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Influence of different coupling agents on the light-phantom interface

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ABSTRACT

Both for therapeutic and diagnosis purposes, light dosimetry is generally based on empirical data reported in the literature. It is known that tissue color, hydration and surface roughness influences the light propagation. In this context, it is important to investigate ways to minimize these effects leading to an enhanced phototherapy or photodiagnosis application. This study aims to evaluate how different coupling agents alter the light distribution at the light-phantom interface. Diffuse reflectance measurements were performed in order to compare the light interaction with the phantom with and without the coupling agents.

Keywords: refractive index matching, coupling agent, light propagation, light dosimetry

1. INTRODUCTION

When a laser beam is incident on a biological tissue it can be reflected, refracted, transmitted, scattered and absorbed. Light-tissue interaction depends on the tissue optical properties (absorption, scattering, and anisotropy), which is related to the wavelength of the incident light and is intrinsic to the target tissue.[1] The response of a biological tissue to an incident light beam can be used for therapeutic and diagnostic purposes.

Light coupling to the tissue is also relevant and strongly related to surface texture; smooth or rough surfaces reflect light in different ways.[2] Although there are several studies addressing light propagation in biological media, in particular there are some that consider the influence of the matching of refractive index,[3,4] there is still lack of information on how light coupling may influence light distribution and dosimetry.

In most part of the phototherapy and photodiagnosis applications, light is incident on the patient skin, and the dosimetry is established regardless, for instance, patient's age and skin color. However, it is clear that these features modify the light interaction and hence the light propagation and dosimetry. This way, it is necessary to improve the knowledge on how these features may influence light propagation in order to establish a more personalized dosimetry enhancing the clinical applications.

The present study aims to evaluate the effect a coupling agent (CA) placed on the turbid optical phantom surface has on the diffuse reflectance measurements when the incident light beam is a 660 nm collimated laser.

2. MATERIAL AND METHODS

For this study, a turbid optical phantom (figure 1) was prepared using the similar method as the one described by Long,[5] consisting of a mixture of pure beige cosmetic cream foundation (Koloss Makeup, Brazil) at a 2.54 mg/ml concentration in silicone (SQ 8000/50M RTV-2, SILAEX® QUÍMICA LTDA, Brazil) and 10.54 mg/ml of Al_2O_3 (Aluminum oxide 10 μm avg. part. size, SIGMA-ALDRICH).

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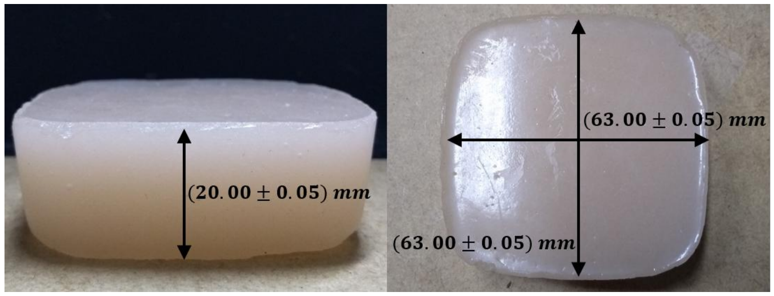


Figure 1. Silicone turbid optical phantom and its respective dimensions

The diffuse reflectance was evaluated at the interface of the CA with the optical phantom using the setup presented in figure 2, where the light source was a 660 nm collimated diode laser. A laser beam with normal incidence was placed near one of the edges of the phantom. An isotropic optical fiber probe placed in contact with the optical phantom was used to collect the diffuse reflected light signal by means of a USB2000 OceanOptics Spectrometer connected to the fiber end. The minimum distance between the laser beam and the probe was 0.5 cm. For measuring the diffuse reflectance on the phantom surface, the distance x between the probe and the laser beam was varied.

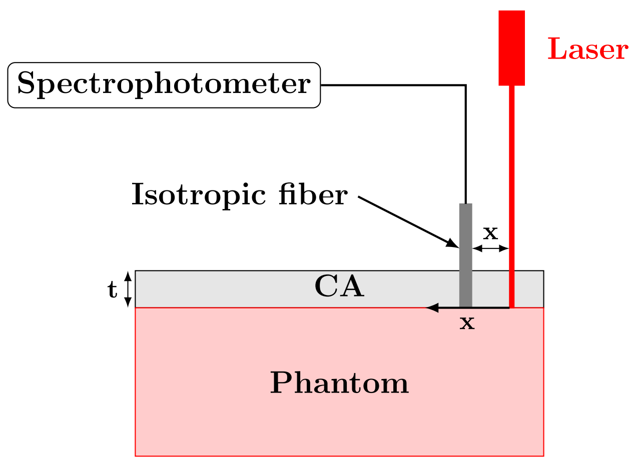


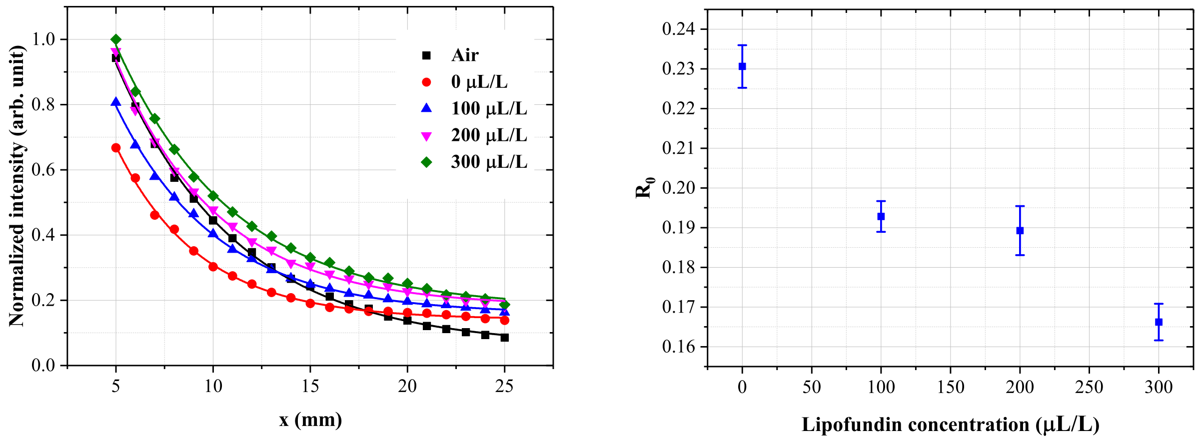
Figure 2. Schematics of the used experimental setup.

In order to evaluate the changes in the diffuse reflectance caused by the presence of a CA with different scattering degrees (but same refractive index), a layer of thickness t=0.5 cm (Figure 2) was placed on the top of the phantom. As CA we used: water and water with lipidic emulsion (lipofundin® MCT/LCT 20%) in different concentrations (100, 200 and 300 μL/L). To verify how the refractive index of the CA affects the light reflectance in the phantom interface, a layer of different materials was used: water, lipofundin® in water at a concentration of 200 μL/L, glycerin and petroleum jelly.

In all measurements, 4 spectra were acquired for each distance x and the data analysis was performed using a MATLAB® routine in which the average spectrum was calculated then the calculated value at 660 nm was recorded. This procedure was performed for all x values and then, using OriginLab® (2017) they were normalized by the maximum intensity of the measured data set and the diffuse reflectance intensity was plotted as a function of x for all tested CAs.

3. RESULTS AND DISCUSSION

The first aspect evaluated was the influence of scatterers in the CA. Figure 3.a shows the result of adding water with different scattering degrees on the diffuse reflectance at phantom surface. When no CA was added, we had the "air" interface condition. Fitting the curves by a first-order exponential decay, using the equation $y = y_0 + a_1 e^{-R_0 x}$ we were able to compare the decay coefficients for each CA.

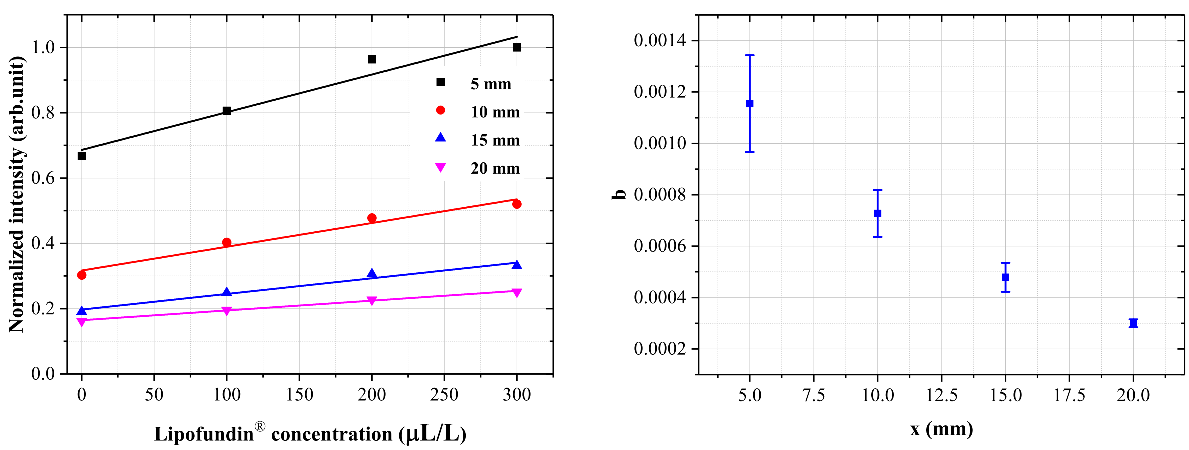


(a) (b)

Figure 3. (a) Comparison of the normalized intensity as a function of the distance x for the different concentrations of Lipofundin®; and, (b) fitting parameter R_0 as a function of Lipofundin® concentration. The curves of the graph (a) were fitted by $y = y_0 + a_1 e^{-R_0 x}$ to obtain the values of R_0 parameter.

The graph of figure 3.a shows us that the highest value of light intensity measured at x=5mm was measured when 300μL/L was placed on the phantom surface and lowest value at x= 5mm was when pure water was placed. From these figure we can also notice, as expected, that the shape of the curves was similar, but with different decay velocities for each situation. This observation becomes more clear in figure 3.b where we present the decay coefficient, R_0, as a function of lipofundin® concentration. R_0 decreased as the lipofundin® concentration increased.

We also evaluated the behavior of light intensity as a function of lipofundin® concentration for different source - detector separations (5, 10, 15 and 20 mm), the results are shown in figure 4.a. A linear fitting was performed using an equation of the type $y = y_0 + bx$, and a comparison of the linear coefficient b for each separation is presented in figure 4.b, where we can see that b decreases as the separation increases. We also see from Fig. 4.a that the light intensity collected for shorter separations shows a stronger influence of the scatterer concentration. For long separations, b approaches to zero (Fig. 4.b).



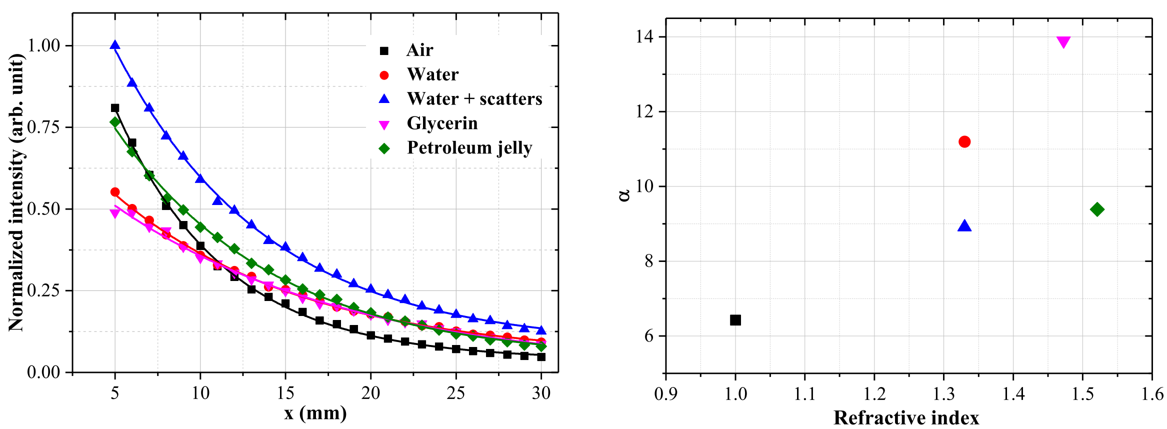
(a) (b)

Figure 4. (a) Comparison of the normalized intensity as a function of Lipofundin® concentration for the different source-detector separations; and, (b) fitting parameter as a function of source-detector separation. The curves of the graph (a) were fitted by $y = y_0 + bx$ to obtain the values of b parameter.

When different materials were used as a CA, the influence of the refractive index was evaluated. In figure 5.a we present the results of diffuse reflectance measurements acquired at the phantom surface for the different CAs. Fitting the curves by a first-order exponential decay, using the equation $y = y_0 + A_1 e^{-\frac{x}{\alpha}}$ we were able to compare the decay coefficients as a function of the refractive index (n) (reference values from literature as presented in Table 1). For lipofundin® in water, we considered n=1.333, the same as water.

Table 1. Refractive index for all CAs analyzed.

Material	Refractive index (n)
Water	1.333
Glycerin	1.4725[6]
Petroleum jelly	1.521[7]



(a) (b)

Figure 5. 5 (a) Comparison of the normalized intensity as a function of the distance x for the different coupling agents; and, (b) fitting parameter α as a function of the refractive indexes. The curves of graph (a) were fitted by $y = y_0 + A_1 e^{-\frac{x}{\alpha}}$ to obtain the values of α.

It is possible to observe from Figure 5.a that the highest value of light intensity was measured when lipofundin® at 200 μL/L was used on the top of the phantom.The fastest decay happened for the air-phantom interface and the slowest decay occurred when glycerin was used, however, for the glycerin, the light intensity was lower than for the other materials.

From Fig. 5.b, we observe that the α constant increase until the the refractive index close to 1.5 and after this start a decay. If we look in the literature the refractive index of this similar phantom media, the silicone, we obtained that is around 1.5.[8] So the maximum α constant happens when the refractive index is similar to the media.

In the present study, an isotropic fiber optic probe was used, it means that light coming from all directions could be collected. The probe was located on the top of the phantom surface, i.e., at the interface of the phantom with the air or with the CA. Figure 6 presents a simplified schematic of the light interactions when CA is a transparent media which may take place in our experiment.

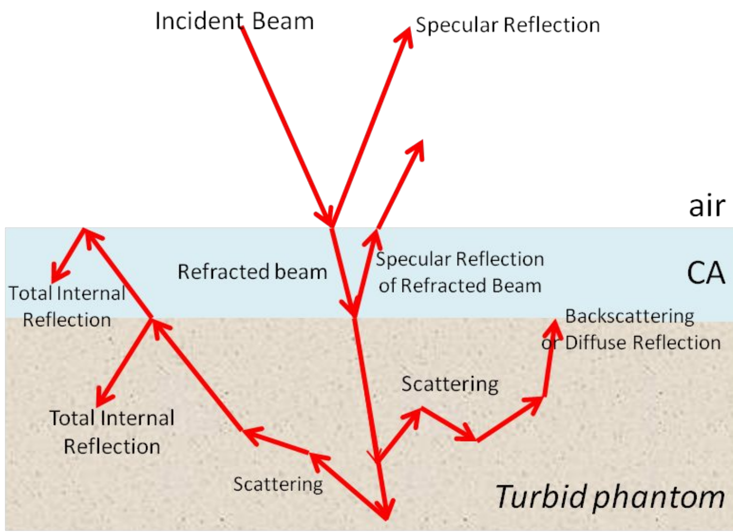


Figure 6. Interaction of light with a turbid phantom when a transparent medium is placed on its top surface.

As we can see, if the probe is placed at the interface, light coming from specular reflection, total internal reflection and diffuse reflection (or backscattering) can be simultaneously collected.

It is important to remember that total internal reflection (TIR) occurs when the light beam strikes an interface with a medium with a lower refractive index with an angle of incidence above the critical angle (when the angle of refraction is 90°). The critical angle, θ_c, is given by the Snell's Law as:

$$\theta_c = \sin^{-1}\left(\frac{n_t}{n_i}\right), \tag{1}$$

where n_t is the refractive index of transmission medium and n_i is the refractive index of the incidence medium. It is easy to observe that the critical angle will be larger as closer are n_t and n_i. The TIR will occur more often for lower critical angles.

Table 2 presents the critical angles for the cases we assessed. The calculations considered the refractive indices presented in Table 1.

Table 2. Critical angles for the cases analyzed.

Interface (incidence - transmission)	θ_c (°)
Phantom - Air	41.8
Water - Air	48.6
Phantom - Water	62.7
Glycerin - Air	42.8
Phantom - Glycerin	79
Petroleum jelly - Air	41.1
Phantom - Petroleum jelly	80.4

We can conclude that the combination of media that would maximize the light collected by the probe was that when backscattering and TIR with the CA-air interface are favored and not TIR at the Phantom-CA interface. This explanation corroborates our experimental results when water and glycerin had the best result of light attenuation, with lower decay rates.

4. CONCLUSION

Our results show that when lipofundin® in concentration 300 μL/L was placed on the top of the optical phantom, the diffuse reflectance signal collected at the interface was higher than when no CA was used. We also presented a comparison of different materials, showing that depending on the refractive index and scattering properties of the material, the light coupling can be improved or worsened. In our measurements, the best result was obtained when water with lipofundin® was used. It is possible to conclude that the presence of a coupling material may be useful for clinical applications as it modifies the way light propagates at the material interface. Since in the present study we only measured the light propagation on the phantom surface, other experimental and theoretical studies are in progress in our group aiming to evaluated how light propagation within the material can be changed by the presence of these CAs.

ACKNOWLEDGMENTS

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