Study of the Optical Properties of Biological Tissues Quantitative Assessment Possibility using Spatial-Frequency Domain Imaging

Alexander V. Kolpakov, Yuliya V. Ivanova, Svetlana A. Yushina and Anastasia S. Semenova
Department of Biomedical Technical Systems, Bauman Moscow State Technical University,
2-nd Baumanskaya str., 5/1, Moscow, Russia

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Abstract: The paper is devoted to the study of the possibility of using spatial-frequency domain imaging (SFDI) technology in the tasks of visualizing neurovascular structures in the brain tissue during endosurgical intervention, as well as the detection and objective quantitative assessment of lesions in the tissues of the oral cavity. As a result of the initial stage of experimental studies in vivo, it was shown that SFDI allows tracking the dynamics of optical parameters of tissues as a result of changes in blood filling and is potentially applicable for detecting subsurface optical inhomogeneities in tissues.

1 INTRODUCTION

In recent decades, optical imaging has become increasingly important in the field of medicine and biology. The use of biological tissues optical properties is widely used: from fundamental research to obtain new knowledge about biological processes to screening and numerical assessment of the pathological processes stage.

The interest in optical methods is the result of their unique property - non-invasiveness. The sources of optical contrast are two main physical phenomena - absorption and scattering of photons in tissue.

One of the technologies for studying the optical properties of tissue is the spatial frequency domain imaging (SFDI). The main advantage of SFDI is the ability to separate absorption and scattering effects in the formation of optical contrast.

As a result of research in recent years, a number of laboratories have shown the possibility of visualizing the distribution and objective quantitative assessment of the optical properties of biological tissues using SFDI (Applegate, 2020; Svaasand et al., 1999; Cuccia et al., 2019; Svaasand et al., 1994; Cuccia et al., 2009; Hielscher et al., 1975; Groenhuis et al., 1983; O'Sullivan et al., 2012; Gioux et al., Carole et al., 2019).

At present, on the basis of the Department of Biomedical Technical Systems of the Bauman Moscow State Technical University, studies of SFDI are being carried out, the purpose of which is to determine the possibility of using SFDI in a number of areas of medicine, in particular:

- in neurosurgery to solve the problem of visualizing neurovascular structures in the brain tissue during endosurgical intervention. The hypothesis being tested is that due to the peculiarity of SFDI, namely, due to the possibility of separating with its help the contribution of absorption and scattering to the total attenuation of backscattered radiation, there is the possibility of separate visualization of blood vessels, as more absorbing structures, and nerves, as more dissipative;
- in dentistry for visualization and quantitative assessment at an early stage of inflammatory processes, as well as erosive and ulcerative lesions. The difference in the values of the absorption and scattering coefficients of intact and affected tissues of the oral cavity can be hypothetically determined using SFDI and used in the system for automatic detection and control of the dynamics of inflammatory and precancerous processes in the tissues of the oral cavity at an early stage.

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As a result of previously conducted research at the Department of Biomedical Technical Systems:

- proved that the problem of detecting blood vessels and cranial nerves during endoscopic removal of tumors of the base of the skull can be solved using the methods of automatic detection of blood vessels and cranial nerves based on methods of multispectral image analysis and quantitative spectrophotometry with local sensing in red and near infrared (hereinafter - RNIR) wavelength ranges (Safonova et al., 2019; Safonova et al., 2020; Safonova et al., 2019; Safonova et al., 2019; Safonova et al., 2019).

Under the conditions of the stand experiment the possibility of detecting blood vessels located in the tissues of the brain at a depth of up to 3 mm using images of the red and near infrared range confirmed (Kolpakov et al., 2021).

The possibility of visualization of the oral cavity soft and hard tissues structure using radiation of the near infrared wavelength range by diaphanoscopy has been proven, as well as the possibility of detecting lesions in the oral cavity tissues using visualization in the near infrared range (Kolpakov et al., 2016).

SFDI is a new quantitative imaging technique, a broadband diffuse optical technique that can separate the effects of absorption and scattering and therefore approximately determine the number of chromophores in tissues. The method can be used to measure the concentrations of tissue components such as oxyhemoglobin, deoxyhemoglobin, lipids, and water (Applegate et al., 2020).

Spatial frequency domain imaging consists of projecting a two-dimensional (2-D) light pattern, usually in the form of a harmonic periodic grating (HPG), and analyzing the effect of multiple scattering and absorption in tissue on the amplitude of attenuated radiation, backscattered or past. In this case, the amplitude of the attenuated radiation is considered as a function of the spatial frequency of the pattern.

2 MATERIALS AND METHODS

2.1 Stand for SFDI Research

To study the possibility of using SFDI, an experimental stand is required. Currently, scientists from Boston University (Applegate et al., 2020) have created an openSFDI guide to create such a stand from publicly available components (hereinafter - the stand).

The stand contains three main modules: a lighting module, a spatial modulation subsystem and an image registration module (Figure 1).

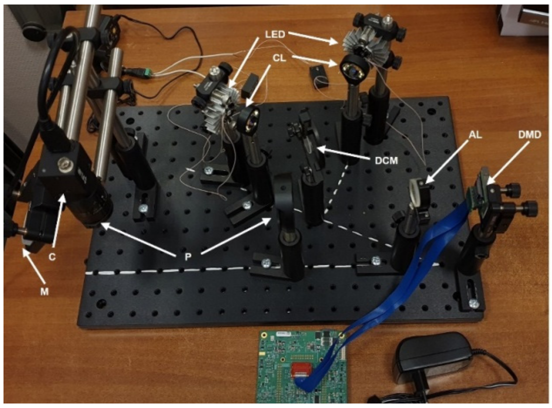


Figure 1: The complete stand (off State). LED – light-emitting diodes; CL - collimating lenses; DCM – dichroic mirrors; AL - achromatic lens; P - linear polarizers; M – guiding mirror; C - camera; DMD - digital micromirror device.

An example of generating a lighting pattern is shown in Figure 2. The object under study must be placed in the illumination area.

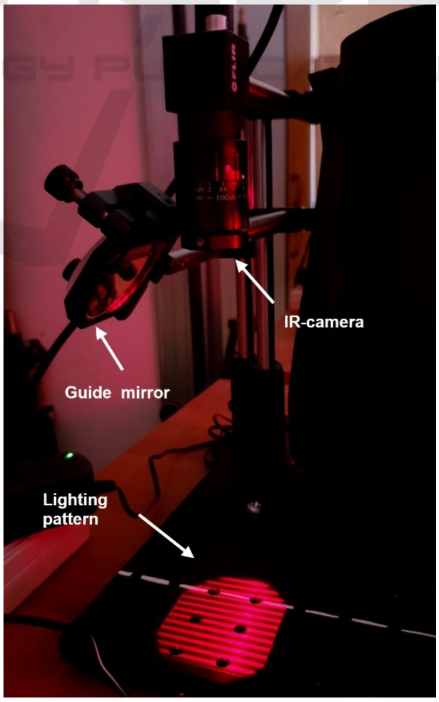


Figure 2: Registration of the template (HPG) at the stand.

The programming of the controller with the spatial modulator DMD was carried out in accordance with the instructions for the openSFDI system (Applegate et al., 2020).

To generate lighting patterns and register the resulting images, we used software based on the LabView platform, developed by a research group from Boston University (Applegate et al., 2020).

The assembled stand allows image registration at wavelengths of 660 and 850 nm at various spatial radiation modulation frequencies.

The processing of experimental results in the general case for SFDI technology consists of four stages:

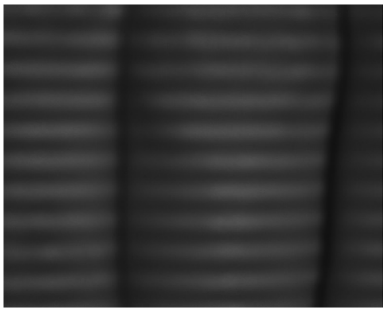
- demodulation over three images at the same spatial frequency: with phases of 0, 120 and 240 degrees,
- calibration to separate the instrument response function (IRF or MTF_{system}) from the response function of the test sample,
- determination of the diffuse reflection coefficient of the recorded sample,
- determination of the optical characteristics of the recorded sample as a result of solving the inverse problem: from the known values of the diffuse reflection coefficient R_d at two (or more) spatial frequencies, the values of the optical parameters of the object are determined, which satisfy the radiation transfer equation.

Figure 3 shows images with phases of 0, 120 and 240 degrees, obtained at the stand, as well as the result of demodulation of these images. From three images obtained in three phases, as a result of demodulation, one image is obtained without stripes.

2.2 Initial Experimental Study

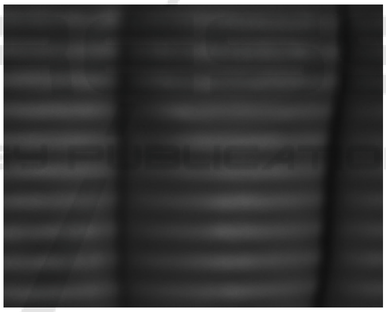
In order to initially test the possibility of measuring the dynamics of biological tissues optical parameters using SFDI, an experiment was carried out on the assembled stand, during which the change in the absorption and scattering coefficients on the surface of the back of the volunteer's palm was monitored during the change in the blood volume of the hand using an occlusive cuff.

In the course of the experiment, the cuff was put on a few centimeters above the bend of the subject's elbow, and SFDI images of the back of the hand were registered (Figure 4) at radiation wavelengths of 660 and 850 nm in the non-occluded mode, in venous oclussion mode (cuff pressure values 90 and 110 mm. Hg) and arterial occlusion mode (cuff pressure value 220 mm Hg).

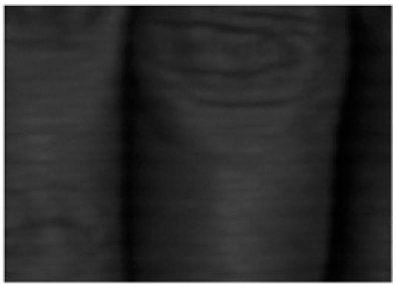


a)

b)



c)



d)

Figure 3: Images of the object taken at the stand. a) -c) Illumination with a spatial frequency of 0.5 mm^{-1}, with phases of 0 °, 120 ° and 240 °; d) result of demodulation.

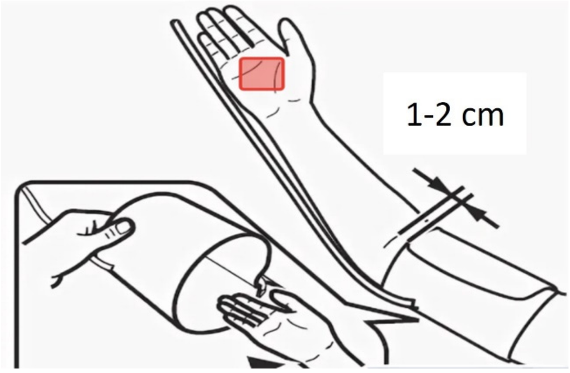


Figure 4: Scheme of SFDI images registration in an experiment with an occlusal cuff: the area of registration is marked with a red rectangle.

The registered images were used to determine the values of the absorption and reduced scattering coefficients averaged over the selected area.

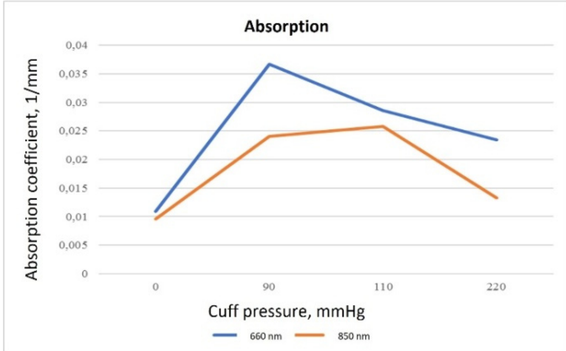
3 RESULTS AND DISCUSSION

As a result of the initial work, a stand for researching the SFDI technology was assembled. The performance of the stand is confirmed by obtaining a high-quality demodulated image.

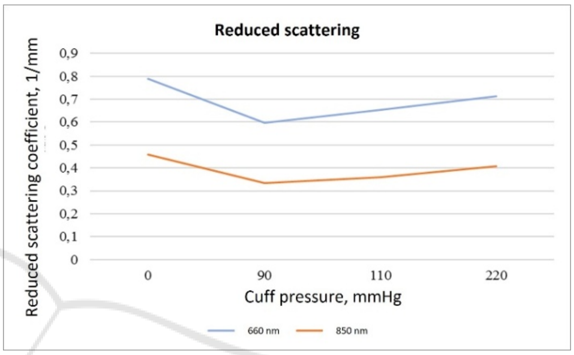
The experimental dependences of the absorption and reduced scattering coefficients on the pressure in the occlusal cuff, obtained as a result of the experiment, are shown in Figure 5.

The extrema of the values of the absorption and reduced scattering coefficients were registered in the mode of venous occlusion, corresponding to the maximum blood filling of the investigated area. This observation corresponds to the hypothetical dynamics of the optical properties of the studied tissues under the conditions of the experiment. Thus, as a result of the analysis of the obtained experimental dependences, it was found that the SFDI technology makes it possible to adequately monitor the dynamics of optical parameters of tissues as a result of changes in blood filling and is potentially applicable for the detection of subsurface optical inhomogeneities in tissues, such as blood vessels, inflammation foci.

To determine the accuracy of tissues optical parameters SFDI measurements, it is required to conduct a series of measurements on a larger sample of subjects, as well as to develop SFDI metrological support, including sets of measures, and methods for verifying the results of SFDI measurements.



a)



b)

Figure 5: Parameters of absorption and scattering obtained during the experiment on the stand: a) the value of the absorption coefficient of the palm, depending on the pressure in the cuff; b) the value of the reduced scaterring coefficient of the palm depending on the pressure in the cuff.

In the course of further work, it is planned:

- verification of the obtained experimental dependences of the results of SFDI measurements on the pressure in the occlusal cuff on a larger number of subjects;
- verification of the results of SFDI measurements using phase modulation spectrophotometry;
- carrying out research at the stand in order to determine the best values of the radiation and registration parameters of the SFDI system for the possibility of using it in the tasks of visualizing neurovascular structures in the brain tissue during endosurgical intervention, detecting lesions in the tissues of the oral cavity;
- development of metrological support for SFDI systems;
- development, manufacture and clinical testing of prototypes of SFDI systems for visualization of neurovascular structures in

the brain tissue during endosurgical intervention, detection and objective numerical assessment of lesions in the tissues of the oral cavity.

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