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Cite as: AIP Conference Proceedings **2140**, 020027 (2019); https://doi.org/10.1063/1.5121952
Published Online: 12 August 2019

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A Mathematical Model of Non-invasive Glucometer Based on Spectrometric Principle

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Abstract. A mathematical model of spectrometric device which provides the possibility to find the glucose concentration in human blood without blood extraction, has been proposed and based. The model includes formation and solution of the linear equations system where the concentrations of different light-absorbing components of human organ are variables, and the absorption factors of these components at different wavelengths are parameters. The conditions of this system solution convergence as well as influence of the medium total absorbance experimental values range at the same wavelengths on this convergence, have been considered. The correction of the presented mathematical model has been demonstrated.

INTRODUCTION

Light which is incident into human organ, is scattered and absorbed by different substances of this organ – blood, tissues, skin, and their numerous components. Scattering is caused by phase modulation of light by complex distribution of refractive index, preferably due to proteins, and absorption caused by amplitude modulation caused by absorption factors of substances composing blood, skin, and tissues. The absorption phenomenon can be used in the spectrometric devices for different diagnostic purposes [1, 2]. The basic obstacle which prevents the objective data obtaining by this method is the fact that the light absorption bandwidth of glucose is significantly overlapped with those of water and other substances being contained in human skin and tissues. Hence, the problem appears how to determine the light intensity part absorbed just by glucose.

The device which we discuss in the present paper, provides spectroscopic determination of glucose contents in blood using numerous measurements of light absorption at different wavelengths. Such measurement became possible by using a mathematical model which provides calculation of the glucose concentration in blood proceeding from the total absorption. We propose to solve this problem by means of measurements of light intensity transmitted through the human blood-containing organ in multiple wavelengths inside the absorbing spectrum of glucose and other components in the range of 750…1100 nm. Developing this method we considered that the absorption factors of all the absorbing components are known in all this range of wavelengths. Sometimes, however, the spectral absorption curves must be checked, so the preliminary calibration of several components spectral absorbing characteristics must be performed.

Below we present a mathematical model which describes how glucose concentration in human blood can be calculated proceeding from the measured values of near IR irradiation absorption in blood-containing human organ at different wavelengths.

MATHEMATICAL MODEL DESCRIPTION

Light absorption and transmission in blood-containing human organ can be described by the relationships which follow from Bouguer-Lambert-Beer law

$$I_0 = I(l) \bullet e^{k_\lambda l}, \tag{1}$$

XIV Russian-Germany Conference on Biomedical Engineering (RGC-2019)
AIP Conf. Proc. 2140, 020027-1–020027-3; https://doi.org/10.1063/1.5121952
Published by AIP Publishing. 978-0-7354-1883-7/$30.00

where I_0 – incident light intensity, $I(l)$ – light intensity transmitted the absorbing medium, k_i – absorption factor, l – length of absorption.

In the case of multiple absorbing media as it takes place in the proposed device, the law can be converted as

$$I_0 = Ie^{k_m \bullet n_m + k_p \bullet n_p + ... + k_z \bullet n_z}, \tag{2}$$

where k_m – absorption factor of m-th substance multiplied by substance layer thickness, and n_m – concentration of m-th substance.

A simple linear equation can be obtained after certain conversion

$$k_m \bullet n_m + k_p n_p + ... + k_z n_z = \ln \frac{I_0}{I}. \tag{3}$$

If the measurements are made at N wavelengths inside the absorption spectrum of glucose, so it is possible to compose N linear equations with N variables – concentrations of each absorbing components. This system can be solved using specially developed software, and the required glucose concentration is one of this system solutions.

Two methods of the linear equations system solutions have been considered – Gauss method and singular factorization method. The last one can provide more accurate system solution if the system determinant is close to zero. In the other cases it is better to use Gauss method which produces good results if the absorbing components have significantly different spectral absorption characteristics, as it usually takes place. This method provides consequent elimination of the variables in order to determine a root of one equation with the last variable, and then it returns consequently to each of the eliminated variables.

The most serious problem which appears while this model application, is the problem of the convergence of equations system solution. In order to provide the convergence reliably, we foresee the following procedures:

- accumulation of the statistical data regarding to the irradiation absorption at each wavelength and calculation of average value and medium deviation;
- mathematical correction connected with finite transmission band of irradiation beam at each wavelength;
- mathematical correction connected with finite size of multielement photodetector used during measurements;
- increasing of the amount of equation in the system without increasing of variables amount, by means of the absorbed light measurements at additional wavelengths.

Another problem is that not all the absorbing components are studied enough regarding their absorbing factors at all the necessary wavelengths. Hence, the mathematical model application in the real device requires some additional experimental investigations which we now perform.

FAST ABSORBED LIGHT INTENSITY MEASUREMENTS AT DIFFERENT WAVELENGTHS

The absorbed light measurements at all the necessary wavelengths in real time mode can be provided using a specific light source which is based on the concept proposed in our early patent [3]. It contains a set of LEDs which transmission bandwidths cover all the necessary wavelengths range. Its optical circuit is shown in Fig. 1.

The light source involves a supply unit which is controlled from PC. This supply unit feeds LEDs which are located in certain places of the device housing. Light of each LED is collimated by microoptics and then it is directed to the diffraction grating. The LEDs location is so that angle of incidence α from the light of each i-th LED satisfies to condition

$$d(\sin\alpha_i + \sin\beta) = m\lambda_i, \tag{4}$$

where d is the diffraction grating spacing, λ_i - light wavelength which is related to ith LED, β - diffraction angle, m is an integer. Hence, light from all the LEDs goes along the same axis as it is shown in Fig. 1.

In order to provide as narrow transmission band as it is used in the traditional spectrophotometers, an acousto-optic tunable filter (AOTF) can be used in series in the considered polychromic light source configuration. The spectrum width provided by each LED is varied in the range of 30…60 nm, hence the optical circuit presented in fig. 1 does not allow to attain the narrower transmission band. However, the AOTF application can help to perform the control of the output irradiation parameters, and due to that, the transmission band can be reduced down to 7…12 nm in near IR range.

The switch time from one light wavelength to the other one in arbitrary order does not exceed decades of microseconds, hence, the wavelength tuning is provided in real time mode, and operation speed of the device becomes very fast. Moreover, the spectral range can be scanned several times during one measurement, so the statistical data can be collected.

The basic problem in such kind of light sources – low output light power – now is solved be application of new powerful LEDs with very small irradiating area, which allows to collect bigger part of the power into optical fiber.

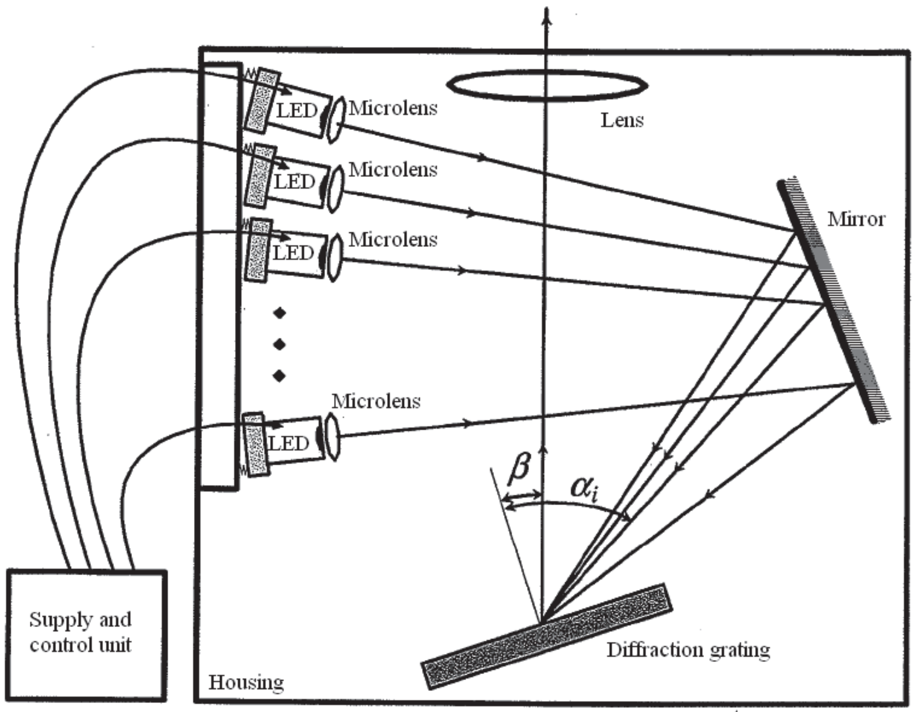

FIGURE 1. Configuration of the light source with controlled wavelength based on the set of LEDs.

CONCLUSION

The proposed mathematical method provides the calculation of glucose concentration in human blood proceeding from the spectroscopic measurements of the irradiation transmitted through human blood-containing organ. The method has been experimentally verified at different simple models, and it has demonstrated its efficiency. Further this method will be used in the real non-invasive glucometer.

ACKNOWLEDGEMENTS

The present investigation has been supported by the Ministry of Education and Science of the Russian Federation (agreement № 14.575.21.0141, 26.09.2017, R&D unique identifier - RFMEFI57517X0141).

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