Quantifying scattering coefficient for multiple scattering effect by combining optical coherence tomography with finite-difference time-domain simulation method

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Abstract. In optical coherence tomography (OCT) systems, to precisely obtain the scattering properties of samples is an essential issue in diagnostic applications. Especially with a higher density turbid medium, the light interferes among the adjacent scatters. Combining an OCT experiment with the finite-difference time-domain simulation method, the multiple scattering effect is shown to affect the scattering properties of medium depending on the interparticle spacing. The far-field scattering phase function of scatters with various diameters was simulated to further analyze the corresponding anisotropy factors, which can be introduced into the extended Huygens-Fresnel theory to find the scattering coefficient of measured samples.

Keywords: optical coherence tomography; multiple scattering effect; finite-difference time-domain method; extended Huygens-Fresnel theory.

1 Introduction

Optical coherence tomography (OCT) is a potentially noninvasive sensing optical imaging system for various clinical diagnostic applications, and has a lot of developments particularly in the past decade. As an emerging imaging system, OCT can provide high-resolution axial structure images inside tissue from two- (A-scan) to three-dimensional (A-scan and B-scan). It is an interferometry-based optical technique, collecting the backscattered light from the sample to further extract the optical characteristic details within the tissue. Currently in this field, precise analysis of optical properties from the inhomogeneous and dense tissue remains challenging work. Different models of OCT have been established to obtain the optical properties of samples with further consideration of multiple scattering effect. Among these works, Thrane et al. were the first to propose the use of modulated interferometer signals of an OCT system, which can be expressed analytically based on the extended Huygens-Fresnel (EHF) principle, and to further consider the effect of multiple scattering. In addition, EHF theory has commonly been utilized to numerically quantify optical properties from A-scan signals of OCT images. However, in the EHF theory, there are two main flexible parameters highly correlated with the slope of OCT signals, i.e., the scattering coefficient (μs(θ)) and the anisotropy factor (g). Koach et al. reported in 2011 that the scattering phase function in a backward direction could be determined as the ratio of the backscattering coefficient to the scattering coefficient (only single scattering) detected from the CCD, but without the consideration of multiple scatterings. Then in 2013, Nguyen et al. further improved the OCT system by introducing a new setup of the transmission OCT system, in order to detect transmitted signals, and they introduced the structure factor (Percus–Yevick theory) to show the concentration-dependent scattering coefficients. In 2015, Almasian et al. proposed that a concentration-dependent scattering coefficient of the sample could be obtained from the Mie theory by incorporating the structure factor of Percus–Yevick theory in the calculation procedure. In this study, we propose a new analysis flow by combining the OCT system with the finite-difference-time-domain (FDTD) simulation method, to quantify the scattering coefficient of mesoporous TiO2 beads after introducing gdep factors into EHF theory. The benefit of combining with the FDTD method is that the characteristics of objects can be flexibly modified, including the shape (not only sphere), the refractive index, and the arrangement for inhomogeneous morphology. For comparison to the Percus–Yevick theory mentioned above, the structure factor can only hypothesize for a set of two hard spheres with fixed diameter size at a specific condition. In addition, differing from the algorithm of calculating the radial correlation function (radial distribution function) between adjacent particles in P-Y theory, the near-field electrical field of the FDTD method can briefly demonstrate and show the light interaction when the object is scattered by incident light, and the far-field scattering pattern can be further determined.

First, the anisotropy factor gdep represents the intrinsic scattering characteristic properties (angular scattering pattern). The multiple scattering phenomena depending on the interparticle spacing (IPS) will be discussed in Sec. 3. From this method, the scattering phase function [Pdep(θ)] can be simulated to predict the corresponding anisotropy factor gdep of mesoporous TiO2 beads samples with different diameters varied from 20, 150, 300, to 500 nm, respectively. In Sec. 4, the A-scan profiles
are extracted by signal processing procedures from the interference patterns and then fitted by the EHF theory with consideration for the corresponding anisotropy factor $\beta_{\text{dep}}$, which is introduced to the EHF model to fit the scattering coefficient of each mesoporous TiO$_2$ bead sample. Also, different calculations of the anisotropy factor $\beta_{\text{dep}}$ between the Mie scattering model and the FDTD method are compared.

2 Methods and Experimental Setup

2.1 Finite-Difference-Time-Domain Method

Since the development of the FDTD method,\(^\text{13}\) it has been utilized to solve Maxwell’s equation numerically in the time domain to describe the complex behavior of light interaction and widely applied in solving the scattering issue in biological fields.\(^\text{16-19}\) In this study, we have utilized the R-Soft software with fullwave mode based on the FDTD algorithm. The FDTD algorithm is the computation process for implementing time and space derivatives of the electric and magnetic fields in Yee’s cell.\(^\text{21}\) Solve the Maxwell’s curl equations by first discretizing the equations with central differences in time and space and these equations can be further numerically solved by the software. To estimate the optical scattering properties of TiO$_2$ beads with different diameters and embedded in thin-films, we align the scattering direction along with the line connecting the TiO$_2$ beads, and they are separated by the IPS, which varies from 0 to 1000 nm in an interval of 250 nm. The model used for FDTD is shown in Fig. 1(a): the wavelength of the incident plane wave is $\lambda_0 = 853$ nm, while the refractive index of mesoporous TiO$_2$ beads is $n = 2.5$\(^\text{18,19}\) and assumed to be homogeneous and isotropic in distribution. The polarization of the incident wave is set as TE polarized. The grid size of calculation is set as 0.005 nm, time step is 0.005 s, and the incident wave is a plane wave in the enclosed area, respectively. With a perfectly matched layer (PML), it is composed of several grid points as the edge of the domain for the enclosed area, which can absorb the incident lights and result in no reflection.

In order to obtain the far-field scattering patterns, the virtual box with appropriate PML boundary is set to enclose the scattering objects (mesoporous TiO$_2$ beads) and launch a plane wave inside an enclosed area, which is shown in Fig. 1(a). In the meantime, there are only scattering fields from objects propagating beyond the enclosed launch boundary, and unscattered light will be absorbed at the PML boundary. For obtaining the scattering phase function, the corresponding far field can be calculated using the near-field to far-field transformation from the simulation data in software.\(^\text{20}\)

2.2 Preparation of Mesoporous TiO$_2$ Beads

Samples

Mesoporous TiO$_2$ bead samples with average diameters ($D$) of 20, 150, 300, and 500 nm were prepared by the sol–gel process. Initially, the TiO$_2$ powder weight percentage is 13 wt. % (US Research Nanomaterials, Inc.) mixed with different percentages of isopropyl alcohol and DI water. Adding polyethylene glycol to the mixture, the TiO$_2$ pastes were obtained after more than 1 week of stirring, and the TiO$_2$ pastes prepared on glass substrates were heated by an oven at 450°C for 30 min to evaporate the solvent. In the process, the TiO$_2$ were assumed to be homogeneously distributed. The final volume fraction of TiO$_2$ bead samples was fixed as 0.03 for TiO$_2$ beads with diameters varied from 20 to 500 nm, respectively. Afterward, the samples of mesoporous TiO$_2$ bead films on glass substrates were obtained.

For a suspension of colloidal system, the samples of TiO$_2$ beads with volume fraction of 0.03 for different diameters are assumed to be homogeneously distributed; the schematic diagram of TiO$_2$ beads in a unit cell (1 $\mu$m$^3$) for different diameters from 20 to 500 nm is shown in Fig. 1(b). The IPS parameter $\text{IPS} = 2\pi [\frac{1}{2} \varphi - 1]$ is defined as the distance from the surface of one particle to the other [the line of connection between the two through the center of each bead, as shown in Fig. 4(a)], which changes according to the volume fraction in the colloidal system.\(^\text{21}\) The maximum volume fraction is $\varphi_{\text{m}}$ with TiO$_2$ samples, while $\varphi$ is the volume fraction of TiO$_2$ bead samples, and $r$ is the radius of TiO$_2$ beads. With the volume fraction of 0.03, the values of IPS are 25, 187, 373, and 623 nm for select TiO$_2$ diameters between 20 and 500 nm.
2.3 Extended Huygens-Fresnel Theory (Multiple Scattering) and Signal Analysis

First, as an assistant method, the FDTD simulation process was utilized to calculate the electromagnetic near field and then transformed to a far-field scattering pattern, which is also called the phase function $p_{\text{dep}}(\theta)$, for different IPS between mesoporous TiO$_2$ beads with different diameters from 20, 150, 300, and 500 nm. Here, the far-field $p_{\text{dep}}(\theta)$ is indicated as the probability density function of photons for every scattering angle ($\theta$), and the anisotropy factor $g_{\text{dep}}$ is the integral of phase function $p_{\text{dep}}(\theta)$ over all scattering angles, which can be expressed as

$$g_{\text{dep}} = 2\pi \int_0^\pi p_{\text{dep}}(\theta) \cos(\theta) \sin(\theta) d\theta = \langle \cos \theta_{\text{dep}} \rangle,$$

where

$$\int_0^\pi p_{\text{dep}}(\theta) 2\pi \sin(\theta) d\theta = 1.$$

Second, based on EHF theory, the amplitude of experimental OCT signals versus depth $z$ can be modulated as the function of two main flexible parameters for $g$ and $\mu_s$. Once the multiple scattering effect appears, the right-hand side of point spread function (PSF) can be changed by slope variation at a larger axial depth as compared to that of a signal with only single scattering effect. In practice, the most common method to date to quantifying the scattering coefficient for multiple scattering effect is called OCT signals versus depth. Except for the fixed optical system parameters, the resulting heterodyne signals $\langle S^2(z) \rangle$ [Eqs. (3) and (4)] in depth can be mainly modulated by two competing factors, the anisotropy factor ($g = \langle \cos \theta_{\text{rms}} \rangle$, $\theta_{\text{rms}}$ is average scattering angle) and the scattering coefficients ($\mu_s$). In addition, the fixed parameters in the system include the power $P_R$ and $P_S$ measured at the reference and sample arms; the quantum conversion efficiency $\alpha$ of the CCD; the backscattering cross-section $\sigma_b$; and the $1/e$ irradiance radii $w_H$ and $w_S$ for the absence and presence of scattering; the refractive index for medium $n$; the radius of the sample beam at the focal plane $w_0$; and the focal length of objective lens $f$, as follows:

$$\langle S^2(z) \rangle \alpha \exp(-2\mu_s z) + \frac{2 \exp(-2\mu_s z) [1 - \exp(-\mu_s z)]}{1 + \frac{W_H^2}{W_S^2}},$$

$$\frac{W_S^2}{W_H^2} = 1 + \frac{4}{3} (\mu_s z) \left[ \frac{\pi \mu_s \theta_{\text{rms}}}{nf} \right]^2.$$

In the EHF theory, it should be noted that it is not easy to predict the optical coefficients of $g$ and $\mu_s$ at the same time due to the fact that they are competing parameters. Therefore, using the other method to obtain one of them is a general solution to approach. After obtaining the $g_{\text{dep}}$ for mesoporous TiO$_2$ beads with different diameter sizes for various IPS from the FDTD method, introducing the value of $g_{\text{dep}}$ for specific TiO$_2$ beads samples, the corresponding scattering coefficient $\mu_s$ can be further derived for the PSF of A-scan signal based on EHF theory.

![Fig. 2](image-url) (a) Schematic diagram of SD-OCT system at the central wavelength of 853 nm, where the mesoporous TiO$_2$ films with different average diameters are placed on the sample arm. (b) Schematic diagram of the sample shows the scattering effects of mesoporous TiO$_2$ scatter films occur, with incident lightwave illuminated on the samples.
2.4 Optical Coherence Tomography Setup

The schematic diagram of the SD-OCT system using an 853-nm super-luminescent diode as the source is shown in Fig. 2(a). A single mode fiber (Thorlabs 780HP) is used to direct the light into the reference and sample arms. This OCT system has a numerical aperture of 0.042, with an objective lens focal length of 17.9 mm. The interferometer signal strikes a transmission grating (1200 lines/mm) and the objective lens then collects and focuses the diffracted light onto the CCD (e2V, 2048 pixels, 28-kHz line rate). Each A-scan profile (in depth) was averaged over 1000 measurements and subtracted by the reference arm intensity, to obtain the interferometer signal without the DC term.

3 Results

3.1 Scattering Phase Function of Single TiO$_2$ Bead Simulated by FDTD

The optical behavior of a single TiO$_2$ bead with different diameters has to be confirmed prior to the simulation of multiple beads, with the FDTD method analysis. Figure 3 shows the plots of angular-dependent scattering patterns of a single TiO$_2$ bead with diameters of 20, 150, 300, and 500 nm, obtained by using the FDTD method, and is compared with the results from the Mie scattering model.\textsuperscript{24-26} These comparison results show that both methods are consistent and verify that the settings in the FDTD method are appropriate. The resultant values of $g_{\text{dep}}$ obtained for single TiO$_2$ bead with diameters from 20, 150, 300, and 500 nm are 0.003, 0.174, 0.525, and 0.327, respectively.

3.2 Interparticle Spacing Effects of Near-Field Scattering Patterns

To study the multiple scattering effects that occur within high density tissues, multiple TiO$_2$ beads (for smaller IPS in Sec. 2.2) are simulated, with near-field scattering patterns as shown in Fig. 4(b). In analyzing actual OCT signals, the presence of multiple scattering makes it difficult to acquire the corresponding anisotropy factors $g_{\text{dep}}$.\textsuperscript{27,28} We simplify the scatter geometry to in-line configuration of TiO$_2$ beads separated by different IPS in order to investigate the scattering phenomenon. In Fig. 4(a), the electrical field patterns for in-line TiO$_2$ beads with a diameter of 300 nm are shown; the IPS is varied from 0 to 1000 nm in intervals of 250 nm. The light propagates in the upward direction and is incident onto the beads from underneath, as shown in Fig. 4. According to the results of far-field scattering patterns, except for the main lobe that resulted from the Mie scattering effect, the presence of side-lobes was found by considering the effect of multiple scattering. This needs to be noted when the IPS is increased.

Fig. 3 Far-field scattering patterns of single TiO$_2$ bead calculated from Mie scattering model (red solid line) and compared with FDTD method (green dash line) for different diameters of (a) 20, (b) 150, (c) 300, and (d) 500 nm.
Fig. 4 (a) The modeling geometric structure schematic of mesoporous in-line TiO$_2$ beads embedded in a unit cell with different diameters ($D$) of 20, 150, 300, and 500 nm, which show the various IPS between adjacent TiO$_2$ beads. (b) Scattering patterns of near-field electrical field magnitude of in-line TiO$_2$ beads for 300 nm separated by IPS. The light is incident from the bottom in each subfigure.

Fig. 5 Far-field angular scattering patterns [phase function $p_{\text{deg}}(\theta)$] against variable IPS from 0, 250, 500, 750, and 1000 nm of TiO$_2$ beads for different diameters of (a) 20, (b) 150, (c) 300, and (d) 500 nm.
3.3 Interparticle Distance Effects-Dependent Phase Function

To approach the realistic \( g_{\text{dep}} \) [Eq. (1)], the far-field angular phase function \( \phi_{\text{dep}}(\theta) \) of in-line TiO\(_2\) beads was further simulated using the FDTD method. Figure 5 shows the effect of IPS on the angular scattering patterns for mesoporous TiO\(_2\) beads with diameters of 20, 150, 300, and 500 nm. In each case, we observe adjusting the value of \( P \) (\( P = \text{IPS} + \text{D} \)), where \( P \) is the period for in-line TiO\(_2\) beads, which can be defined as the sum of IPS and the diameter of TiO\(_2\) bead. Changing of \( P \) induces variation on the phase function \( \phi_{\text{dep}}(\theta) \) [Figs. 5(a)–5(d)], including the contribution ratio between backward and forward scatterings, and the appearance of side-lobes. Apart from the characteristic nature of Mie scattering \( \phi_{\text{Mie}}(\theta) \), shown for each diameter size of TiO\(_2\) bead, the incident wave also leads to scattering field interference through the propagation path.

For the 150-nm-diameter TiO\(_2\) beads, the appearance of side-lobes can be found as the IPS is increased beyond 750 nm. When IPS is smaller than 500 nm, the scattering patterns are similar to Mie scattering ones; these can be maintained except for the main-lobe energy leakage with increasing IPS, without diffraction associated side-lobes. The side-lobes can be detected at scattering angles of 52 deg and 128 deg. The two lobes are symmetric with respect to the main lobe, and when reaching the condition of \( P > \lambda_0/2 \), the interference phenomenon induced by phase delay between adjacent TiO\(_2\) beads [see Fig. 4(b)] produces a grating diffraction effect.\(^{29,30}\) The interference pattern can be likened to a multiple-slit interference pattern from the geometric arrangement of in-line TiO\(_2\) beads [Fig. 4(a)], by analogizing the diameter of TiO\(_2\) beads as the width of the slit, and the TiO\(_2\) bead periodicity as the grating period. The detected intensity was simulated by the function which can be expressed\(^{31} \) as

\[
I = I_0 \frac{p(\theta) \sin(\alpha)}{\alpha^2} \cos(\beta),
\]

where \( I_0 \), the intensity of incident wave, \( \alpha \) is the signal of single slit diffraction, where

\[
\alpha = \frac{1}{2} k D \sin \theta,
\]

and \( \beta \) is the signal of the wave interference by phase delay, where

\[
\beta = \frac{1}{2} k P \sin \theta.
\]

The minor side-lobes can be approximated by using the above equations at the angles of 48.1 deg and 131.4 deg with some small, but acceptable within margin, amount of errors, as compared with the data from the FDTD method. As shown in Figs. 6(a)–6(d), the \( g_{\text{dep}} \) factors of TiO\(_2\) beads with different diameters from 20 to 500 nm versus the IPS from 0 to 1000 nm were simulated and calculated by the FDTD method, which integrated the phase function overall the scattering angles. In addition, the curves as the function of IPS for these samples were fitted with the B-spline function.\(^{32}\) With the experimental volume fraction condition of 0.03, the corresponding \( g_{\text{dep}} \) values extracted from the curves in Figs. 6(a)–6(d) are 0.0025, 0.1685, 0.3181, and 0.3866 for TiO\(_2\) bead diameters of 20, 150, 300, and 500 nm respectively. The dash lines are the \( g \) factors calculated based on a Mie scattering model, and the red star shows the \( g \) factor of experimental condition with an error value of 5% as compared to the value on the curve.
500 nm, respectively. Introducing the specific IPS values of 25, 187, 373, and 623 nm for TiO2 diameters between 20 and 500 nm with the volume fraction of 0.03 into FDTD method, shows the slight difference within 5% error deviation as compared to the curve of $g_{dep}$ as simulated in Figs. 6(a)–6(d). Therefore, the curves of $g_{dep}$ versus IPS can be further used in scattering analysis, and the scattering coefficients ($\mu_s$) of different samples can be obtained by inserting the $g_{dep}$ factors into EHF model. Therefore, the trend of IPS-dependent $g_{dep}$ for different diameters of TiO2 beads can be determined. As illustrated in Figs. 6(a) and 6(b), the TiO2 with smaller diameters for 20 and 150 nm show $g_{dep}$ factor results similar to those from the Mie scattering effect, which implies that the variation of IPS affects weakly for smaller TiO2 beads. However, when increasing the size of TiO2 up to 300 and 500 nm, the IPS-dependent $g_{dep}$ factor deviates from the Mie scattering effect due to the diffraction and interference phenomena between adjacent TiO2 beads. With this, an approximation of the anisotropy factor ($g_{dep}$) of each TiO2 bead sample can be made using the OCT system, and can be further introduced into the EHF theory to find the most fitted scattering coefficient ($\mu_s$).

4 Extended Huygens-Fresnel Theory

After verifying the value of $g_{dep}$ for each of the TiO2 bead samples, the corresponding $\mu_s$ can be further fitted by the EHF theory. Figure 7(a) shows a plot of OCT A-scans for the experimental and fitted curves of the mesoporous TiO2 sample with 300 nm diameter. With the fitted results, the slope of A-scan signals is dependent on the optical parameters ($g, \mu_s$) introduced by the EHF model, simulated by fixing the $g_{dep}$ factor from the Mie scattering model and FDTD method. In Fig. 7(b), the scattering coefficient fitted for different TiO2 bead diameters is shown. When increasing the diameter from 20 to 500 nm, the calculated scattering coefficient is $12.9 \pm 0.3$, $20.8 \pm 0.3$, $14.2 \pm 0.3$, and $19.5 \pm 0.3$ mm$^{-1}$, with the $g_{dep}$ factors calculated from the FDTD method. In comparison, the calculated scattering coefficient is $13.5 \pm 0.6$, $16.5 \pm 0.6$, $20.2 \pm 0.6$, and $18.5 \pm 0.6$ mm$^{-1}$, respectively, when the $g$ factors are obtained by using the Mie scattering model. In Table 1, the calculated correlation factors ($\rho$), between the experimental results and the fitted OCT results, show good agreement ($\rho = 1$), verifying the accuracy of the obtained IPS-dependent $\mu_s$-FDTD with $\mu_s$ factors for each TiO2 bead sample. The $\rho$ can be calculated from the mean and stand deviation of the experiment, with fitted A-scan signals to estimate the linear dependence between these two signals. The highest $\rho$ can be calculated for different TiO2 bead diameters of 20, 150, 300, and 500 nm, and the results are 0.9431, 0.9617, 0.9721, and 0.9241, respectively. This shows that, once the $g_{dep}$ for specific IPS can be accurately determined, the corresponding scattering coefficient ($\mu_s$) can be more accurately quantified with reduced error value from 0.6 to 0.3. Also from the results, the $\mu_s$-MIE fitted can be observed to be overestimated, when the TiO2 bead diameter is increased up to 300 nm, for which the multiple scattering effect becomes more pronounced along with the increased TiO2 bead diameter. The oscillation behavior of scattering coefficient $\mu_s$ for different TiO2 bead diameters from 100 to 300 nm is shown in Table 1 and Fig. 7(b) while the fitting is based on FDTD method. Due to the limitations of the experiment, the scattering coefficient trend can only be observed within the narrow range of variable TiO2 bead sizes. However, similar results can also be found in other research. In addition, the $\mu_s$-FDTD fit can be obtained when $g_{dep}$

<table>
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<th>TiO2 beads (D)</th>
<th>$\theta_{ang}$ (Mie)</th>
<th>$\mu_s$ (Mie)</th>
<th>Correlation factor</th>
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<tbody>
<tr>
<td>20 nm</td>
<td>1.5678</td>
<td>13.5 ± 0.6</td>
<td>0.9429</td>
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<td>16.5 ± 0.6</td>
<td>0.9569</td>
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<tr>
<td>500 nm</td>
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<td>18.5 ± 0.6</td>
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<table>
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<th>TiO2 beads (D)</th>
<th>$\theta_{ang}$ (FDTD)</th>
<th>$\mu_s$ (FDTD)</th>
<th>Correlation factor</th>
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<tbody>
<tr>
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<td>0.9721</td>
</tr>
<tr>
<td>500 nm</td>
<td>1.1739</td>
<td>19.8 ± 0.3</td>
<td>0.9241</td>
</tr>
</tbody>
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Fig. 7 (a) Experimentally measured OCT A-scan signal and the fitted A-scan signals based on Mie scattering model and FDTD method. (b) The curves of fitted scattering coefficients based on Mie model and FDTD method for different TiO2 bead diameters of 20, 150, 300, and 500 nm.
factors calculated from the FDTD method show the smaller error values decreased from 0.6 to 0.3. The results of lower \( \mu_{s,FDTD} \) as compared with \( \mu_{s,MIE} \) are consistent with the findings from other research\(^{11} \), which had showed that the presence of the multiple scattering effect, due to larger diameter size and larger volume fraction, can induce the deviation from the \( \mu_s \) calculated based on Mie scattering. Therefore, in these cases, the FDTD method is proved to be useful for accurately quantifying the optical properties for multiple scattering.

5 Discussion
Alternatively, one similar analysis was shown using the structure factor in Percus–Yevick theory (2015).\(^{11} \) It interpreted the spherical particles illuminated by scattering light that induce the non-linearly scattering cross section, to show that the oscillatory behavior depends on the volume fraction. With scatter of larger diameter, despite taking into account the concentration dependence, the optical properties induced by multiple scattering cannot be completely described. Our study based on the FDTD method can be used to directly observe the far-field scattering pattern for different TiO\(_2\) samples. In addition, with methods based on Monte Carlo simulation, it is difficult to perform proper algorithm modeling.\(^{35,36} \) Therefore, in this work, the OCT and FDTD combination method stands out for its flexibility in simulating complex structures (cellular morphology, cancer cells, etc.)\(^{37,38} \) to directly acquire the original phase function \( P_{a\theta}(\theta) \) for further expansions in biological applications, and as opposed to making indirect predictions in the other methods mentioned above.

6 Conclusion
In this work, we successfully demonstrated that combining the OCT system with the FDTD method can be used to obtain the \( g_{dep,FDTD} \) factor of high density tissues in the presence of multiple scatterings. Combining with the FDTD method, the light scattering interactions for near- and far-field patterns between adjacent TiO\(_2\) beads can be determined to identify the anisotropy factor, which also can be utilized for other scatters with different shapes or arrangements. The \( \mu_{s,FDTD} \) can be further extracted by using a fitting process based on the EHF theory. The increase in the sample density is accompanied by smaller IPS, and the near-field scattering patterns show that the photons interact and interfere between adjacent scatters through propagating the sample. A new analysis flow to accurately quantify the optical properties of the samples through the use of OCT and FDTD combination method is flexible and has future potential in the biomedical field.

Disclosures
The authors have no relevant financial interests in this article and no conflicts of interest to disclose.

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References

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