Optical properties of biological tissues evaluation with a hybrid goniometer and integrating-sphere technique and Monte Carlo mathematical modelling

N V Kovalenko¹, G A Aloian¹, D M Mukhankov², O A Ryabushkin¹²
¹ Moscow Institute of Physics and Technology, Institutskiy per. 9, Dolgoprudny
Moscow region, 141700, Russia
² Fryazino branch of Kotelnikov Institute of Radio-engineering and Electronics of RAS, Vvedensky Sq.1, Fryazino Moscow region, 141190, Russia

E-mail: nikiomsol94@gmail.com

Abstract. A novel technique for measurements of optical properties of biological tissue samples is proposed. The scattered radiation pattern of the irradiated tissue was measured experimentally by changing the distance from the sample to the inlet of the integrating sphere. A Monte Carlo method was used for simulations of the radiation propagation in the sample. The optical properties of the aloe arborescens were determined via comparison of the simulation results to the experimentally measured angular dependence of the light power scattered and transmitted through the sample.

1. Introduction
Optical radiation is widely applied for the development of various methods for medical diagnostics and surgical procedures in ophthalmology, dentistry, etc. [1]. Laser radiation is also used for the analysis and control of the food quality [2]. In turn, light-emitting diodes (LEDs) employed for the optimization of cultivation processes of medicinal and food plants [3]. An aloe (lat. Aloë) plant is one of the most promising candidates for the study of photothermal phenomena. It has a wide range of pharmacological applications [4]. The extract of aloe is used in the green synthesis of nanoparticles [5].

In order to describe the interaction of laser radiation with biological tissues, it is necessary to know its optical properties. The main optical parameters of biological materials are the refractive index $n(\tilde{s}, \lambda)$, absorption $\mu_a(\tilde{s}, \lambda)$ and scattering $\mu_s(\tilde{s}, \lambda)$ coefficients and the phase scattering function $p(\tilde{s}, \tilde{s}', \lambda, \lambda')$, that depend on the radiation wavelength $\lambda$ and its propagation direction $\tilde{s}$. Along with mentioned parameters the scattering anisotropy $g(\tilde{s}, \lambda)$, i.e. the average cosine of the angle between radiation propagation direction before and after scattering $\cos \theta$, is also introduced.

The propagation of radiation inside an isotropic medium in the absence of inelastic scattering can be described using the basic equation of the transport theory:

$$\frac{1}{c} \frac{\partial I(\tilde{r}, \tilde{s}, t)}{\partial t} = -\left(\tilde{s}, \nabla I(\tilde{r}, \tilde{s}, t)\right) - \mu_s I(\tilde{r}, \tilde{s}, t) \quad \quad \quad (1)$$

$$+ \mu \int_{4\pi} p(\tilde{s}, \tilde{s}') I(\tilde{r}, \tilde{s}, t) d\omega' + \varepsilon(\tilde{r}, \tilde{s}, t)$$
Where \( I(\vec{r}, \vec{s}, t) \) is the brightness at the point corresponding to the radius-vector \( \vec{r} \), \( \mu_t = \mu_a + \mu_s \) is the attenuation coefficient, \( e(\vec{r}, \vec{s}, t) \) - function describes the distribution of light sources, \( d\omega' \) - is the solid angle with the normal-vector \( \vec{s}' \).

A conventional measurement approach is based on the application of optical integrating spheres that average the power of the radiation that enters inside [2], [6]. Several parameters can be measured using integrating spheres: radiation scattered by the sample in backward and forward directions, as well as the collimated transmitted radiation. Optical parameters of the investigated tissue can be obtained relying on experimentally measured data and mathematical modeling of radiation propagation inside the sample. Although an experimental base is well-developed, the parameters of various tissues reported in the literature can considerably differ [7]. This is primarily due to initial distinctions of the properties of different samples and non-identical experimental conditions. On the other hand, however, a small number of measured parameters used for the simulations also plays a significant role.

The approach based on goniometric measurements is used to improve modelling accuracy. Here the angular dependence, i.e. directional pattern, of the radiation scattered by the sample is investigated. Such measurements allow accurate determination of the phase scattering function and are usually carried out with samples having thicknesses that commensurate with a free path of the photon inside the substance \( \mu_t^{-1} \). For some biological tissues, it was shown that a good agreement between experimental and calculated data can be achieved using the Henyey-Greenstein (HG) function, as the phase scattering function [8]:

\[
p(\theta) = \frac{1}{2} \frac{1-g^2}{(1+g^2-2g \cos \theta)^{3/2}}
\] (2)

In this paper, we introduce a novel method for characterization of optical properties of biological tissues, which combines the advantages of both an application of integrating spheres and a goniometric approach. The optical properties \((\mu_a, \mu_t, g)\) of aloe arborescens were measured using the proposed technique.

2. Materials and methods

A block-scheme of the experimental setup is shown in figure 1. The aloe sample was irradiated by the modulated laser radiation with a wavelength at 589 nm and 0.3 mW average power.

The sample was located between two integrating spheres \( S_T \) and \( S_R \) (indexes "T" and "R" refer to transmittance and reflectance respectively). Each sphere was \( D_p = 8 \) cm in diameter and had \( D_{hole} = 7 \) mm round hole. The centers of the spheres were located along the laser radiation propagation direction. The distance \( L_T \) between the sample and the outlet of \( S_T \) was varied, as well as the distance \( L_R \) between the sample and the inlet of \( S_R \).

The measurement of scattered radiation is based on a lock-in detection. The incident radiation was modulated using the optical chopper. The scattered radiation power, averaged inside the sphere, was measured at the modulation frequency using \( D_T \) and \( D_R \) photodetectors with built-in amplifiers.

The dependences of \( P_T(L_T) \) and \( P_R(L_R) \) powers of the optical radiation going into the spheres on the distances \( L_T \) and \( L_R \) were measured. Obtained power values were normalized in respect to the corresponding values measured for an incident optical power using each sphere separately. All measurements were carried out under normal conditions.

Longitudinal slices of the pulp of aloe arborescens leaf were used as the samples. Samples with the thickness \( h_s \) of 1.68 and 2.18 mm were made using a razor blade. Each sample was sandwiched between the microscope slides. In order to avoid the mechanical deformation of the samples the distance between the covering slides was fixed with the help of rigid spacers.
3. Experimental and simulation results

The measured dependences of normalized optical powers $P_T(L_T)$ and $P_R(L_R)$ on corresponding distances are shown in figure 2. There are monotonically decreasing functions of distances. For the dependence $P_T(L_T)$ at large distances $L_T$, there is a tendency to converge to a non-zero value, which corresponds to the collimated transmittance.

![Figure 1. A block-scheme of the experimental setup](image)

**Figure 1.** A block-scheme of the experimental setup

The aloe slices were considered as an isotropic medium without an inelastic scattering. In such case its interaction with laser radiation can be described using the equation (1).

The direct problem of the propagation of light in a sample was solved exploiting the Monte Carlo method. It is based on the simulation of independently propagating photon groups. The program code was written and verified according to the paper [8]. The HG function (2) was used as the scattering phase function.

For the approximation of the dependence $P_T(L_T)$, we calculated the fraction of photons enclosed in the circle with a diameter of $D_{hole}$, which center was located on the axis of the incident radiation at a given distance $L_T$. In turn, for the approximation of the dependence $P_R(L_R)$ the difference of the fractions of photons enclosed in the circles with a diameter of $D_{hole}$ with the centers located at the distance $L_R$ and at the distance $L_R + D_{sp}$ was calculated.

![Figure 2. Experimental and simulation data of obtained for the pulp slice (1.68 mm) of aloe leaf.](image)

**Figure 2.** Experimental and simulation data of obtained for the pulp slice (1.68 mm) of aloe leaf.
The experimental data were approximated by solving the direct problem (1) via variation of \( \mu_a, \mu_s, g \) parameters. The best fitting values of corresponding parameters obtained for two investigated aloe samples are listed in table 1. It can be seen from the figure 2 that calculated data are in good agreement with experimentally measured ones. Differences in the restored optical properties of the aloe slices may be associated with inhomogeneities arising from the fabrication of samples.

Table 1. Simulation results for the aloe samples optical properties.

| \( h_s, \text{mm} \) | \( \mu_a, \text{cm}^{-1} \) | \( \mu_s, \text{cm}^{-1} \) | \( g \) |
|-----------------|-----------------|-----------------|-----|
| 1.68            | 0.5             | 7.5             | 0.952 |
| 2.18            | 0.5             | 9.8             | 0.952 |

4. Conclusions
We have introduced an original experimental method for measurements of optical properties of different biological tissues. It is based on measurements of the scattered radiation pattern of the irradiated tissue using integrating spheres. Optical parameters of the tissue are obtained relying onto the experimental data using Monte Carlo simulations.

Larger amount of experimental data comparing to conventional integrating sphere methods makes the proposed method more reliable. Furthermore, this method deals with integral characteristics and therefore has several advantages against a goniometric approach. A novel method was successfully applied for the determination of optical properties of the pulp of \textit{aloe arborescens} leaves.

References
[1] Niemz M H 2004 Laser-tissue interactions: fundamentals and applications ; with 33 tables (Berlin: Springer)
[2] Zhang M 2019 Optical properties of blueberry flesh and skin and Monte Carlo multi-layered simulation of light interaction with fruit tissues Postharvest Biol. Technol. 14
[3] Berkovich Yu A, Konovalova I O, Erokhin A N, Smolyanina S O, Smolyanin V G, Yakovleva O S, Tarakanov I G and Ivanov T M 2019 LED lighting optimization as applied to a vitamin space plant growth facility Life Sci. Space Res. 2093–100
[4] Singab A-N B, El-Hefnawy H M, Esmat A, Gad H A and Nazeam J A 2015 A Systemic Review on \textit{Aloe arborescens} Pharmacological Profile: Biological Activities and Pilot Clinical Trials: ALOE ARBORESCENS PHARMACOLOGICAL PROFILE Phytother. Res. 29 1858–67
[5] Sangeetha G, Rajeshwari S and Venckatesh R 2011 Green synthesis of zinc oxide nanoparticles by aloe barbadensis miller leaf extract: Structure and optical properties Mater. Res. Bull. 46 2560–6
[6] Yaroslavsky A N, Schulze P C, Yaroslavsky I V, Schober R, Ulrich F and Schwarzmaier H-J 2002 Optical properties of selected native and coagulated human brain tissues in vitro in the visible and near infrared spectral range Phys. Med. Biol. 47 2059–73
[7] Jacques S L 2013 Optical properties of biological tissues: a review Phys. Med. Biol. 58 R37–61
[8] Jacques S L 2011 Monte Carlo Modeling of Light Transport in Tissue (Steady State and Time of Flight) Optical-Thermal Response of Laser-Irradiated Tissue ed A J Welch and M J C van Gemert (Dordrecht: Springer Netherlands) pp 109–44