5].

In this paper we consider the linear and nonlinear effects of femtosecond laser radiation on the skin and a mathematical model that describes the approximate exposure to individual processes. In the future the model will be used to determine the maximum permissible energy levels of FLS.

2. Mechanism of action of femtosecond radiation on the skin
Human skin is optically transparent turbid medium (there are both the absorption and scattering). At the same time the skin is a heterogeneous structure consisting of the inclusion of various types and sizes (blood vessels, hair follicles, and so forth.), that complicates the understanding of the processes taking place under the influence of laser radiation on the skin. The main components of the skin are water (70%) and proteins (27%). The main structural protein of body is collagen, which is about 70% of the dry weight of skin. Moreover, the water molecules can be divided into two separate classes: the free molecules and water molecules in the bound state, involved in protein compounds (in triple helical collagen group
represents about 500 molecules of water) [6]. Thus, in a first approximation, the skin can be considered water with protein inclusions by electrodynamics properties close to semiconductors.

![Figure 1. Model of human skin](image)

| Tissue layer            | d, mm | $\mu_a$, 1/mm | $\mu_s$, 1/mm | g  | n      | C, J/gK | k, W/mK |
|-------------------------|-------|---------------|---------------|----|--------|---------|--------|
| Epidermis               | 0,03-2| 0,083         | 21,37         | 0,85| 1,5    | 3,05    | 0,29   |
| Dermis                  | 0,5-5 | 0,026         | 9,67          | 0,86| 1,5    | 3,52    | 0,41   |
| Subcutaneous adipose tissue | $>10$ | 0,025      | 12,39         | 0,86| 1,5    | 2,3     | 0,2    |

Where $d$ - depth of the layer, $\mu_a$ - absorption coefficient, $\mu_s$ - scattering coefficient, $g$ - mean cosine of the scattering angle, $n$ - refractive index of the medium, $C$ – heat capacity, $k$ - the coefficient of thermal conductivity.

For evaluation we chose a wavelength of 800 nm for the most common FLS Ti: sapphire. The duration of the pulses in the system may vary from 10 to 150 fs. Irradiation of ultrashort laser pulses results in damage that cannot be explained by the mechanism of the heat fusion [8]. Such changes may be caused by the excitation of valent electrons with laser pulses [9, 10]. There are 500 water molecules for a triple helical collagen group. Thus the molecules of water are used as the transmission link between absorbing energy from the laser and exciting vibrational (phonon) mode of collagen (relaxation time is about 3 ps) [11, 12].

### 3. Mathematical model

In this study we used balanced system, the dynamic equation of electron-phonon subsystem. In the model atoms interact through semi-empirical potentials and electronic degrees of freedom are not taken into account. Due to the influence of the laser radiation non-equilibrium carriers is generated, which are described by the integral concentration [13]. We can neglect the process of Auger-recombination and impact ionization as it has small effect.

Yakovlev, E. B. proposed the idea of the definition of the relationship between the potentials of the atoms and the state of the electron subsystem, allowing to simulate the effects of heat when to femtosecond pulses expose on the dielectric material. [14]. Kinetic model of photo-excited semiconductor structure is taking into account external electron emission is a system of differential equations with the appropriate boundary and initial conditions. Differential Bouguer-Lambert law most accurately determines the
distribution of laser intensity $J(x,t)$ within a solid (the $z$ axis is directed into). Below there is a system of equations of thermal conductivity in one-dimensional approximation describing the dynamics of the electron and phonon subsystems:

$$\frac{\partial T_e}{\partial t} = \alpha_e \frac{\partial^2 T_e}{\partial z^2} - \frac{1}{c_e \tau_{ep}} (T_e - T_a) + \frac{a_{ehv}}{c_e} J(t,z) \quad (1.1)$$

$$\frac{\partial T_a}{\partial t} = \alpha_a \frac{\partial^2 T_a}{\partial z^2} + \frac{1}{c_a \tau_{ep}} (T_e - T_a) \quad (1.2)$$

where $C_e = \frac{\pi^2 k_B T_e^3}{2 E_F}$; $J(t,z)$ – distribution of the intensity of the laser radiation within a solid, $C_e$ - electron gas heat capacity, $C_a$ - atomic heat capacity, $\tau_{ep}$ - time of electron-phonon relaxation (3 pc), $T_e$ - the electron temperature, $T_a$ - the temperature of the atoms, $\alpha_e$ and $\alpha_a$ - thermal diffusivity; $E_F$ - Fermi energy; $k_B$ - Boltzmann constant.

To simulate the effects of a femtosecond laser radiation on the skin, we chose the following boundary conditions:

$$T_e|_{x=0} = T_e|_{x=L} = T_0 \quad (2.1)$$

$$\frac{\partial T_e}{\partial x}|_{x=0} = \frac{\partial T_e}{\partial x}|_{x=L} = 0 \quad (4.2)$$

Since the pulse width is negligible ($t \ll \frac{\lambda^2}{a_t}$, $t \ll \frac{\lambda^2}{a_a}$, where $\lambda$ - a spatial representation of the pulse, and the thermal diffusivity of biological tissue: $\alpha_a = 1.54 \times 10^{-3}$ cm$^2$/c [15], a $\alpha_a < \alpha_e$), we can put $a_e \frac{\partial^2 T_e}{\partial x^2}, a_a \frac{\partial^2 T_a}{\partial x^2} = 0$, and $a_{ehv} \frac{\partial T_e}{c_e} \cdot J(t,z)$ can be replaced by a function $\Gamma \delta(\lambda - vt)$ describes a heat source due to the absorption of radiation in the environment. Solution can be obtained in the form of:

$$T_e(t) - T_e(0) = \int_0^t \left( A + \left(1 - A\right) \exp(-\lambda(t - t')) \right) \cdot \Gamma \delta(\lambda - vt') dt' \quad (3.1)$$

$$T_a(t) - T_a(0) = \frac{1}{\tau_{ep} c_e} \int_0^t \left( 1 - \exp(-\lambda(t - t')) \right) \cdot \Gamma \delta(\lambda - vt') dt' \quad (3.2)$$

where $A = \frac{1}{C_e} + \frac{1}{C_e + C_a}, \ \lambda = \frac{1}{\tau_{ep} c_e} + \frac{1}{c_a}$.
4. Results

With the help of numerical simulation propagation of radiation in the skin tissues was obtained the data of the intensity distribution in depth:

Figure 2. The intensity of the radiation on the depth of penetration (at $\lambda = 800$ nm).

Figure 2 shows that at a depth of 0.3 mm the radiation intensity is less than 30% of the initial level. Based on these data, we assume that most of the radiation is absorbed in a thin layer of the epidermis.

The dynamics of the electron subsystem can be described by the energy distribution. Figure 3 shows the energy distribution of the electrons as a function of time after the pulse: status of the electronic subsystem immediately after exposure, after 1 ps (some of the electrons relaxed after transferring energy to the phonon subsystem), more than 3 ps (most of the electrons transferred energy to the atomic subsystem, the whole system tends to thermodynamic equilibrium).

The dynamics of the electron subsystem can be described by the energy distribution:
Figure 3. The distribution of the electron energy depending on the time: 1 - energy transfer to the electron subsystem, 2 and 3 - partial relaxation of electrons and atomic energy transfer subsystem.

Thus the dynamics of electron-phonon subsystem can be represented as:

Figure 4. Thermodynamics of system, where $T_e$ is the dynamics of the electron gas temperature, $T_a$ is the dynamics of the crystal lattice temperature.
The process of exposure to the skin can be divided into three stages: the first - during the action of a femtosecond pulse multiphoton excitation of water molecules. The ionization energy in this process is 6.5 eV, so for the ionization of one water molecule about 5 photons (800 nm) are required, which is the reason for the decrease of the quantum efficiency of the process (≤ 20%); at the same time there is the process of impact ionization. As a result by the end of the laser pulse \( N_{\text{max}} \approx E/\hbar \omega \) (\( E \) is the energy of the pulse) of the electrons will be initiated in the upper ionized water molecules with more energy \( U_a = 6.5 \) eV. The second stage occurs after the action of a femtosecond pulse and continues until the full transfer of electronic energy to phonon subsystem, thus there is a cooling of the electron gas and heating the collagen. The third stage - the heat distribution by bulk.

5. Discussion
The maximum temperature of the electron gas is achieved at the end of the pulse; the phonon subsystem can be heated to a maximum temperature in a time longer than the duration of the pulse. Thus femtosecond radiation exposure on the skin is the process of heat transferring, extended in time to far greater time, than the duration of the pulse. From this system of equations the time at which the temperature of the crystal lattice of the gas reaches a maximum is calculated by the formula [13]:

\[
t_{\text{max}} \approx C_e \ln(1 + \frac{\beta C_a}{\kappa a^2 C_e})
\]

where \( \beta \) - the heat transfer coefficient between the electronic and lattice subsystems; \( c_i, c_e \) - the heat capacity of the crystal lattice and the electron gas; \( k \) - the lattice thermal conductivity. However, if we believe that the radiation is absorbed by a thin layer, the maximum temperature will be almost identical under the influence of 10 fs and 150 fs pulses with the same energy. Thus the three stages of exposure for short times can be set independently (since the time of the pulse is much shorter than the time of establishing the equilibrium temperature) between the atomic lattice and the electron gas which in its turn is negligibly compared with the time characterizing the heat dissipation. A more detailed analysis of the system of equations is needed in terms of the intensity distribution in the volume of the illuminated object and keeping multiphoton effects which depend on the intensity.

6. Conclusion
A mathematical model of femtosecond radiation as it passes through the skin was presented. With the help of numerical simulation (Monte-Carlo method), the dependence of the radiation intensity on the depth of penetration was measured. The solution of the equations was made by analytical methods describing the electron balance between electronic and atomic subsystem, while establishing thermal equilibrium. The mechanism of femtosecond radiation exposure on the skin was described.

Acknowledgements
Results of this work were obtained within the framework of the state order №3.1675.2014/K of Ministry of Education and Science of the Russian Federation.

Thanks to Sergey Chivilikhin for consultations on mathematical questions and substantial contribution to the paper.

7. References
[1] Akhmanov SA, 1988 Optics femtosecond laser pulses (Moscow: Nauka)
[2] Rulliere, C. 2005 Femtosecond laser pulses (Springer, Ed. Rulliere)
[3] Yilbas, B. S., and A. F. M. Arif. 2005 Laser short-pulse heating with time-varying intensity and thermal stress development in the lattice subsystem. (Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science) pp 73-81
[4] Habbema, Louis, 2012 Minimally invasive non-thermal laser technology using laser-induced optical breakdown for skin rejuvenation (Journal of biophotonics) pp. 194-199.
[5] GOST 50723-94 1995 Laser Safety. General safety requirements for the design and operation of laser products (M.: Publishing Standards) 34c.
[6] Sriramoju V., Alfano R. R. 2015 *In vivo studies of ultrafast near-infrared laser tissue bonding and wound healing* (Journal of biomedical optics)

[7] Pushkareva AE (2008) *Methods of mathematical modeling of biological tissues in optics: the manual* (St. Petersburg: ITMO)

[8] Fredriksson, Ingemar 2008 *Optical microcirculatory skin model: assessed by Monte Carlo simulations paired with in vivo laser Doppler flowmetry* (Journal of Biomedical Optics)

[9] P. Stampfli and K. H. Bennemann 1990 *Theory of the instability of the diamond structure of Si, Ge, and C induced by a dense electron–hole plasma* (Phys. Rev. B42)

[10] P. Stampfli and K. H. Bennemann 1992 *Dynamical theory of the laser-induced instability of silicon* (Phys. Rev. B46)

[11] M. F. Kropman and H. J. Bakker 2001 *Dynamics of water molecules in aqueous solvation shells* (Science 291(5511)).

[12] M. F. Kropman, H. K. Nienhuys, and H. J. Bakker 2014 *Real-time measurement of the orientation dynamics of aqueous solvation shells in bulk liquid water* (Phys. Rev. Lett. 88(7)).

[13] Lipp V. P. et al. 2014 *On the interatomic interaction potential that describes bond weakening in classical molecular-dynamic modeling* (Journal of Optical Technology) pp 254-255.

[14] Dyukin R. V. et al. 2011 *Dynamics of the permittivity of a semiconductor acted on by a femtosecond laser* (Journal of Optical Technology) pp. 558-562.

[15] Serebryakov VA et al. 2015 *Laser mid-infrared spectral range for precision surgery* (Opt/ Opt.. - V. 82)