

# Chapter 1

## Methods Describing the Interaction of Laser Radiation with Biological Tissues

**Abstract** We consider the structure and optical properties of biological tissues, blood and thermophysical characteristics of the elements in the skin tissue.

### 1.1 Introduction

Scattering and absorption of electromagnetic radiation are widely used in various fields of science and technology to study the structure and properties of heterogeneous environment. Theoretical models, techniques of experimental research and methods of data interpretation were developed by specialists of various disciplines (from astrophysics to laser ophthalmology), so there are differences in traditions and terminology barriers that impede the efficient interaction of different schools of thought. For example, experts in the field of atmospheric optics and astrophysics use the ideology of natural radiation transport equation, but for interpretation of data, small-angle X-ray and neutron scattering—more familiar language—using the apparatus of the correlation functions and structure factor scattering.

Due to the large variety and structural complexity of the biological environment the development of adequate models of optical scattering and absorption of light is often the most difficult part of the study. These models cover almost all the major sections of optical dispersion media: a simple single-scattering approximation, incoherent multiple scattering, which is described by the transport equation, and the multiple scattering of electromagnetic waves in condensed systems interacting lenses or irregularities.

Before proceeding to the consideration of principles of mathematical models to calculate the interaction of laser radiation with biological structures and objects of different degrees of complexity and organization, consider the structure and optical properties of biological tissues.

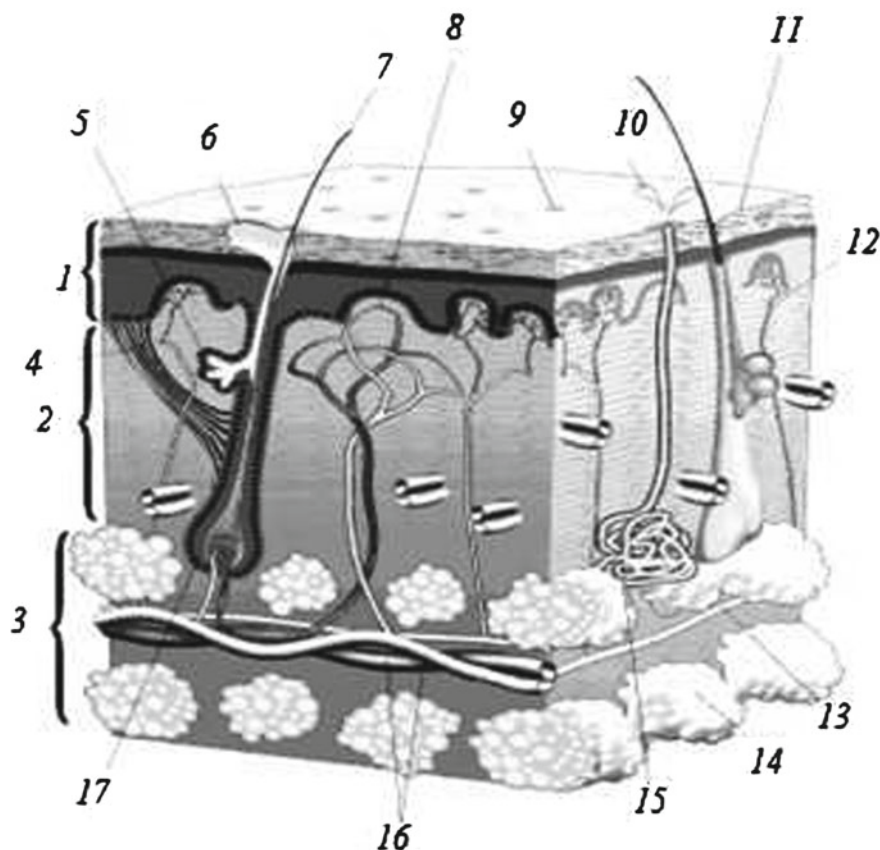
## 1.2 The Structure and Optical Properties of Biological Tissues

From the point of view of controlling the optical parameters of tissues the fibrous tissues (sclera eyes, dermis of skin, dura, etc.) are of the most interest makes. Fibrous tissue make up approximately 50 % of body weight. Loose connective tissue of fatty tissue, dens, tendons and intermuscular fascial layers, derma of skin and an intraorganic stroma of parenchymatous organs, neuroglia and peritoneum are all connecting fabrics or fibrotic thanks to the existing characteristics of fibrillar structures [1]. All varieties of fibrous tissue in spite of their morphological differences, are built on a common, with the same principles, which mainly include the following [1]: (a) the connective tissue contains cells, but compared to other tissues there are fewer. As a result, the amount of intercellular substance is larger than the cellular elements; (b) the connective tissue is characterized by the presence of fibrous (fibrous) structures—collagen, elastin and reticular fibers, which are the main structural elements of the fibrous tissue, and surrounded by intercellular substance; (c) the connective tissue is rich with the intercellular substance when has a very difficult chemical composition. The characteristic component of the structure in fibrous tissue (tendons, cartilage, the dermis of the skin, eye sclera, etc.) are the collagen fibers. They carry protective functions. For collagen, the specific amino-acid structure and a unique spatial location of polypeptide chains is a characteristic. As opposed to other proteins, large number of amino acids are contained in collagen: glycine, proline, hydroxyproline, lysine, oksilizin. Collagen makes up 25–30 % of the total protein in adult, or 6 % of total body weight [2]. The molecule of collagen consists of three polypeptide chains forming structure of a threefold spiral. The length of the collagen molecule is 280 nm, the diameter of 1.4–1.5 nm [3].

### The Structure and Optical Properties of the Skin

Human skin is an example of a multicomponent turbid biological medium and it is very difficult to describe the construction of the models. Optical characteristics of such complex environment as a whole depend on many factors. To correctly build the model of the skin and the description of optical properties one needs to get some understanding in the biological features of the structure of skin (see Fig. 1.1).

Skin consists of two main layers [4]. The external layer is the multilayered flat keratinized epithelium—epidermis. The average thickness of the epidermis, of which there is relatively little change in thickness, is approximately 100  $\mu\text{m}$  [5]. Epidermis consists of two various layers of cells: an external, corneal layer of dry acaryocytes (*Stratum corneum*) and inside cellular layers, i.e. actual epidermis from which, after modification, there are superficial cells: (*Living epidermis*) [6]. The main type of cells in this epithelial continuum is the epidermal cell, most often called keratinocyte, so called because the family of fibrous proteins is keratins. The epidermis unites subpopulation of migrating cells of tree-like types: melanocytes and melanosomes



**Fig. 1.1** Biological structure of the human skin: 1 epidermic, 2 dermis, 3 hypodermic fatty tissue, 4 muscle, lifting the hair, 5 oil gland, 6 fatty secret, 7 hair, 8 capillaries, 9 oscule, 10 sweat, 11 keratin (corneal layer), 12 nerve ending, 13 nerve, 14 fat lobule, 15 sweat gland, 16 blood vessels, 17 hair sac

are pigment-producing melanin; Langerhans cells, considered as monokletki derived from bone marrow, and Merkel cells, considered as derivatives of keratinocytes [2].

Epidermis is constantly in a state of renovation: the division of basal keratinocytes, some daughter cells move out, and then they separate, go to the upper layers and attach to the corneal layer. Normal human epidermis is renewed in a period which lasts 45–75 days [2]. The leading mechanism in the difficult and multi-stage process directed on the formation of a corneal layer of skin is the formation of a keratin: the main protein in epidermis. In the process of cellular replacement, the epidermis forms the pigment melanin, which is a polymer-granules which are 30–400 nm in diameter [7]. Melanin is produced in melanocytes, containing large number of structural organelles: melanosomes filled with pigment. Melanosomes have a diameter of about 400 nm [7].

Under the epidermis is dense fiber tissue and elastinic tissue, which is called the dermis. Dermis is the main component and volume of the skin. The average thickness of the dermis is about 1500–2000  $\mu\text{m}$  [8]. In the dermis there are the elements of the vascular and nervous systems, the excretory gland. Under the skin is the hypodermis. Hypodermis is a subcutaneous tissue, which is a fatty and connective tissue of varying thickness citebriggman.

The dermis is separated from the epidermal basal membrane and gradually goes into the subcutaneous fatty tissue. The composition of the dense connective tissue in the dermis includes collagen and elastin fibers with a diameter of about 60 nm, packed in bundles of fibers with a diameter about 60 nm called lamels, and an amorphous substance (interfibrilyarny gel), of salt and water. Connective tissue contains widely branched vascular structures of the skin, the nervous network and epithelial glands. Derma is randomly divided into two anatomical areas: papillary (Stratum papillary dermis) and reticular (Stratum reticulare dermis) [9]. More subtle is the so-called papillary dermis, the outer part of the dermal connective tissue that is formed under the epidermis.

Papillary dermis contains more free distribution of elastin and collagen fibers than the reticular layer. Bundles of collagen fibers of papillary dermis are 0.3–3.0  $\mu\text{m}$  in diameter. Papillary dermis also contains lymphatic plexus and blood vessels. The second major part of derma, and the underlying papillary dermis, is called the reticular dermis. Vascular structure of the skin is clearly divided into two systems: a system of vessels that provide nourishment skin and deep, mainly subcutaneous, and arterial and larger venous capillaries which perform the function of heat exchangers of blood with the environment [2].

Biological tissues, such as skin, are optically inhomogeneous absorbing media with an average refractive index greater than that of air, so the boundary between biological object-air part of the radiation is reflected (Fresnel reflection), and the remaining part penetrates the tissue. The skin is characterized by a significant light scattering, i.e., it is highly scattering turbid medium, because it consists of a large number of scattering centers randomly distributed in the volume. The degree of scattering depends on the wavelength of the radiation and the optical properties of biological tissues.

Absorption of light is a physical phenomenon, which characterizes the energy loss when light passes through the biological structure (skin) [10]. The energy of the absorbed light transferred into heat is spent on photochemical reactions or released in the form of radiation luminescence. The absorption spectra of any tissue, including skin, determined by the presence of all biologically important molecules involved in double bonds (chromophores of skin), and containing water in biological tissues. In the epidermis the role of chromophores perform various fragments comprising the amino acids and nucleic acids, absorbing light in the ultra-violet wavelength range [11]. In the visible spectrum one of the most prevailing chromophores of skin is the pigment melanin [2]. The absorption spectrum of melanin has no pronounced absorption bands; however, it effectively absorbs in all spectral regions from 300 to 1200 nm. In the near ultraviolet radiation and visible regions of the spectrum, aside from melanin, the basic skin chromophores are bilirubin, vitamins, flavins, flavin

ferments, carotenoids, phycobilins, phytochrome, and others, as well as elastin and collagen fibers [12].

The dermis of the skin include blood vessels, which contain hemoglobin, the absorption spectrum of which significantly affects the absorption spectrum of the skin. The higher the content of blood in the dermis, the greater absorption of its radiation at corresponding to the absorption of blood. Therefore, when calculating the optimal parameters of the radiation blood content in the dermis and the diameter of blood vessels should be considered. In the in vivo biological tissue hemoglobin binds oxygen present in the blood. The absorption spectra of the two forms of hemoglobin are slightly different from each other: oxyhemoglobin has an absorption band near 405 nm (Sore band) and the characteristic double peak absorption in the area of 545–575 nm; deoxyhemoglobin strongly absorbs near 430 nm and a weak close to 550 nm [13, 14].

In the infrared region of the spectrum all biomolecules have quite intense vibrational absorption bands.

Starting with  $\lambda = 1500$  nm and above, the absorption spectrum of the skin is largely determined by the absorption spectrum of water.

The absorption of subcutaneous fatty tissue is defined as absorption bands of lipids, water, and  $\beta$ -carotene. The main absorption band of fatty tissue lies in the ultraviolet and infrared regions of the spectrum. Skin tissue is characterized by a significant light scattering, as it consists of a large number of randomly distributed scattering centers in volume [15]. Light scattering happens because of fluctuations in the density of scatterer and refractive index fluctuations in the volume of tissue.

The nature of scattering depends on the correlation of the wavelength of the scattered radiation and the size of the light scattering particles, and the ratio of the refractive index of the scattering particle and its environment [16]. Light scattering in media consisting of a large number of particles is significantly different from the scattering of light by individual particles.

This is explained by firstly the interference of the waves scattered by the individual particles with each other and with the incident wave, and second, in many cases, multiple scattering effects are important (reradiation), when the light is scattered by a single particle, others are dissipated again and thirdly, the interaction between the particles does not allow them to consider independent movement.

To account for multiple scattering and absorption of the laser the beam is broadened and attenuated during propagation in the skin. Volume scattering is the cause of a significant proportion of the radiation propagation in the reverse direction (backscattering). Cell membranes, nucleus and organelles are the main scatterers in many biological tissues. The absorbed light is converted into heat, is reradiated as fluorescence or phosphorescence, and spent photobiochemistry reaction.

The absorption spectrum is determined by the type of dominant absorption centers and water content in the tissue. The natural photo of laser radiation of biological tissue is determined by its composition and the absorption coefficient at the wavelength of radiation. The ultraviolet and infrared ( $\lambda > 2$  nm) spectral region dominates the absorption and scattering, and the contribution is relatively small and shallow. Light penetrates into the biological tissue, only to one or more cell layers in the

short-visible and spectrum of light penetration depth for a typical tissue that is 0.5–2.5 mm. In this case the main role is absorption and thus scattering, which predominates in the reflected radiation from the skin (affects approximately 15 % to 50 % of the incident beam). At wavelengths from 600 to 1500 nm scattering prevails over absorption and penetration depth is increased to 8–10 mm.

Depending on the type of tissue the wavelength of the reflection coefficient can vary widely. Thus, the optical properties of biological tissue are determined by its structure, physiological condition, the level of hydration, homogeneity, specific variance, the nature of the measurements in-vivo-in-vitro and others. The attenuation of the laser beam in biological tissue follows the exponential law. The intensity of the collimated radiation is estimated under Bouguer law. Other important optical parameters of the tissue is the optical depth penetration.

The significant value of the scattering anisotropy of biological tissues and multiple scattering gets a deviation from the Bouguer law. In the description of the effects that occur in the tissues under the influence of radiation, absorption of water is important because it is the main component of most tissues. The human body contains from about 55–65 % water. An adult with a body weight of 65 kg contains an average of 40 liters of water, of which about 25 l is inside cells, 15 l are in the extracellular fluids. Water is the primary medium in which many chemical reactions take place and the physical and chemical processes (assimilation, dissimulation, osmosis, diffusion, transport and others) that important for life. In the ultraviolet, visible and near infrared wavelengths the absorption coefficient of water is very small. In these areas, the absorption of tissue determines the absorption spectra of pigments, especially for the skin—the absorption spectra of melanin and blood count (hemoglobin and oxyhemoglobin). Melanin absorption is the most important component of the total absorption of the epidermis and the corneal layer.

For the calculation of interest the optical density ( $OD$ ) of the epidermis is needed, which is the result of the following product:

$$OD = \mu_{\text{melanin}} \cdot h,$$

where  $\mu_{\text{melanin}}$  is the absorption coefficient of melanin,  $h$  is the thickness of the epidermis.

Optical density depends on the amount of melanin in the basal layer, which depends on many factors, the main one of which is the type of skin. Note that the dermis is very different from the epidermis in the composition and structure. The scattering coefficient of the dermis stronger at shorter wavelengths. Scattering plays a major role in determining the depth of penetration of radiation at different wavelengths in the dermis. Therefore, longer wavelengths penetrate deeper rather than shorter. It is explained by the presence of melanin, which absorbs more shorter wavelengths than long. According to [15] for a sample consisting of the epidermis and dermis, the depth of which is 0.15–0.2 mm (wavelength 632.8 nm) and 0.21–0.4 mm (wavelength 675 nm).

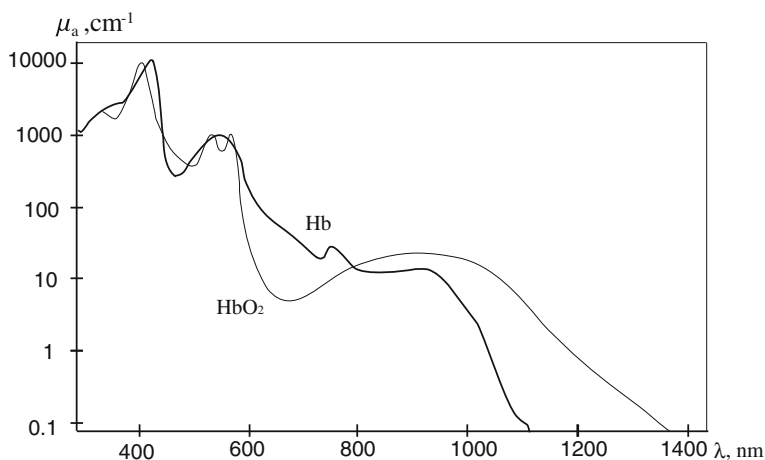
### 1.3 Structure and Optical Properties of Blood

Blood is one of the most important biological fluids. Blood is the liquid part of the plasma (57 % of blood volume) and suspended in its cell (enzymatic) elements (43 %). Plasma consist from 90–91 % water; 6.5–8.0 % are protein molecules and the remaining 2 % are low molecular substances. In addition, the blood contains platelets 99 % of the blood cells are red blood cells, and 1 % are white blood cells and platelets.

Red blood cells have a biconcave disk shape with a diameter of about  $7\text{ }\mu\text{m}$  and a thickness varying from 1 to  $2\text{ }\mu\text{m}$  center to the edges. The cell contains hemoglobin molecules that easily join the oxygen molecules, when they are converted into oxyhemoglobin. Accordingly, we have different venous and arterial blood. The hematocrit is volume percentage of red blood cells in whole blood.

The most important parameter is also the oxygen saturation ( $OS$ ), defined as the ratio of oxygenated hemoglobin to total hemoglobin. The absorption of the blood is determined mainly by water absorption, hemoglobin and oxyhemoglobin. The absorption spectra of these pigments is shown in Fig. 1.2 [17]. If the hematocrit increases, this means that the number of red blood cells is increasing and there is an increase in the scattering. At higher hematocrit  $H > 0.5$  erythrocytes stick together, forming a homogeneous mass absorbed by hemoglobin and scattering occurs on the plasma cavity located between the masses of red blood cells. This section contains the optical parameters of the biological structures without their temperature dependences. Note that with increasing temperature the optical characteristics of tissues and their components will change.

Now consider the basic principles of mathematical models to calculate the interaction of laser radiation with a turbid medium. One example of such an environment



**Fig. 1.2** The absorption spectra of hemoglobin and oxyhemoglobin.



is human biological tissue. Biological tissue is a multilayer medium containing various inclusions, such as, for example, blood vessels, in which the blood moves. Consider the main approaches in the theory of mathematical models that describe the interaction of laser radiation with multi-layered turbid media.

## References

1. T.T. Berezov, B.F. Korovkin, *Biological Chemistry*. (Medicine, Moscow, 1990)
2. E.A. Pylypenko, The reflectivity and fluorescence spectroscopy of human skin in vivo: Ph.D. dissertation, Saratov: Saratov State University, 1998
3. G.D. Weinstein, R.J. Boucek, Collagen and elastin of human dermis. *J. Investig. Dermatol.* **35**, 227–229 (1960)
4. G.F. Odland, The morphology of the attachment between the dermis and the epidermis. *Anat. Rec.* **108**, 339–413 (1950)
5. S.L. Jacques, The role of skin optics in diagnostic and therapeutic uses of lasers, in *Lasers in Dermatology*. (Springer-Verlag, Berlin, 1991) pp. 1–21
6. The skin (structure, function, general pathology, therapy) Ed. AM Chernuha, A.M., Frolov E.P. Moscow, 1982
7. N. Kollias, R.M. Sayer, L. Zeise, M.R. Chedekel, Photoprotection by melanin. *J. Photochem. Photobiology B.* **9**, 135–160 (1991)
8. I.V. Meglinski, Simulation of the reflectance spectra of optical radiation from a randomly inhomogeneous multilayer strongly scattering and absorbing light environments using the Monte Carlo. *Quantum Electron.* **31**(12), 1101–1107 (2001)
9. G.F. Odland, Structure of the skin, in *Physiology, Biochemistry, and Molecular Biology of the Skin* ed. by L. A. Goldsmith (Oxford: University Press, New York, 1991) pp. 3–62
10. V.V. Tuchin, Light scattering study of tissues. *Successes phys. sci.* **167**, 517–539 (1997)
11. U.A. Vladimirov, A.Y. Potapenko, *Physical and Chemical Basis of Photo-Biological Processes*. (Higher school, Moscow, 1989)
12. S.R. Utz, J. Barth, P. Knuschke, YuP Sinichkin, Fluorescence spectroscopy of human skin. *Proc. SPIE.* **2081**, 48–57 (1993)
13. P.H. Andersen, P. Bjerring, Spectral reflectance of human skin in vivo, *Photodermatol. Photoimmunol. Photomed.* **7** 5–12 (1990)
14. Anderson R. R., Parrish J. A., Jaenicke K. F. Optical properties of human skin, in *The Science Photomedicine*, ed by J.D. Rogan, J.A. Parrish (Plenum Press, New York, 1982) pp. 147–194
15. W.-F. Cheong, S.A. Prahl, A.J. Welch, A review of the optical properties of biological tissue. *IEEE J. Quant. Electr.* **26**(12), 2166–2185 (1990)
16. C.F. Bohren, D.R. Huffman, *Absorption and Scattering of Light by Small Particles*. (Mir, Moscow, 1986)
17. K. Johnson, A. Guy, Impact of non-ionizing electromagnetic radiation on biological systems and the environment. *Proc. IEEE.* **60**(6), 49–79 (1972)



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