Infrared Physics & Technology 87 (2017) 139–142

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Regular article

The limitation of the proposed collection efficiency for fiber probes on the visible and near-infrared diffuse spectroscopy

Linna Zhang [a,*], Hongyan Ding [a], Ling Lin [b], Yimin Wang [a], Xin Guo [a]

[a] Faculty of Mechanical & Material Engineeing, Huaiyin Institute of Technology, Huai'an 223003, China
[b] State Key Laboratory of Precision Measurement Technology and Instruments, Tianjin University, Tianjin 300072, China

HIGHLIGHTS

- we explored the collection efficiency in different optical environment with Monte Carlo simulation method.
- We find the collection efficiency was almost stable in weak absorbing and strong scattering media.
- We tried to explain the stability of the collection efficiency in this condition.

ARTICLE INFO

Article history:
Received 12 October 2017
Accepted 23 October 2017
Available online 28 October 2017

Keywords:
Limitation
A fiber probe
Monte Carlo simulation
Turbid media

ABSTRACT

A fiber is usually used as a probe in visible and near-infrared diffuse spectra measurement. However, the use of different fiber probes in the same measurement may cause data mismatch problems. Our group has researched the influence of the parameters of fiber probe, including the aperture angle, on the diffuse spectrum by a modified Monte Carlo model. To eliminate the influence of the aperture angle, we proposed a fitted equation of correction coefficient to correct its difference in practical range. However, we did not discuss the limitation of this method. In this work, we explored the collection efficiency in different optical environment with Monte Carlo simulation method, and find the suitable conditions—weak absorbing and strong scattering media, for the proposed collection efficiency. Furthermore, we tried to explain the stability of the collection efficiency in this condition. This work gives suitable conditions for the collection efficiency. The use of collection efficiency can help reduce the influence of different measurement systems and is also helpful to the model translation.

1. Introduction

Visible and near-infrared diffuse spectrum has been widely used to characterize the optical properties of turbid media [1,2]. Typically, DS uses a fiber probe to deliver light to turbid media at one position. The incident light is both scattered and absorbed by the turbid media. Then the reflected light is collected by another fiber probe, which is moved a fixed scanning interval along the radial direction at the same side of the incident light, and the transmitted light is collected at the other side of the sample surface. The collected light, either in visible waveband or near-infrared waveband, contains quantitative information about components [3,4] and composition [5,6] of turbid media, including urine (463–1737 nm) [7,8], serum (12,500–4000 cm^{-1}) [9], biological tissues [10] and so on.

Monte Carlo model has been a non-experimental standard for other light propagation models [11–14]. Monte Carlo method can be also applied to the research of simulations for theoretical validations [15,16]. In accustomed Monte Carlo model, the emitted photons will be recorded by the corresponding grid system, without collection conditions. However, the detectors are usually not ideal, which cannot collect the emitted photons with all angles at a particular position. Consequently, Monte Carlo model must take the practical detecting conditions into consideration, especially when Monte Carlo model is used to study the relationship between the detected diffuse spectra and the components and the structure of the detected object. Many researchers have tried to explore the influence of the different fiber probes on the diffuse signals. Zonios [17] discussed the collection efficiencies of the fiber probes with different optical parameters. Kanick's study [18] showed that the normalized diffuse reflectance would be greatly different when we took fibers with different diameters, and the normalized diffuse reflectance increased with the increase of fiber diameters. And

* Corresponding author.
E-mail address: zhlin_na@126.com (L. Zhang).

https://doi.org/10.1016/j.infrared.2017.10.008
1350-4495/

many researchers have studied the difference between a measured diffuse reflectance and a modeled diffuse reflectance from Monte Carlo simulation [15,16,19]. Our group has researched the influence of the parameters of fiber probe, including the aperture angle, on the diffuse spectrum by a modified Monte Carlo model. To eliminate the influence of the aperture angle, we had proposed a fitted equation to correct its difference in practical range [20]. All these researches indicated that the difference was stable and can be eliminated by a constant, which is the ratio of the modeled spectrum and the measured spectrum of same optical properties. But no relative report discussed the limitation of the collection efficiency.

In this work, we tried to analyze the limitation of the collection efficiency in different optical environment with Monte Carlo simulation method, and found the suitable conditions for the proposed collection efficiency.

2. Theory and methods

2.1. Theoretical introduction

It is commonly acknowledged that only when the emitted photons meet the exact conditions, such as their locations within certain areas and the emitting angles within a certain range, can they be collected by the fiber probe. The numerical aperture of the fiber probe is defined as NA. It is widely known that only the photons with emitting angles within β (shown in Fig. 1, from Ref. [20]) can be collected by the fiber probe. The relationship of β and NA can be described as:

$$\beta = \arcsin\left(\frac{NA}{n}\right) \tag{1}$$

where n is the refractive index of the turbid medium, and n = 1.37. To simplify the calculation, we took aperture angle β as a parameter of the fiber probe.

Here we proposed collection efficiency k, based on the correction coefficient, which was defined as Eq. (2). The collection efficiency was fitted by MATLAB curve fitting toolbox based on Monte Carlo simulation, which was shown as Eq. (3). The collection efficiency is proportional to the square of the aperture angle. The fitting root mean square error (RMSE) is 0.0022, and the determination coefficient (R2) is 0.9998. The fitting equation is only available for practical aperture angle range (0.14–0.5 rad) of the fiber probe.

$$k = \frac{Dr_{\beta}}{Dr_{\beta=\pi/2}} \tag{2}$$

$$k = 1.882 \times \beta^2 + 0.00394 \tag{3}$$

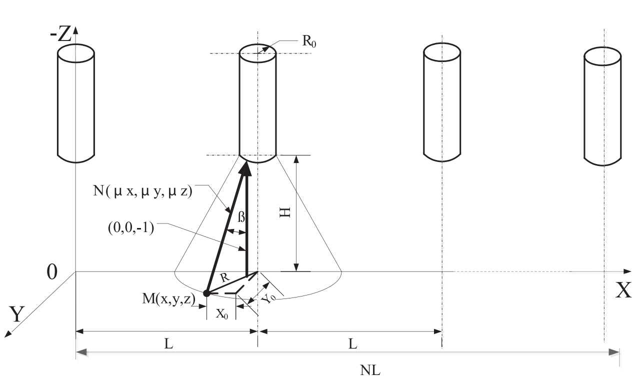

Fig. 1. Relative position of the emitted photon and the fiber probe.

2.2. Methods

To analyze the limitation of collection efficiency, we tried to explore the collection efficiency in different optical environments. We divided the turbid media into three basic types: highly scattering media, strong absorption media and weak scattering and weak absorbing media. Specifically, we used modified Monte Carlo simulation method to obtain the collection efficiency in media with different optical coefficients. The coefficients set in Monte Carlo simulation was the same as Ref. [20]. Concretely, we took a single layer model. The total number of the incident photons was 10^8. The absorption coefficient (μa) was 0.5 cm^{-1}; the scattering coefficient (μs) was 50 cm^{-1}; the anisotropy factor (g) was 0.9; the thickness (d) was 1 cm. The refractive index (n) was 1.4; the ambient refractive index (n_0) was 1.0. More details were described in Ref. [15].

To explore the influence of absorption properties to the collection efficiency, we studied the collection efficiency in the media with the same scattering property, but with different scattering properties. The scattering coefficient was set as 10 cm^{-1}, 100 cm^{-1} and 300 cm^{-1}. Moreover, to explore the influence of scattering properties, we studied the collection efficiency in the media with the same absorption property, but with different scattering properties. The absorption coefficient was set as 0.1 cm^{-1}, 1 cm^{-1} and 3 cm^{-1}.

3. Results

In Fig. 2(a)–(c), we illustrate the variation of collection efficiency with the increase of absorption coefficient, with scattering coefficient fixed at 10 cm^{-1}, 100 cm^{-1} and 300 cm^{-1}, respectively. We can find that the collection efficiency decreases with the increase of absorption coefficient. The collection coefficient was approximately stable in weak absorbing environment. And the critical point of absorption coefficient was increased with the increasing of scattering coefficient. Then we can conclude that the collection coefficient was closely related to the absorption coefficient and the scattering coefficient. To thoroughly obtain the influence of scattering property, we studied the variation of the collection efficiency in the media with different scattering properties.

In Fig. 3(a)–(c), we illustrate the variation of collection efficiency with the increase of scattering coefficient, with absorption coefficient fixed at 0.1 cm^{-1}, 1 cm^{-1} and 3 cm^{-1}, respectively. We can find that the collection efficiency increases with the increase of the scattering coefficient. And the collection coefficient was approximately stable at strong scattering environment. And the critical point of scattering coefficient was increased with the increasing of absorption coefficient. Then we can conclude that the collection coefficient was stable for weak absorption and strong scattering media, especially for the media that the scattering coefficient far bigger than the absorption coefficient.

Therefore, the collection efficiency is almost constant for weak absorbing and strong scattering media. However, for strong absorbing and weak scattering media, the collection efficiency would decrease with the increasing of absorption coefficient and with the decrease of the scattering coefficient.

4. Discussion

In this paper, we found that collection efficiency is almost constant for weak absorbing and strong scattering media, especially for the media that the scattering coefficient far bigger than the absorption coefficient. The calculation of the collection efficiency was provided in our previous work in Ref. [15]. Our result was consistent with the research by Bargo (Ref. [21]). In their study, the