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Light Fluence Dosimetry in Lung-simulating Cavities

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Abstract

Accurate light dosimetry is critical to ensure consistent outcome for pleural photodynamic therapy (pPDT). Ellipsoid shaped cavities with different sizes surrounded by turbid medium are used to simulate the intracavity lung geometry. An isotropic light source is introduced and surrounded by turbid media. Direct measurements of light fluence rate were compared to Monte Carlo simulated values on the surface of the cavities for various optical properties. The primary component of the light was determined by measurements performed in air in the same geometry. The scattered component was found by submerging the air-filled cavity in scattering media (Intralipid) and absorbent media (ink). The light source was located centrally with the azimuthal angle, but placed in two locations (vertically centered and 2 cm below the center) for measurements. Light fluence rate was measured using isotropic detectors placed at various angles on the ellipsoid surface. The measurements and simulations show that the scattered dose is uniform along the surface of the intracavity ellipsoid geometries in turbid media. One can express the light fluence rate empirically as $\phi = 4S/A_s R_d / (1 - R_d)$, where R_d is the diffuse reflectance, A_s is the surface area, and S is the source power. The measurements agree with this empirical formula to within an uncertainty of 10% for the range of optical properties studied. GPU voxel-based Monte-Carlo simulation is performed to compare with measured results. This empirical formula can be applied to arbitrary geometries, such as the pleural or intraperitoneal cavity.

Keywords

Photodynamic therapy; light fluence; light dosimetry; intra-cavitary treatment planning; MC simulation

INTRODUCTION

PDT is a local treatment aptly suitable to treat malignant, localized tumors such as those observed in malignant pleural mesothelioma (MPM).^{1,2} To treat MPM, PDT is coupled with surgical resection of the tumorous tissue. Within the thoracic cavity, the light delivery is continuously administered by a moving point source applied by radiation oncologist or the surgeon. As the light source is applied, the knowledge of how well each particular area of

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the thoracic cavity is being irradiated will make the entire treatment process more effective and efficient and can serve to better personalize treatment delivery.

In order to improve the dosimetry accuracy of light fluence calculation inside the lung cavity, it is necessary to accurately determine the scatter light fluence rate inside an arbitrary shaped cavity. The scattered light fluence rate is expected to be a constant because of the so-called integrating sphere effect.^{3,4} The purpose of this study is to verify if this assumption is accurate for an ellipsoid-shaped cavity emerged inside liquid optical phantom with different tissue optical properties. In addition, the accuracies of a two analytical equations to determine the light fluence rate are evaluated.

2. METHODS

2.1 Experimental setup

Two types of egg-shaped lung phantoms were constructed: one for a small lung size and another for a large lung size. Figure 1 shows the experimental setup and geometry of the lung-shaped phantoms. Three isotropic detectors (model IP 1250, Medlight SA, Switzerland) located at different locations right outside the transparent egg-shaped lung phantom through 3 transparent catheters. The isotropic light source (model SD 1250, Medlight SA, Switzerland) is located at center (Fig. 1b) and an offset location (see Fig. 2). Figure 2 shows the shape of the lung phantom (only half is shown because of cylindrical symmetry) and the coordinates of the nominal location of the point source and the isotropic detectors.

2.2 Light fluence calculation

One can calculate the light fluence rate (ϕ) by summing up the direct and the scattering light during pleural PDT. The direct light follows a simple formula for a point source, i.e.,

$$\phi_{dir} = \frac{S}{4\pi r^2} A(\theta), \quad (1)$$

where r is the distance from the point of interest to the laser point source and $A(\theta)$ is the anisotropy correction function of the point source. $A(\theta)$ is shown in Fig. 3 for the full range of angles used (0 – 180°). The data is renormalized so that:

$$\int_0^\pi A(\theta) d\Omega / 4\pi = 1. \quad (2)$$

The definitions of the angles are consistent with the orientation of the measurements in the ellipsoid phantom (Figs. 1&2).

For an integrating sphere, the scattered light fluence rate inside the sphere, assuming an infinite number of reflections, is uniform and can be calculated according to ^{3,5}:

$$\phi_{sc} = \frac{4S}{A_s} \cdot R_d \cdot (1 + R_d(1-f) + R_d^2(1-f)^2 + \dots) = \frac{4S}{A_s} \cdot \frac{R_d}{1 - R_d(1-f)}, \quad (3)$$

where S is the light source power (mW), R_d is the diffuse reflectance of the scattering wall surface, $A_s (=4\pi R^2)$ is the total surface area with R the radius of the sphere, and f is the fraction of the open surface area to the total surface area and is assumed $f=0$ in our current setup since the whole lung phantom is completed sealed. The relationship between tissue optical properties and diffuse reflectance is given elsewhere⁶. For comparison, we can also use the analytical solution developed by Star:⁴

$$\phi_{sc} = \frac{S \cdot (1 - R_{21})}{A_s} \cdot \left(\frac{\mu_{eff}}{\mu_a} - 3 \right), \quad (4)$$

where μ_a is the absorption coefficient, μ_{eff} is the effective attenuation coefficient. The surface areas (A_s) in Eqs. (3) and (4) can be calculated using either the actual surface area ($A_{s,a}$) or volume averaged surface area ($A_{s,v}$) based on the corresponding surface volume of a sphere:

$$A_{s,v} = 4\pi \left(\frac{3V}{4\pi} \right)^{2/3}, \quad (5)$$

where V is the actual volume of the cavity.

3. RESULTS

3.1 Measurement of scatter fluence rate in egg shaped lung phantoms

Tables 1 and 2 show the total, primary, and scatter fluence rate per power measured in the small lung phantom for two different intralipid concentrations (0.5% and 1.0%), respectively, for three different ink concentrations (0.002%, 0.01%, and 0.02%) per each intralipid concentration. The scatter fluence rate per power is calculated as the difference between the total and primary fluence rate per power. The mean measured scatter fluence rates per power and its standard deviation are also shown per each optical properties (μ_a , μ_s '). For comparison, calculated scatter fluence rate per power using Eqs. (3) and (4) are also shown using two different surface areas ($A_{s,a}$, $A_{s,v}$). Table 3 shows the corresponding light fluence rate per power measured in the large lung phantom for an intralipid concentration (1.0%). Note the data in parenthesis in Tables 3 is not used in the average for scatter light due to suspicion of measurement error.

4. DISCUSSION AND CONCLUSION

Tables 4 – 6 shows the percentage errors between the analytical calculations (Eqs. 3 and 4) and the measured average scatter fluence rate per power. The bold data in tables 4 – 6 show the best agreement between measurement and calculation. For the large lung phantom the

difference between actual surface area ($A_{s,a} = 373.3 \text{ cm}^2$) and the volume averaged surface area ($A_{s,v} = 369.8 \text{ cm}^2$) are very close, within 1%, and thus the difference in the calculated scatter fluence rate per power between the two areas are negligible. Our measurements in general seem to indicate that Eq. 3 predicts measured scatter fluence rate per power better than that based on Star formula (Eq. 4) to within 10%. The agreement is better if the actual surface area is used.

Some preliminary comparisons of scatter fluence rate per power between GPU voxel-based Monte-Carlo (MC) simulations using DosieSOFT from Simphotech, Inc. and the measurements are made for the small lung phantom with the source on the central axis (see Table 7). The agreement between MC calculation and measurement are similar to that based on Star's formula (Eq. 4) and are less than 23%.

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References

1. Pass HI, DeLaney TF, Tochner Z, Smith PE, Temeck BK, Pogrebniak HW, Kranda KC, Russo A, Friauf WS, Cole JW, et al. Intrapleural photodynamic therapy: results of a phase I trial. *Ann Surg Oncol.* 1994; 1(1):28–37. [PubMed: 7834425]
2. Pass HI, Tochner Z, DeLaney T, Smith P, Friauf W, Glatstein E, Travis W. Intraoperative photodynamic therapy for malignant mesothelioma. *Ann Thorac Surg.* 1990; 50(4):687–688. [PubMed: 2222072]
3. SphereOptics. Integrating sphere design and application technical information. LabSphere manual. 2007
4. Star WM. The relationship between integrating sphere and diffusion theory calculations of fluence rate at the wall of a sphere. *Phy Med Biol.* 1995; 40:1–8.
5. Dimofte A, Zhu TC, Finlay JC, Cullingham M, Edmonds CE, Friedberg JS, Cengel KC, Hahn SM. In-vivo light dosimetry for pleural PDT. *Proc SPIE.* 2009; 7164:71640A.
6. Ong Y, Zhu TC. Analytic function for predicting light fluence rate of circular fields on a semi-infinite turbid medium. *Opt Exp.* 2016; 24(23):26261–26281.

Figure 1.

(a) Experimental setup of light fluence rate measurement for the small lung shaped phantoms. (b) Schematics of the light sources at center of the lung-phantom geometry and the locations of the isotropic detectors during measurement: 0°, 45°, 90°. The lung-phantom can be approximated by ellipsoid with long and cylindrically symmetrical short axes of 3.9 and 2.8 cm, and 6.8 and 4.8 cm, respectively, for the small and large lung phantoms.

Figure 2.

(a) Schematics for the center and off-axis positions (0 and 1.5 cm off) for the small lung phantom, where $V=134.4 \text{ cm}^3$, $A_{s,a} = 112.6 \text{ cm}^2$, and $A_{s,v} = 126.6 \text{ cm}^2$. (b) Schematics for the center and off-axis positions (0 and 1.5 cm off) for the large lung phantom, where $V = 668.8 \text{ cm}^3$, $A_{s,a} = 373.3 \text{ cm}^2$, and $A_{s,v} = 369.8 \text{ cm}^2$. The coordinates of the three isotropic detectors locations (0° , 45° , 90°) are shown as well.

Figure 3.
Re-normalized angular anisotropy (Eq. 2) of the point source based on in-air measurements on a rotational platform.

Table 1

ϕ/S (1/cm²) of light fluence vs. optical properties in small lung phantom ($\mu_s' = 5.5 \text{ cm}^{-1}$ (Intralipid 0.5%))

Location\(μ_a (Ink %))	0.088 (0.002%)	0.34 (0.01%)	0.83 (0.020%)	In air, primary
Centered PS				
0°				
Total, Meas.	0.0537	0.0248	0.0162	0.0072
Scatter, Meas	0.0465	0.0177	0.0090	
45°				
Total, Meas.	0.0580	0.0349	0.0244	0.0160
Scatter, Meas	0.0420	0.0190	0.0085	
90°				
Total, Meas.	0.0551	0.0313	0.0199	0.0095
Scatter, Meas	0.0456	0.0218	0.0104	
Off-Center PS (1.5 cm down)				
0°				
Total, Meas.	0.0604	0.0363	0.0281	0.0187
Scatter, Meas	0.0416	0.0176	0.0094	
45°				
Total, Meas.	0.0651	0.0387	0.0332	0.0222
Scatter, Meas	0.0428	0.0164	0.0110	
90°				
Total, Meas.	0.0484	0.0318	0.0162	0.0074
Scatter, Meas	0.0410	0.0244	0.0088	
Mean $\pm$ sd, Scatter, Meas	0.0433 $\pm$ 0.0023	0.0195 $\pm$ 0.0030	0.0095 $\pm$ 0.0010	
Scatter, Eq. 3, $A_{s,v}$	0.0414	0.0174	0.0089	
Scatter, Eq. 3, $A_{s,a}$	0.0465	0.0195	0.0100	
Scatter, Eq. 4, $A_{s,v}$	0.0533	0.0213	0.0097	
Scatter, Eq. 4, $A_{s,a}$	0.0599	0.0240	0.0109	

Table 2

ϕ/S (1/cm²) of light fluence vs. optical properties in small lung phantom ($\mu_s' = 11.8 \text{ cm}^{-1}$ (Intralipid 1.0%))

Location\(μ_a (Ink %)	0.0805 (0.002%)	0.525 (0.01%)	0.9445 (0.020%)	In air, primary
Centered PS				
0°				
Total, Meas.	0.04108	0.01566	0.01039	0.00667
Scatter, Meas	0.0638	0.0201	0.0111	
45°				
Total, Meas.	0.04241	0.01697	0.01253	0.00861
Scatter, Meas	0.0656	0.0211	0.0133	
90°				
Total, Meas.	0.04055	0.01835	0.01422	0.01174
Scatter, Meas	0.0622	0.0217	0.0142	
Off-Center PS (1.5 cm down)				
0°				
Total, Meas.	0.048	0.021	0.017	0.01667
Scatter, Meas	0.0659	0.0202	0.0131	
45°				
Total, Meas.	0.042	0.018	0.015	0.01156
Scatter, Meas	0.0626	0.0198	0.0141	
90°				
Total, Meas.	0.038	0.017	0.013	0.00865
Scatter, Meas	0.0599	0.0228	0.0148	
Mean $\pm$ sd, Scatter, Meas	0.0633 $\pm$ 0.0023	0.0210 $\pm$ 0.0011	0.0134 $\pm$ 0.0013	
Scatter, Eq. 3, $A_{s,v}$	0.0601	0.0190	0.0125	
Scatter, Eq. 3, $A_{s,a}$	0.0675	0.0214	0.0140	
Scatter, Eq. 4, $A_{s,v}$	0.0787	0.0235	0.0147	
Scatter, Eq. 4, $A_{s,a}$	0.0885	0.0264	0.0165	

Table 3

ϕ/S (1/cm²) of light fluence vs. optical properties in large lung phantom ($\mu_s' = 5.5 \text{ cm}^{-1}$ (Intralipid 0.5%))

Location\ μ_a (Ink %)	0.133 (0.002%)	0.47 (0.01%)	0.864 (0.020%)	In air, primary
Centered PS				
0°				
Total, Meas.	0.0119	0.0046	0.0038	0.0021
Scatter, Meas	0.0098	0.00257	0.00177	
45°				
Total, Meas.	0.0147	0.0094	0.0064	0.0045
Scatter, Meas	0.0102	0.00496	0.00194	
90°				
Total, Meas.	0.0169	0.0114	0.0098	0.0063
Scatter, Meas	0.0107	0.00514	0.00358	
Off-Center PS (1.5 cm down)				
0°				
Total, Meas.	(0.0068)	0.0063	0.0053	0.0029
Scatter, Meas	(0.0039)	0.00336	0.00241	
45°				
Total, Meas.	0.0152	0.0104	0.0095	0.0060
Scatter, Meas	0.0092	0.00437	0.00346	
90°				
Total, Meas.	0.0188	0.0100	0.0073	0.0055
Scatter, Meas	0.0133	0.00446	0.00174	
Mean $\pm$ sd, Scatter, Meas	0.0106 $\pm$ 0.0016	0.0041 $\pm$ 0.0010	0.0025 $\pm$ 0.0008	
Scatter, Eq. 3, $A_{s,v}$	0.0096	0.0040	0.0025	
Scatter, Eq. 3, $A_{s,a}$	0.0097	0.0040	0.0025	
Scatter, Eq. 4, $A_{s,v}$	0.0122	0.0047	0.0025	
Scatter, Eq. 4, $A_{s,a}$	0.0123	0.0047	0.0025	

Table 4

%error between calculation and measurement for Table 1

Scatter, Eq. 3, $A_{s,v}$	-4.4%	-10.8%	-6.3%
Scatter, Eq. 3, $A_{s,a}$	7.5%	0.3%	5.3%
Scatter, Eq. 4, $A_{s,v}$	23.2%	9.4%	1.9%
Scatter, Eq. 4, $A_{s,a}$	38.4%	22.9%	14.5%

Table 5

%error between calculation and measurement for Table 2

Scatter, Eq. 3, $A_{s,v}$	-5.1%	-9.4%	-7.0%
Scatter, Eq. 3, $A_{s,a}$	6.6%	2.1%	4.2%
Scatter, Eq. 4, $A_{s,v}$	24.2%	12.1%	9.4%
Scatter, Eq. 4, $A_{s,a}$	39.7%	25.9%	22.8%

Table 6

%error between calculation and measurement for Table 3

Scatter, Eq. 3, $A_{s,v}$	-8.4%	-1.9%	1.2%
Scatter, Eq. 3, $A_{s,a}$	-9.3%	-2.8%	0.3%
Scatter, Eq. 4, $A_{s,v}$	16.1%	14.3%	2.4%
Scatter, Eq. 4, $A_{s,a}$	15.0%	13.3%	1.4%

Table 7

MC DosieSOFT calculated scatter fluence rate per power for small lung phantom ($\mu_s' = 5.5 \text{ cm}^{-1}$ (Intralipid 0.5%)) with the centered PS (Table 1)

Location\ μ_a (lnk %)	0.088 (0.002%)	0.34 (0.01%)	0.83 (0.020%)
DosieSOFT, 0°	0.0336	0.0191	0.0110
DosieSOFT, 45°	0.0404	0.0231	0.0133
DosieSOFT, 90°	0.0359	0.0197	0.0108
Mean $\pm$ sd, Scatter, MC	0.0366 $\pm$ 0.0035	0.0206 $\pm$ 0.0022	0.0117 $\pm$ 0.0014
MC/meas (%)	-15%	5.8%	23%