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An integrated fiber-optic probe combined with support vector regression for fast estimation of optical properties of turbid media

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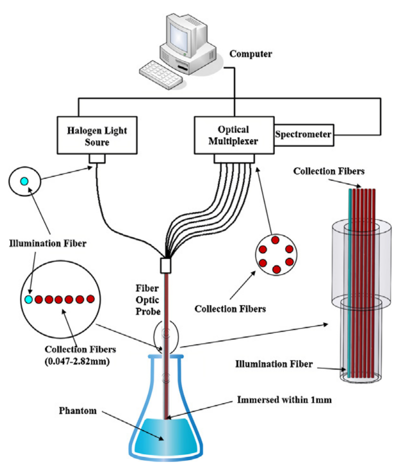
HIGHLIGHTS

- A novel integrated fiber probe is proposed to estimate the optical properties.
- SVR models the relationship between diffuse reflectance and optical properties.
- This approach is fast, efficient and do not rely on the simulation results from MC.
- This approach avoids the theoretical limitation from RTE and DT.
- SVR overcomes the over-fitting problem and fits the non-linear relationship well.

GRAPHICAL ABSTRACT



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ABSTRACT

A fiber-optic probe system was developed to estimate the optical properties of turbid media based on spatially resolved diffuse reflectance. Because of the limitations in numerical calculation of radiative transfer equation (RTE), diffusion approximation (DA) and Monte Carlo simulations (MC), support vector regression (SVR) was introduced to model the relationship between diffuse reflectance values and optical properties. The SVR models of four collection fibers were trained by phantoms in calibration set with a wide range of optical properties which represented products of different applications, then the optical properties of phantoms in prediction set were predicted after an optimal searching on SVR models. The results indicated that the SVR model was capable of describing the relationship with little deviation in forward validation. The correlation coefficient (*R*) of reduced scattering coefficient μ_s' and absorption coefficient μ_a in the prediction set were 0.9907 and 0.9980, respectively. The root mean square errors of prediction (RMSEP) of μ_s' and μ_a in inverse validation were 0.411 cm^{-1} and 0.338 cm^{-1}, respectively. The results indicated that the integrated fiber-optic probe system combined with SVR model were suitable for fast and accurate estimation of optical properties of turbid media based on spatially resolved diffuse reflectance.

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1. Introduction

The optical properties of turbid media have been taken seriously as an indicator in the fast and non-destructive diagnosis. The tissue component and structure can be interrogated by the interaction of light with biological tissues [1,2]. Monitoring of blood oxygenation, tissue metabolism, and skin malignancies are typical application in biomedical area [3], and there are also many reports in therapeutic optical technologies, such as photothermal and photodynamic therapy [4,5]. Recently, the optical properties have become a powerful tool for quality and safety inspection of agro-products [6]. Firmness, maturity, and components (sugar, acid, etc.) of various fruits have been evaluated by optical properties measurement [7–9]. Therefore, a method for fast and effective estimation of optical properties of turbid media is in great demand in many fields, such as biomedicine, biology, agriculture, and other related areas.

These optical properties can be characterized by absorption coefficient μ_a and reduced scattering coefficient μ_s'. The absorption coefficient μ_a may be related with components or chromophores of samples, and the reduced scattering coefficient μ_s' provides microstructure information [10]. Several methods for optical properties estimation have been reported, including time resolved method, frequency domain method and spatially resolved method [11,12]. However, both time resolved and frequency domain methods require expensive instruments which limits their applications. The spatially resolved method (SR), which has been considered as an alternative choice estimates optical properties by spatially resolved diffuse reflectance [13].

The conventional spatially resolved method uses the CCD camera with lens or optical fibers to capture the diffuse reflectance at different radial distances [14]. Therefore, instruments with excess volume are required in the SR method, and it can not be used as a fast and portable method. In addition, the movement of optical fibers causes lots of measurement errors, so the system calibration should be carried out in each initialization. With the development of fiber-optic manufacturing technique, it is possible to integrate several optical fibers in one probe. Integration of illumination and collection fibers in one optic-probe has been gradually applied in the diffuse reflectance measurement. Several applications of micro fiber-optic probes have been reported to measure the diffuse reflectance of human tissues [15,16]. Furthermore, those fiber-optic probes are promoted to the optical assessment of apple or other fruits [17].

The SR method with integrated fiber has advantages of non-destructive, fast, portable and low-cost, but this approach still needs to be further investigated when photons propagate through the integrated fiber probe. The Maxwell's equations accurately describe the light propagation in turbid media, but there are lots of limitations for solving these equations. An alternative method is radiative transfer equation (RTE), which describes the energy distribution of photon propagation, but figuring out the RTE is mathematically impossible [18]. In order to get the simple solution of RTE, diffusion approximation (DA) is used for approximation of RTE [19]. Whereas the DA is available for turbid media that is highly scattering or scattering dominant. The illumination and collection fibers arranged in probe surface are very close or in a few millimeters, and it is proved that such short distance causes lots of approximation errors in DA [20]. Another way for simulating the light propagation is numerical approach through Monte Carlo simulations (MC) which configures the optical properties of samples from simulated diffuse reflectance, and it has been applied in many fields [21]. However, the MC approach is time consuming, so it can not meet the requirement of fast or online detection. Moreover, the look-up table based on MC is established to save the simulation time [22]. The MC simulation results of light propagation are often corrupted by the random noise. Nonetheless, the diffuse reflectance from the fiber probe is sensitive to the random noise from one or several MC simulations, which lowers the stability of optical properties estimation.

Because of the limitations of RTE, DA and MC, different kinds of fitting methods have been used for direct modeling between optical properties and diffuse reflectance. The modeling by different splines is based on hypothesis of specific forms of fitting functions, but it is uncertain whether these functions are suitable for regression [23]. Avoiding the priori assumption of regression function, nonparametric regression gets the better performance since it only relies on the optical properties and diffuse reflectance of phantoms. One of these typical approaches is neural network that has been trained with the datasets both generated by MC simulation and phantoms of turbid media [24,25]. Some experiment results show it is difficult to achieve satisfying accuracy by using MC simulation data, but it is feasible to be trained with phantom dataset [26]. The performance of neural network is related to the amount of phantoms with measured optical properties, and the insufficient amount of phantoms lowers the regression performance of neural network. However, as mentioned above, nonparametric regression has been used to fit the non-liner relationship, and it remains an effective idea for retrieving the optical properties.

With the insufficient number of phantoms, the regression model between optical properties of turbid media and diffuse reflectance encounters the problem of over-fitting because of empirical risk minimization that is the main principle of net training. But the support vector regression (SVR) is beneficial to mine the information in high-dimensional space, and this feature is suitable for the situation of the fuzzy relationship between optical properties and diffuse reflectance in low-dimensional space [27,28]. The conventional nonparametric regression takes no account of spectral structure, whereas the SVR automatically learns the data structure of diffuse reflectance via training algorithm with various kernel functions.

In this study, a diffuse reflectance probe system with seven optical fibers laid out in a line at probe surface was designed by our laboratory, and an approach based on the SVR model was proposed for fast and accurate estimation of optical properties of turbid media. The objectives of this research were to: (1) evaluate whether the fiber-optic probe system was qualified for collection of diffuse reflectance of turbid media with a wide range of optical properties; (2) build the SVR models between spatially resolved diffuse reflectance and optical properties of phantoms; (3) predict the optical properties of phantoms by the optimal searching on SVR models; and (4) verify whether the integrated fiber-optic probe system combined with SVR was suitable for fast and accurate estimation of optical properties of turbid media.

2. Materials and methods

2.1. Fiber-optic probe system

A fiber probe system for collecting spatially resolved diffuse reflectance at the wavelength of 633 nm was developed, as shown in Fig. 1. It consisted of a halogen light source, an illumination fiber, six collection fibers, a multiplexer, a spectrometer and a computer. The halogen light source (HL-2000, Ocean Optics, USA) with 633 nm optical filter illuminated the sample surface through the illumination fiber. The illumination fiber and six collection fibers were placed in a line at the probe surface, setting the distance between every fiber center as 0.47 mm, and the distance between the illumination fiber and the collection fibers varied from