Effective Optical Properties of Two-Layered Turbid Media
Using the Frequency-Domain Multi-Distance Method

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Abstract

We measured the effective absorption and reduced scattering coefficients on the surface of two-layered turbid media using a frequency-domain multi-distance method. We measured the amplitude and the phase of the modulated intensity at source-detector distances ranging from 1.5 to 3.0 cm. We considered several combinations of one layer (L) (thickness: 0.1-1.6 cm) placed on top of one block (B) (thickness = 5 cm). We found that for layers less than about 0.40 cm thick the frequency-domain multi-distance method yields the optical properties of the underlying block. We also found that for layers more than 1.3 cm thick the frequency-domain multi-distance method yields a reduced scattering coefficient which reproduces that of the superficial layer. For a layer thickness in the range of 1.3-1.6 cm, the effective absorption coefficient approaches the layer absorption coefficient but does not match it to within experimental errors.

Keywords:


1. Introduction

The quantitative determination of the optical properties of tissues has a valuable potential in noninvasive diagnostics. In recent years, newly developed techniques have achieved accurate measurements of the absorption and reduced scattering coefficients in homogeneous turbid media [1-3]. While these techniques are accurate in homogeneous media, there are still questions about their validity in vivo, where the presence of layers and inhomogeneities may significantly affect optical measurements. For this reason, it is of interest to investigate the photon migration in layered turbid media [4, 5]. The purpose of this article is to investigate the meaning of the effective optical properties measured in two-layered turbid media with a multi-distance protocol based on the semi-infinite geometry and assuming homogeneous media [6].

2. Methods

The data were collected using a frequency-domain (110 MHz) spectrometer we have previously described [7] (ISS, Inc. tissue oximeter Model 96208). The light sources were 4 laser diodes emitting at 750 nm, and 4 at 840 nm. Four source-detector separations were used (between 1.5 and 3 cm) (Fig. 1(a)). The samples (underlying blocks and superficial layers) were made of gelatin. Different quantities of black India ink and white paint were added in order to have various absorption and reduced scattering coefficients. From 5 batches of gelatin (each having different optical properties), we made 5 blocks (labeled 1 to 5) and 5 sets of 4 superficial layers with different thicknesses (labeled a to d) (Fig. 1(b)). The measurements were performed on all the combinations of one underlying block and one superficial layer. From the raw data, using a frequency-domain multi-distance approach for the semi-infinite geometry [3] we recovered the optical properties of each block ($\mu_a^{(0)}$ and $\mu_s^{(0)}$) and the effective optical coefficients of all the combinations of one superficial layer on top of one underlying block ($\mu_a^{(eff)}$, $\mu_s^{(eff)}$).
Figure 1. (a) Schematic diagram of the experimental apparatus. (b) Thickness, absorption ($\mu_a$), and reduced scattering ($\mu'_s$) coefficients at 750 nm of the blocks and the layers employed in this study.
3. Results and Discussion

When the underlying block and the superficial layer had the same optical properties, we found that, in most cases, $\mu_{a}^{(\text{eff})}$ and $\mu_{s}^{(\text{eff})}$ recovered the common values of $\mu_{a}$ and $\mu_{s}$ to within the experimental error of 10% and 20%, respectively. This means that there was no significant inhomogeneity introduced by the contact surface between the block and the layer.

Figure 2(a) shows the recovered optical coefficients ($\mu_{a}^{(\text{eff})}$ and $\mu_{s}^{(\text{eff})}$) for different thicknesses of one superficial layer having the same scattering and different absorption than the underlying block. For all thicknesses, the recovered reduced scattering coefficient was close to the common value of 9.2 cm$^{-1}$ (maximum deviation 13%). At thicknesses up to 0.62 cm, the recovered absorption coefficient was close to that of the underlying block (maximum deviation 3%), while at a layer thickness of 1.6 cm, the recovered absorption coefficient was closer to the layer value.

![Graph of effective optical properties versus layer thickness in three different cases:](image)

**Fig. 2.** Effective optical properties versus layer thickness in three different cases:
(a) layer and block with different absorption and same reduced scattering coefficients;
(b) layer and block with the same absorption and different reduced scattering coefficients;
(c) layer and block with different absorption and different reduced scattering coefficients.
Figure 2(b) reports the results for different thicknesses of one superficial layer having the same absorption and different scattering than the underlying block. For all thicknesses, the recovered absorption coefficient was close to the common value of 0.147 cm⁻¹ (maximum deviation 11%). At thicknesses up to 0.24 cm, the reduced scattering coefficient was close to that of the underlying block (maximum deviation 8%), while at a layer thickness of 1.3 cm, the recovered scattering coefficient was to within 2% of that of the superficial layer. For the intermediate layer thickness of 0.60 cm the recovered absorption and scattering coefficients are in between the block and layer values.

A similar trend is found in the cases where the layer and the block differ in both absorption and scattering. Figure 2(c) shows the case for different thicknesses of layer 4 on top of block 3. In the case of layer thickness less than 0.40 cm, the recovered absorption and reduced scattering coefficients coincide with those of the underlying block to within 10%. In the case of the thickest layer (1.6 cm), the recovered reduced scattering coefficient coincides with that of the upper layer to within 5%, while the absorption coefficient is does not reproduce the upper layer. For the intermediate layer thickness of 0.55 cm the recovered absorption and reduced scattering coefficients are as shown in figure 2(c).

Figure 3 reports a summary of results obtained on the layer/block combinations where μ eff (λ) and/or μ s eff (λ) differ from μ eff (b) and μ s eff (b), respectively. This figure reports a normalized deviation between μ eff (a) (μ s eff (a)) and μ eff (b) (μ s eff (b)). This normalized deviation is defined as:

\[ \frac{\mu_{\text{eff}}(a) - \mu_{\text{eff}}(b)}{\mu_{\text{eff}}(a) - \mu_{\text{eff}}(b)} \]

where μ indicates either μ eff or μ s eff.

This normalized deviation takes a value of 0 when μ eff (a) = μ eff (b) and a value of 1 when μ eff (a) = μ eff (b).

(a) Absorption coefficient

(b) Reduced scattering coefficient

Fig. 3. Normalized deviations between the effective optical coefficients ((a) absorption; (b) reduced scattering) and the corresponding coefficients of the block. The various thicknesses, and the relationship between the layer and block optical properties are indicated in the legends.

We can divide all the cases considered into three categories:

1. Layer and block with same μ eff and different μ s eff:

\[ (\mu_{\text{eff}}(a) = \mu_{\text{eff}}(b), \mu_{s\text{eff}}(a) \neq \mu_{s\text{eff}}(b)) \]

In this case, μ s eff differed from the value μ s eff (b) by less than 10% for all of the layer thicknesses (except for 2 cases: layer 1c on top of block 4 and layer 3c on top of block 5 for which the difference was about 30%). The difference between μ s eff (a) and μ s eff (b) was less than 20% for layer thicknesses in the range 0.08-0.5 cm. For layer thicknesses 1.3-1.6 cm μ s eff coincided with μ s eff (b). For thicknesses in the range of 0.5-0.62 cm, the values of the optical coefficients were in between the block and layer values.

2. Layer and block with different μ eff and same μ s eff:

\[ (\mu_{\text{eff}}(a) \neq \mu_{\text{eff}}(b), \mu_{s\text{eff}}(a) = \mu_{s\text{eff}}(b)) \]

The difference between μ eff (a) and μ eff (b) was less than 10% for layer thicknesses in the range 0.08-0.62 cm. For layer thickness in the range of 1.3-1.6 cm, μ eff (a) approached μ eff (b), from which, however it usually differed by more than the experimental error. The difference between μ s eff (a) and the common value μ s eff (b) was less than 20% for all the layer thicknesses.

3. Layer and block with different μ eff and different μ s eff:

\[ (\mu_{\text{eff}}(a) \neq \mu_{\text{eff}}(b), \mu_{s\text{eff}}(a) \neq \mu_{s\text{eff}}(b)) \]

In this case, μ eff (a) differed from the value μ eff (b) by less than 10% for layer thicknesses in the range of 0.08-0.4 cm. For layer thickness in the range of 1.3-1.6 cm μ eff (a) approached μ eff (b). For layer thicknesses in the range of 0.4-0.62 cm the values are in between the μ eff (b) and μ eff (b).

The difference between μ s eff (a) and μ s eff (b) was less than 20% for layer thicknesses in the range 0.08-0.5 cm. For layer
thicknesses in the range of 1.3-1.6 cm, $\mu_s^{(3)}$ coincided with $\mu_s^{(g)}$. For thicknesses 0.55-0.62 cm, the values of the optical coefficients are in between the block and the layer values.

5. Conclusions

From our data taken in the range of distances 1.5-3 cm, we conclude that in the presence of superficial layers less than about 0.40 cm thick, the effective optical coefficients measured with the frequency-domain multi-distance method are representative of the optical coefficients of the underlying block.

For layers having thickness between 1.3-1.6 cm, the recovered value $\mu_s^{(eff)}$ reproduced the reduced scattering coefficient of the top layer, whereas $\mu_d^{(eff)}$ approached $\mu_d^{(3)}$ but it does not match it to within experimental errors.

For layer thickness of 0.5-0.6 cm the recovered effective optical coefficients are in between the layer and the block values.

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7. References


