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Maximizing fluence rate and field uniformity of light blanket for intraoperative PDT

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Abstract

A light blanket is designed with a system of cylindrically diffusing optical fibers, which are spirally oriented. This 25×30 cm rectangular light blanket is capable of providing uniform illumination during intraoperative photodynamic therapy. The flexibility of the blanket proves to be extremely beneficial when conforming to the anatomical structures of the patient being treated. Previous tests of light distribution from the blanket have shown significant loss of intensity with the length of the fiber. This can be improved through the use of an optical adaptor which will be able to match the numerical aperture of the laser source to the numerical aperture of the blanket fiber; thus transmitting a higher percentage of light.

Keywords

Light blanket; Photodynamic therapy; intraoperative PDT

1. INTRODUCTION

Light, photosensitizers, and oxygen are the three most important factors for photodynamic therapy (PDT). Light distribution over the treatment area is of great importance in terms of treatment efficacy. In current protocols, PDT treatment of malignant pleural or intra-peritoneal diseases uses a point source continuously moving in pleural cavity, which may compromise light dose uniformity, if the movement was not evenly applied. Furthermore, adequate, homogenous light coverage of the entire tumor area can be difficult. Light blanket is a PDT treatment device for uniform light distribution using a single side-emitting optical fiber, which is very promising to solve the light dose uniformity problem. The advantages of the light blanket as a light applicator include ease of OR use, minimal thermal effect under high laser power input, and more importantly, uniform light dose distribution.

A light blanket has been developed for the purpose of uniform light delivery. However, the cylindrical diffusing fibers for the light blanket have a numerical aperture (NA) of 0.22, which dose not match with the NA for the clinically used diode lasers, which have NAs

from 0.37 to 0.39. The objective of this study is to couple the light blanket to a treatment diode laser with a nonmatching NA to the blanket.

2. MATERIALS AND METHODS

2.1 Blanket and adaptor design

The light blanket design was discussed in our previous publications [1,2]. Briefly, a single side emitting fiber was coiled among several PVC layers. The light blanket is flexible and surface area is $25 \times 30 \text{ cm}^2$. On one side of the light blanket, 0.2 % intralipid scattering medium was filled to improve the uniformity of light distribution, and on the other side of the light blanket, a 0.1mm aluminum foil was used to construct the reflection layer for the light transmission to enhance the efficiency of light delivery. In the light blanket, the current side-emitting fiber has 400 micron core size, 10 meters length, 0.22 NA and 20mm minimum bending radius. 665 nm diode laser was used as light source for the light blanket in this study. The light blanket is shown in Figure 1a when the laser is on.

The adaptor for the light blanket was built on a free-space optical table, as shown in Figure 1b. The schematic of the adaptor is shown in Figure 1c. Briefly, the laser beam waist was expanded, and the NA has been changed by the lens set.

2.2 Adaptor theory

According to Figure 1c, The relationship between the NA and geometrical distances can be expressed below:

$$NA = \sin\theta = x / \sqrt{x^2 + bfl^2} \quad (1)$$

$$x = (f_2 - d) / f_2 \cdot w \quad (2)$$

$$bfl = f_3(d - f_3) / (d - f_2 - f_3) \quad (3)$$

$$NA = f(d, w) \quad (4)$$

The relationship between NA and the distance d between the lens are shown in Figure 2a. Even though the theory (solid lines) do not numerically match the experimental measurements (crosses), it is clear that the overall trend follows an empirical fit. For example, with a separation of 2.5 cm, one can obtain NA of 0.37 while NA = 0.22 can be obtained with a separation of 1.5 cm. With appropriate matching of the input end to the NA of laser, one can generate output light with varying NA. The relationship between bfl and the distance d between the lens are shown in Figure 2b. Similar as in Figure 2a, the theory predicted the experimental data well in the overall trend.

2.3 Light emission theory

The light fluence rate along the length (L) of a 10 m long side-emitting fiber can be modeled to a formula [3]. Here the fluence rate at any point can be given by

$$\Phi = \frac{Ae^{-kx} + Ae^{-k(L-x)}}{4\pi R^2} \quad (5)$$

where A is the initial fluence rate, k is the decay constant and R is the distance from the linear fiber. Figure 3a shows the parameter fit to obtain the k value for a specific combination of input NA (0.22) and light intensity. Figure 3b shows that one can predict light fluence dependence based on this formula.

3. RESULTS AND DISCUSSIONS

3.1 Light blanket with adaptor

Additional study is performed to examine the relationship between NA of input light and the decay constant k of side-emitting fibers. Figure 4 shows the results. It is clear that when the input fiber NA matches with that of the side-emitting fiber (0.22), the light intensity is the most homogeneous along the length of the fiber. The change is negligible, when the NA (0.11) of the incident light is smaller than that of the side emitting fiber (0.22). However, when the NA of the input fiber is significantly larger than that of the NA of the side-emitting fiber, then the light intensity becomes very nonuniform because the incident light gets attenuated significantly larger than those of match fibers.

3.2 Blanket design

The pattern was developed in CAD software for defining the separation of the single linear fiber. The center area could not be uniformly covered because of the design constraint of fiber maximum bending radius of 2 cm. We thus use adjacent hot spots and cold spots to make the most optimized choice. The blanket is then fabricated using several layers of PVC and guiding catheters. The layer that contains optical fiber is separated from the treatment area, where an array of parallel catheters are placed for placement of isotropic detectors, by a water tight pocket where intralipid liquid can be contained. This layer serves as additional scatterer to homogenize the light fluence rate distribution. Figure 5 shows the actual light blanket design for a 10 m long side emitting fiber that covers a 25×30 cm² area.

3.3 Fluence rate Profile characterization

The light fluence rate was measured using isotropic detectors on a 2D plane using a dual motor to move the detectors. Fluence rate profiles measurements are shown in Figure 6. Final results of fluence rate profile of the blanket with no liquid in the IL pocket exhibited the highest mean fluence rate per input power of 1.07 mW/cm²/W. The data shows hot spot near the corner of the blanket due to the bending of the fiber, which resulted in higher escaped light. Namely, the leakage of side emitting light increases as the bending radius increases. Using pure water without IL resulted a mean fluence rate of 0.81 mW/cm²/W and a larger 100% isofluence area. There was no appreciable difference between 0.1% and 0.2% IL concentration.

4. CONCLUSION

We have presented evidence that a cost-effective light blanket can be designed to produce uniform light over a reasonable wide region. A theory provides a versatile tool to assess the relationship between light fluence uniformity and the spacing and pattern. The optimal spacing is 1 cm. We have further shown that it is important to match the NA of the input light to the NA of the light blanket to obtain uniform light distribution. An adaptor is proposed to perform the function and an empirical relationship between the spacing between lens and the NA of the outgoing light are demonstrated.

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Figure 1.
Light blanket (a), and experimental setup photo (b) and schematic (c) for the adaptor matching the NA.

Figure 2.

(a) The relationship between the distance between lens D and the resulting NA at the exit end with parallel beam incidence with beam diameters of 1, 1.5, and 2 cm. The symbols are measurements with the beam diameter of 0.6 cm. (b) The relationship between the distance between lens D and the bfl with parallel beam incidence with beam diameters of 2 cm. The symbols are measurements with the beam diameter of 0.6 cm.

Figure 3.

(a) Fluence rate exponential decay along fiber length $A = 1.587 \text{ mW/cm}^2$, $k = 0.000652$

$1/\text{cm}$, $L = 10 \text{ m}$ for $NA = 0.22$. (b) Isofluence plot of the relative light fluence rate at 0.5 cm from the light source.

Figure 4.

The relationship between light fluence vs. distance along the side-emitting fiber for various input NA.

Figure 5.
Reconstructed light fluence rate profile (blue) from 20 light source – detector pairs compared with the measured light fluence rate profiles (red).

Figure 6.

Contour plots, 2D (top) and 3D (bottom), of experimental fluence rate profiles for different intralipid concentrations. Isodose lines for 150%, 100%, 75%, and 50% of the mean, normalized fluence rate (Φ/S) are depicted in the 2D plots.