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Light dosimetry and dose verification for pleural PDT

Andreea Dimofte¹, Anna V. Sharikova¹, Julia L. Meo¹, Charles B. Simone II¹, Joseph S. Friedberg², and Timothy C. Zhu¹

¹Departments of Radiation Oncology, University of Pennsylvania, Philadelphia, PA

²Division of Thoracic Surgery, University of Pennsylvania, Philadelphia, PA

Abstract

In-vivo light dosimetry for patients undergoing photodynamic therapy (PDT) is critical for predicting PDT outcome. Patients in this study are enrolled in a Phase I clinical trial of HPPH-mediated PDT for the treatment of non-small cell lung cancer with pleural effusion. They are administered 4mg per kg body weight HPPH 48 hours before the surgery and receive light therapy with a fluence of 15–45 J/cm² at 661 and 665nm. Fluence rate (mW/cm²) and cumulative fluence (J/cm²) are monitored at 7 sites during the light treatment delivery using isotropic detectors. Light fluence (rate) delivered to patients is examined as a function of treatment time, volume and surface area. In a previous study, a correlation between the treatment time and the treatment volume and surface area was established. However, we did not include the direct light and the effect of the shape of the pleural surface on the scattered light. A real-time infrared (IR) navigation system was used to separate the contribution from the direct light. An improved expression that accurately calculates the total fluence at the cavity wall as a function of light source location, cavity geometry and optical properties is determined based on theoretical and phantom studies. The theoretical study includes an expression for light fluence rate in an elliptical geometry instead of the spheroid geometry used previously. The calculated light fluence is compared to the measured fluence in patients of different cavity geometries and optical properties. The result can be used as a clinical guideline for future pleural PDT treatment.

Keywords

Light dosimetry; photodynamic therapy; HPPH; light fluence

1. INTRODUCTION

Malignant pleural effusions are common clinically and there are no widely accepted curative approaches. Radiotherapy and chemotherapy have little effect in the treatment of malignant pleural mesothelioma. The prognosis of most patients with malignant pleural effusion is poor. The treatment of a malignant pleural effusion usually begins with a thoracentesis which provides temporary relief of symptoms, but often these effusions recur. These poor results have led to investigation of adjuvant photodynamic therapy (PDT).[1] PDT is an

investigative cancer treatment modality that has been under development during the last decades.[2, 3] The basis of this therapy involves the in situ activation of a photosensitizer accumulated in tumor and normal tissue by visible light, causing cell death.

In-vivo light dosimetry for patients undergoing PDT is one of the dosimetry quantities critical for predicting PDT outcome. We evaluated the mean light fluence rate delivered to patients undergoing pleural PDT as a function of treatment time, treatment volume and surface area, and its accuracy. The accuracy of determining the treatment volume among CT, navigation system and surgical determination using saline volume were determined. Direct light and the effect of the shape of the pleural surface on the scattered light were studied. We used a real-time infrared (IR) navigation system to separate the contribution from the direct light.[4]

Theoretical calculations were performed using measured optical properties performed *in-vivo*, to determine the relationship between the treatment time and the treatment area and compared to the measured results.

2. METHODS

2.1 Patient treatment

The patients described here were enrolled in a Phase I trial of HPPH (2-[1-hexyloxyethyl]-2-devinyl pyropheophorbide- α) mediated PDT in combination with surgery for non-small-cell lung cancer (NSCLC) with pleural effusion. All patients underwent thoracotomy. After resection, each patient received PDT to treat the thoracic cavity.

Patients were administered 4mg per kg body weight HPPH 48 hours before the surgery. 665nm (or 661nm) illumination was delivered via a diffusing optical probe consisting of an optical fiber mounted in a modified endotracheal tube that terminated in a balloon filled with 0.1% intralipid. A dilute intralipid solution (1%) was placed in the pleural cavity as a light scattering agent. Eight isotropic detectors (figure 1a) were sown to the wall of the pleural cavity for monitoring the light dose in the following sites: Apex, anterior medial chest wall (ACW), posterior chest wall (PCW), posterior diaphragmatic sulcus (PS), anterior diaphragmatic sulcus (AS), posterior mediastinum (PM), diaphragm (Diaph) and pericardium (Peri) as shown in figure 1b. The illumination was delivered under manual control until the prescribed dose of 15 – 45 J/cm² was reached at all sites. CT and a navigation system were used to determine the volume and treatment area. The tissue optical properties were determined with absorption reflectance spectroscopy.

2.2 Theory of light fluence distribution in pleural cavity

The light fluence rate inside a sphere such as that shown in Figure 5 assuming infinite number of reflections is uniform and can be calculated according to:

$$\phi = \frac{4S}{A_s} \cdot \rho \cdot (1 + \rho(1-f) + \rho^2(1-f)^2 + \dots) = \frac{4S}{A_s} \cdot \frac{\rho}{1 - \rho(1-f)} \quad (1)$$

where S is the light source power (mW), ρ 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, f is the ratio of the open surface area to the total surface area.

The diffuse reflectance can be calculated based on the optical properties of the thoracic wall [5]:

$$\rho = \frac{a'}{2} (1 + e^{-(4/3)A \sqrt{3(1-a')}}) e^{-\sqrt{3(1-a')}} \quad (2)$$

where $a' = \mu'_s / (\mu_a + \mu'_s)$ is the transport albedo, A , the internal reflection parameter.

Using the relationship between the time and total light fluence: $\Psi = \phi \cdot t$ and Eq. (2), one finds the relationship between the treatment time and the treatment area:

$$t = k \cdot A_s \quad (3)$$

where

$$k = \frac{\Psi}{4S} \frac{e^{\mu_a \cdot r}}{\rho(1-f)(1+\rho(1-f)+\rho^2(1-f)^2+\dots)} = \frac{\Psi e^{\mu_a r}}{4S} \left(\frac{1-\rho(1-f)}{\rho(1-f)} \right) \quad (4)$$

where $f = \frac{A_{open}}{A_{total}} = 0.25$, $\Psi = 60 \text{ J/cm}^2$ is the total fluence, $S = 7 \text{ W}$ is the laser power, r is the mean radius of the cavity, we estimated $r = 8 \text{ cm}$ for the patient population studied, and ρ is the diffuse reflectance, which is a function of tissue optical properties (μ_a and μ'_s).

2.3 Determination of tissue optical properties

The optical properties of various tissues in the thoracic cavity (chest wall, diaphragm, esophagus, lung, pericardium, skin, lung) before and after PDT treatment were determined by analyzing the diffuse reflectance spectra measured (Figure 2) in four channels of the detection probe (Figure 3) using an algorithm that quantifies the scattering spectrum and contributions to absorption of hemoglobin and HPPH.[6]

The optical properties before and after PDT treatment were determined by analyzing the diffuse reflectance spectra measured in four channels of the detection probe.[6] This algorithm quantifies the scattering spectrum and contributions to absorption of hemoglobin and HPPH. Using these parameters, the best-fit optical properties at the wavelength of treatment (665nm) can be determined. Table 1 lists the minimum, maximum, and mean values of each parameter from among the 12 patients made on various tissue types (one before and one after PDT) in each of four channels.

2.4 Calibration of isotropic detectors for *in-vivo* light dosimetry

2.4.1 Description of the isotropic detectors used in our study—Isotropic detectors were used to measure the light energy fluence rates delivered to patients undergoing pleural PDT. An isotropic detector consists of a highly scattering material

spherical bulb attached to the tip of a flat cut optical fiber. The fiber detector has a spherical scattering tip that detects light from all directions. The output of the optical fiber is connected to a photodiode via a SMA connector. The light reaching the bulb from any direction is multiply scattered before it contributes to the light that reaches the optical fiber. The spherical detector measures the radiant energy fluence rate Φ (mW/cm²). Figure 4 shows a picture of one of the isotropic detectors used in our study. The isotropic detector has a 0.5mm scattering tip and is manufactured by MedLight S.A. (Switzerland).

2.2.2 Calibration procedure—To calibrate the fluence rate and the laser power, first we calibrate a 1 mm detector under broad beam geometry. A 1mm isotropic detector with good isotropy is placed in the center of the uniform beam, at the same level as the power meter, at the same distance from the light source and is connected to a dosimetry system. The light fluence rate of the isotropic detector is then calibrated in the collimated beam geometry using the measured power S and the calculated light fluence rate ($\phi = S \text{ (mW)} / \pi D^2$, D is the detector diameter) as a transfer standard.

We use a 6" integrating sphere (IS-06-SF, Labsphere, North Sutton, NH) to ensure uniformity and reproducibility of light fluence rate during calibration (figure 5). The integrating sphere contains three 1.5-inch diameter input ports and one 0.5-inch diameter detector port. Because of the multiple scattering inside the sphere, the light fluence rate is uniform everywhere inside the sphere, regardless the relative geometry of the light and the integrating sphere. The fluence rate in air ϕ_0 is proportional to the power reading I of the power meter by a calibration constant α , i.e.

$$\phi_0 = \alpha I. \quad (5)$$

The calibration is performed using the transfer isotropic detector. Using the calibrated integrating sphere, one can calibrate isotropic detectors in the integrating sphere such that the measured photovoltage (V) from the isotropic detector was proportional to the light fluence rate by:

$$\Phi = a(V - b) \quad (6)$$

where a (mW/cm²/V) is the conversion factor for fluence rate and b (V) characterizes the leakage of the photodiode. The isotropic detector is inserted in the integrating sphere via a diffusive tube to ensure that no direct light from the light source reaches the isotropic detector.

2.5 Image guided pleural PDT

An image guided PDT treatment planning system was used in most of the cases. This system uses an infrared camera and tracking tools to locate the irradiation source positions during the treatment. With pre-determined pleural cavity contour, light fluence distribution is calculated and displayed for the surgeon in real time. Preliminary results have been obtained using this prototype system in phantom and patients. This system has been tested with both

630 nm and 661 nm laser irradiation and HPPH photosensitizer. Cavity contours were determined using a contour wand.

3. RESULTS AND DISCUSSION

3.1 Isotropic detector calibration accuracy

3.1.1. Integrating sphere calibration accuracy—The integrating sphere was calibrated for the light fluence rate (figure 6). The variation of the calibration factors, a , over a period of time is plotted in figure 6 (a) for 661nm and (b) for 665nm and summarized in Table 2. The average CF is plotted as a continuous line.

3.1.2 Angular dependence of the isotropic detectors—An ideal isotropic detector would respond to light isotropically from any angle. However, a practical isotropic detector does not respond to light isotropically, because the light incident to the detector at an angle close to the stem of the detector will not be detected because of the blockage by the optical fiber. The angular response of the detectors was measured in two planes: horizontal and vertical, as shown in figure 7. The response of each detector was measured for every ten degree in each plane. Normalized angular response to 0 degree correction factor of eleven 0.5mm isotropic detectors in the vertical plane is shown in figure 7a and normalized angular response to 90 degrees in the horizontal plane is shown in figure 7b. A summary of the variation of the normalized calibration factors, a/a_{avr} , for the eight detectors used is shown in Table 3.

3.2 Relationship between treatment time and the treatment area

Light dosimetry was used for each PDT light delivery to monitor the dose delivered to the cavity. Isotropic detectors were sewed onto the thoracic wall as shown in figure 1 and were used to measure light fluence during treatment. We studied the relationship between the time needed to deliver the prescribed dose as a function of the volume and surface of the treated cavity. We also compared the CT volume and area with the one obtained using the navigation system. We used an image guided pleural PDT system to delineate the cavity contours by using a contouring wand and software. We compared the cavity volumes and area obtained from the CT scans to those obtained using the navigation system, and the results are shown in Table 4. The time for light delivery varied from 2120s to 5407s. The volume of the treated cavity varied from 349 to 3183cm³ and the surface of the treated cavity varied from 385 to 1756cm², as shown in table 4.

Figure 8 plots the time versus the cavity volume and area determined using the navigation system. The relationship between the size of the treated volume and time, as well as the corresponding relationship between the time and the treated area are:

We plotted the relationship between the time and volume Figure 9a and time and area Figure 9b using the CT scans as well as the relationship between the time and cavity volume measured with water Figure 9c.

Figure 10 shows a wire-plot of the treated cavity walls for each of the 20 studied patients. Next to each plot, the volume and area of the structure is shown. It is clear that treating the

thoracic cavity with uniform dose is a difficult task, given the very complex geometry of the thoracic walls. The volume of the treated cavity varied from 349cm^3 to 3183cm^3 . The treated surface area varied from 385cm^2 to 1756cm^2 . The prescribed dose was delivered in a different amount of time for each patient. Time varied between 2089 and 5407s depending on the volume size and geometrical complexity.

Figure 11 plots the lung volume irregularities from the IR navigation system. The volume of the treated cavity varied from 1774cm^3 to 10410cm^3 . The treated surface area varied from 576cm^2 to 1606cm^2 .

Comparison of the cavity volume was made between the ones obtained using the navigation system, CT and water volume filling the cavity measured during the treatment. A plot of the navigation volume vs the CT volume is plot in Figure 12 (a) and the water volume vs Ct volume is plot in Figure 12 (b). A comparison of volumes and area between CT, water and navigation system volumes is shown in Table 5.

3.3 Summary of light fluence rate results

The average fluence rate delivered among the studied patients was 9.3 mW/cm^2 and the calculated fluence rate, based on the prescribed dose and time for delivery was 10.3 mW/cm^2 , as shown in table 6.

An example of dose monitoring during treatment delivery is shown in figure 13. Figure 13 a through d are plots of the cumulative fluence for each of the seven sites monitored by isotropic detectors for prescription dose of 15, 20, 25 and 45J/cm^2 . Figure 13 e through h show the fluence rate received by each of the detectors for a prescription dose of 30J/cm^2 . The fluence rate varies during the treatment; an average overall fluence rate 9.3mW/cm^2 was determined.

4. CONCLUSIONS

We have determined the mean light fluence rate for HPPH-mediated PDT to be between 3.3 to 14 mW/cm^2 . We established that there is no correlation between the treatment time and the treatment volume and area from an analysis of 20 HPPH-PDT patients. The CT volume is always smaller than volume determined in OR by a factor of 2.8 for volume and 1.3 for area. Further studies are needed to find the causes.

Acknowledgments

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References

1. Friedberg JS, et al. Phase II trial of pleural photodynamic therapy and surgery for patients with non-small-cell lung cancer with pleural spread. *J Clin Oncol.* 2004; 22(11):2192–2201. [PubMed: 15169808]
2. Delaney TF, Glatstein E. Photodynamic therapy of cancer. *Compr Ther.* 1988; 14(5):43–55. [PubMed: 2968898]

3. Dougherty TJ, Marcus SL. Photodynamic Therapy. *Eur J Cancer*. 1992; 28A:1734–1742. [PubMed: 1327020]
4. Zhu TC, et al. A real-time treatment guidance system for pleural PDT. *Proc SPIE*. 2012; 8210:821009.
5. Dimofte A, et al. In-vivo light dosimetry for HPPH-mediated pleural PDT. *Proc SPIE*. 2010; 7551:755115.
6. Finlay JC, et al. Diffuse reflectance spectra measured in vivo in human tissue during photofrin-mediated pleural photodynamic therapy. *Proc SPIE*. 2006; 6139:613913:1–7.

Figure 1.

a. Isotropic detector sewn to the patient's chest wall and b. Anatomy of the thoracic cavity showing the placement of 7 isotropic detectors during pleural PDT: (1) Apex; (2) Anterior diaphragmatic Sulcus (AS); (3) Posterior diaphragmatic Sulcus (PS); (4) Pericardium (Peri); (5) Anterior Chest Wall (ACW); (6) Posterior Chest Wall (PCS); (7) Posterior Mediastinum (PM); (8) Diaphragm (Diaph).

Figure 2.
Diffuse reflectance for HPPH patients.

Figure 3.
Optical probe used in measuring diffuse reflectance spectra.

Figure 4.
Isotropic detector with 0.5 mm scattering tip used in our study.

Figure 5. Experimental setup for calibration of isotropic detectors. The integrating sphere provides uniform light. The light fluence rate inside the sphere is determined by the LM-1 detector.

Figure 6.
Fluence rate calibration in an integrating sphere for (a) 661nm and (b) 665nm wavelength

Figure 7.
Angular response of the detectors in: (a) vertical plane and (b) horizontal plane.

Figure 8.
Plot of time vs (a) volume and (b) area when using the navigation system.

Figure 9.
Calculated plot of time vs (a) volume and (b) area and (c) water used to fill the cavity.

Figure 10.
Wire-plots of treated cavity walls showing the lung volume irregularities using CT's.

Figure 11.

Wire-plots of treated cavity walls showing the lung volume irregularities using the navigation system.

Figure 12.

(a) Plot of navigation system volume vs CT volume; (b) water volume vs CT volume.

Figure 13. Cumulative fluence plot of fluence vs time for prescription dose of (a–d) 15, 20, 255 and 45J/cm²; (e–h) 30J/cm².

Table 1

Summary of measured in-vivo optical properties in pleural PDT patients.

S/N	Tissue type	μ_a	std μ_a	μ_s'	std μ_s'
pat 1	Chest wall	0.2	0.0	12.2	0.4
	Diaphragm	0.3	0.0	12.5	0.1
	Esophagus	0.0	0.0	50.5	4.7
	Lung	0.2	0.0	61.6	8.6
	Pericardium	0.4	0.0	12.4	0.1
	Seratus	0.1	0.0	34.1	1.7
	Skin	0.0	0.0	44.7	1.3
pat3	Aorta	0.3	0.0	43.5	1.3
	Chestwall	0.0	0.0	32.0	0.5
	Diaphragm	0.5	0.0	18.0	0.4
	Lung	0.2	0.0	34.7	1.2
	Pericardium	0.1	0.0	52.8	2.7
	Seratus	0.1	0.1	27.0	1.1
	Skin	0.3	0.1	5.3	0.9
pat5	Tumor	0.0	0.0	36.3	0.5
	Diaphragm	1.0	0.0	3.5	0.0
	Diaphragm	1.1	0.1	13.1	0.3
	Lung	0.5	0.0	21.4	0.3
	Pericardium	0.3	0.0	19.0	0.3
	Pleura	1.0	0.1	3.1	0.1
	Seratus	0.5	0.0	18.4	0.2
pat13	Skin	0.7	0.7	5.3	2.1
	Tumor	0.1	0.0	15.7	0.2
	Aorta	0.4	0.2	22.9	3.1
	Chest wall	0.3	0.0	14.1	0.1
	Diaphragm	0.0	0.0	45.6	1.4
	Lung	0.1	0.0	45.8	2.7

S/N	Tissue type	μ_t	std μ_t	μ_s'	std μ_s'
pat15	Pericardium	0.8	0.0	16.9	0.3
	Seratus	0.2	0.1	11.9	1.2
	Aorta	0.3	0.0	18.8	0.2
	Chest wall	0.1	0.0	16.5	0.2
	Diaphragm	0.1	0.0	14.0	0.1
	Lung	0.3	0.0	19.8	0.2
	Pericardium	0.1	0.0	16.1	0.2
	Tumor	0.1	0.0	15.1	0.2
pat16	Aorta	0.3	0.0	18.5	0.1
	Chest wall	0.0	0.0	14.9	0.2
	Diaphragm	0.1	0.2	13.0	5.0
	Lung	1.1	0.0	30.7	0.4
	Pericardium	0.3	0.0	21.2	0.2
pat20	Aorta	0.6	0.1	51.7	5.1
	Esophagus	0.4	0.0	16.6	0.1
	Lung	0.3	0.0	17.9	0.4
	Skin	0.2	0.2	12.2	5.4
pat21	Aorta	0.5	0.0	16.7	0.1
	Diaphragm	0.1	0.0	37.8	1.7
	Lung	0.6	0.0	17.7	0.1
	Pericardium	0.6	0.0	18.7	0.2
pat22	Chest wall	0.4	0.0	6.2	0.1
	Diaphragm	0.1	0.0	12.8	0.1
	Esophagus	0.6	0.0	18.2	0.3
	Lung	0.4	0.0	17.3	0.2
	Pericardium	0.9	0.0	20.3	0.1
pat24	Diaphragm	0.7	0.0	21.2	0.6
	Esophagus	0.0	0.0	10.7	0.1

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S/N	Tissue type	μ_a	std μ_a	μ_s'	std μ_s'
pat28	Lung	0.2	0.0	32.2	1.5
	Pericardium	1.4	0.6	47.2	10.8
	Seratus	0.1	0.0	12.6	0.2
	Chest wall	0.1	0.0	11.6	0.1
	Diaphragm	0.3	0.0	15.3	0.2
	Lung	0.2	0.0	33.5	2.5
pat34	Seratus	0.1	0.0	12.1	0.2
	Aorta	0.2	0.0	18.3	0.2
	Chestwall	0.1	0.0	2.1	0.1
	Diaphragm	0.3	0.0	19.5	0.2
	Lung	0.9	0.0	26.1	0.3

Table 2

Variation over time of fluence rate calibration factors, α , measured for 661 and 665nm.

661nm	11.21.07	10.6.08	10.27.08	11.14.08	7.31.09	9.3.09	9.9.09	12.16.09
α	50	51.31	43.25	45.48	45.19	46.43	41.89	47.05
661nm	3.25.10	10.28.10	3.21.11	8.22.11	12.19.11	4.22.12	7.25.12	10.18.12
α	47.83	42.59	49.89	47.58	45.76	46.69	55.94	42.94
665nm	8.24.11	12.19.11	4.25.12	7.25.12	10.18.12			
α	49.76	44.82	49.8	54.97	54.39			

Table 3

Variation of the normalized calibration factors, a/a_{avr} , for the isotropic detectors over time.

S/N	12.6.10	2.7.11	3.21.11	10.28.11	1.16.12	4.25.12	5.31.12	7.18.12	9.20.12	12.14.12	1.17.13	Stdev	Avr
1506	1.00	0.99	1.00	0.99	0.96	0.97	1.01	1.03	1.04	1.02	1.07	0.03	1.01
1537	0.97	0.95	0.95	1.01	0.96	1.01	0.99	1.05	1.04	1.05	1.08	0.05	1.01
1508	0.98	0.99	0.99	1.01	0.99	0.98	1.03	1.00	1.01	1.00	0.97	0.02	1.00
1566	1.00	1.04	1.07	0.92	1.01	0.98	0.99	0.99	0.99	1.01	1.03	0.04	1.00
1511	0.97	0.93	1.01	0.98	0.99	0.97	1.03	1.01	1.04	0.99	1.00	0.03	0.99
1579	0.96	0.97	1.00	1.02	0.98	0.96	0.97	0.98	1.07	1.08	1.05	0.04	1.00
1513	0.96	0.99	1.00	1.02	0.98	0.98	0.97	0.99	1.03	1.02	1.02	0.02	1.00
1565	1.00	0.95	0.96	1.04	1.01	1.01	1.00	0.99	1.04	1.04	1.10	0.04	1.01

Table 4

Treatment time vs treatment area and volume.

Study #	Time (s)	Φ (J/cm ²)	S (W)	CT Vol (cm ³)	Nav Syst Vol (cm ³)	Agreement	CT Area(cm ²)	Nav Syst Area (cm ²)	Agreement
3	4654	15	5,7	1126	NA		672	NA	
5	4233	22,5	7	1200	2283	✗	705	728	✓
8	2120	22,5	8	1319	7630	✗	809	1480	✗
13	5407	45	8	427	2451	✗	544	769	✓
15	4260	45	8	349	4560	✗	385	1170	✗
16	3102	45	8	2265	4908	✗	1093	1125	✓
20	2452	30	8	1320	9532	✗	986	1573	✗
21	2903	30	8	1263	7694	✗	751	1493	✗
22	2430	30	8,6,8	2607	10497	✗	1127	1619	✗
24	3540	30	8	1011	3782	✗	875	922	✓
26	2212	20	7,5	2876	2472	✓	1296	776	✗
27	3600	25	8	3009	4598	✓	1756	1180	✗
28	2565	20	7	1178	4212	✗	750	858	✓
30	2220	25	8	1299	4949	✗	925	1134	✓
31	4000	25	8,3,4,5	1820	6084	✗	1040	1344	✓
32	2341	30	8	2761	NA		1344	NA	✗
33	3273	30	8,6	637	5531	✗	1109	1381	✓
34	2593	30	8	1315	3625	✗	1562	1149	✓
38	3397	30	8,4	882	NA		633	NA	
39	2089	30	8	3183	NA		1562	NA	

Table 5

Comparison of volumes and area between CT, water and navigation system.

Study #	Volume (cm ³)		Area (cm ²)	
	Water	CT	Nav. Syst.	CT
3	1600	1126		672
5	3000	1200	2283	705
8	4000	1319	7630	809
13	2500	427	2451	544
15	1600	349	4560	385
16	1500	2265	4908	1093
20	2600	1320	9532	986
21	3400	1263	7694	751
22	3700	2607	10497	1127
24	1200	1011	3782	875
26	4100	2876	2472	1296
27	2800	3009	4598	1756
28	3800	1178	4212	750
30	1650	1299	4949	925
31	1800	1820	6084	1040
32	3100	2761		1344
33	2000	637	5531	1109
34	2600	1315	3625	825
38	1750	882		633
39	2400	3183		1562

Table 6

Mean light dosimetry for each treated site.

S/N	PCW	Peri	AS	PS	ACW	PM	Apex	Avr	Calc
3	3.2	3.2	3.5	3.4	3.3	3.3	3.3	3.3	4.6
5	3.9	3.7	3.9	4.0	3.6	3.9	3.7	3.8	6.1
8	10.9	10.9	11.1	10.6	10.5	13.0	9.4	10.9	10.6
13	9.9	10.0	9.3	9.4	10.6	10.1	10.3	9.9	8.3
15	9.8	10.0	9.2	9.3	10.5	9.9	10.2	9.8	10.6
16	16.1	12.3	14.6	14.1	13.9	14.0	14.4	14.2	14.5
20	11.9	13.8	12.8	12.0	12.7	12.1	12.4	12.5	12.2
21	9.8	10.2	10.6	10.9	9.6	9.6	10.1	10.1	10.3
22	8.1	9.1	8.5	8.8	8.8	8.4	8.9	8.7	15.6
26	10.2	8.6	9.2	9.6	9.1	9.1	9.9	9.4	10.7
27	6.9	7.4	6.6	7.4	8.2	7.1	7.8	7.3	6.9
28	7.8	8.7	7.7	8.7	9.7	8.4	8.2	8.5	8.9
30	12.9	10.6	9.0	10.6	11.2	11.1	8.8	10.6	11.3
31	10.8	9.1	9.3	9.9	10.8	9.2	9.9	9.9	11.7
32	10.0	10.9	12.4	10.7	13.2	11.1	10.0	11.2	12.8
33	10.7	9.3	10.2	9.0	9.5	8.1	9.6	9.5	9.2
34	11.1	10.5	9.5	10.2	10.5	11.4	10.3	10.5	11.6
38	10.3	7.6	7.4	6.6	8.5	7.8	7.6	8.0	8.8
39	9.3	7.7	9.0	10.3	9.7	9.5	9.2	9.2	14.4
avr	9.7	9.1	9.1	9.2	9.7	9.3	9.2	9.3	10.3
stddev	2.9	2.6	2.7	2.5	2.7	2.7	2.5	2.6	2.8