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Lightpipe device for delivery of uniform illumination for photodynamic therapy of the oral cavity

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Abstract

A compact and efficient lightpipe device to deliver light to the human oral cavity for photodynamic therapy was designed and fabricated, having dimensions $6.8 \text{ mm} \times 6.8 \text{ mm} \times 46 \text{ mm}$. An average irradiance of 76 mW/cm^2 with an average deviation of 5% was measured on a square 25 mm^2 treatment field for an input power of 100 mW. The device limits irradiation of healthy tissue and offers potential for improvement over the current treatment procedure, which requires shielding of the whole cavity to avoid damage to healthy tissue.

1. Introduction and Background

Photodynamic therapy (PDT) is a cancer treatment that combines the use of photosensitizing drugs and light in the presence of oxygen to initiate chemical reactions that result in cytotoxic action causing irreversible damage to tumor tissues [1]. For treatment of oral cavity cancer with PDT, typically the photosensitizing drug is administered systemically to the patient and light is delivered to the oral cavity either with a cylindrically diffusing fiber or a lensterminated fiber [2]. Light diffusely scattered from the target area illuminates large areas of the normal oral cavity, resulting in undesired toxicity. Prior to the treatment, a complete shielding of the oral cavity is needed in order to protect the healthy tissue from exposure to this diffusely reflected light and ensure that only the cancerous lesion and the immediately adjacent treatment margin are subject to the toxic action of PDT [3]. Lack of shielding of the healthy tissue has been reported to cause inflammation, pain, swelling, burns, and scarring [4]; in some cases the teeth became loose [5].

We recently proposed three compact and efficient designs for delivery of PDT to the oral cavity, to be used in near-contact illumination of a prescribed treatment field, that greatly limit irradiation of healthy tissue by diffusely reflected light, thereby eliminating the need for a complete shielding of the oral cavity prior to the treatment, and that provide an average irradiance of at least 50 mW/cm^2 with an average deviation well below 10%, with input powers that are currently available in the clinic [6,7]. The three designs consisted of a tailored reflector, a cylinder reflector, and a lightpipe device. We report here on an improved design of the lightpipe device together with its fabrication and testing.

2. Design of a Lightpipe Device for PDT

We designed a lightpipe device to receive light from a fiber illuminator and produce uniform illumination over a square target area of 25 mm². The configuration and overall size of the lightpipe device were chosen to provide the required illumination with a compact device, suited for use in the oral cavity, while the minimum feature size of the lightpipe was driven by the available manufacturing capabilities.

We built a model in LightTools (<http://www.opticalres.com>) to simulate the device and identify the optimal configuration as shown in Fig. 1(a). The device consisted of a solid lightpipe with a reflective coating and a square cross section. The lightpipe comprised a 1.6 cm long tapered section, in which the size of the lightpipe increased linearly from 2 mm to 6.8 mm, followed by a 3 cm long straight section. A diffusing film was added to the input face of the light-pipe to increase the angular range of light entering the lightpipe and obtain better uniformity with a compact device. A 45° mirror placed at the end of the lightpipe directed light laterally to the uncoated output window. The resulting device had dimensions of 6.8 mm × 6.8 mm × 46 mm, making it suitable for treatment of flat lesions characteristic of early or pre-cancer in several locations in the oral cavity, including the top and bottom of the tongue, the cheek, and the gumline.

The light source consisted of a fiber with a numerical aperture of 0.25 and a core diameter of 0.1 mm, emitting a power of 100 mW, as is typical in clinical PDT applications. The lightpipe was modeled as BK7 glass with a 90% near-specular reflective coating, with the exception of the input and output windows, which were left uncoated. The diffusing film placed at the input of the lightpipe was modeled as a Lambertian scatterer with 60% transmission. The irradiance was evaluated in a plane at 1 mm distance from the output window, and the uniformity was assessed by calculating the average deviation (the ratio between the standard deviation and the average of the irradiance). The results are shown in Fig. 1(b). An average irradiance of 73 mW/cm² with 6% average deviation was produced on the 25 mm² target area, while the total flux at the output of the lightpipe was 32 mW.

To evaluate the robustness of the device to misalignments of the fiber with respect to the input face of the lightpipe, we studied the irradiance obtained for a combined horizontal and vertical displacement of the fiber up to 1 mm, as shown in Fig. 2. The device proved to be insensitive to misalignments of the source, as the average irradiance started to drop only when the fiber started to miss the input face of the lightpipe.

We performed a tolerance analysis on the lightpipe prior to fabrication. A tolerance of ±1 mm for the length and of ±0.2 mm for the width was found for the tapered and straight sections of the lightpipe, while a tolerance of ±1 degree was established for the 45° mirror.

3. Fabrication and Experimental Validation

A prototype was fabricated out of BK7 glass (Planar Optics, Inc., Webster, New York, USA), as shown in Fig. 3, and tested. The diffusing film (Model 3635-70, 3M, St. Paul, Minnesota, USA), having a transmission that was verified experimentally to be 60%, was applied at the input face of the lightpipe. The light source used was a fiber-coupled laser (Model BWF-670-300-E/55370, B & W TEK, Inc., Newark, Delaware, USA) emitting a power of 100 mW, with a central wavelength of 668 nm to match the 665 nm absorption peak of HPPH, a photosensitizer currently being investigated in clinical trials for PDT of the oral cavity [8]. The internal transmittance of Schott N-BK7 glass for a thickness of 25 mm is 0.994 for a wavelength of 660 nm and 0.996 for a wavelength of 700 nm; this results in a glass absorption of less than 2% as light traverses the lightpipe.

A first experimental validation was done leaving the lightpipe device uncoated and only coating the 45° mirror with the reflective coating (metalized Mylar tape, CS Hyde, Inc., Lake Villa, Illinois, USA) as shown in Fig. 3(a). The reflectivity of the coating was verified experimentally to be greater than 90% at the wavelength of interest. The experimental results, obtained by sampling the irradiance with a scanning pinhole and power meter (Model 818-ST, Newport Corp., Irvine, California, USA) in steps of 0.5 mm, and the corresponding numerical simulation are shown in Fig. 4. It can be noted how the falloff in the irradiance was greater on the right side than the left both in the simulation and in the experimental measurement. The experimental average irradiance on the 25 mm² target area was 87 mW/cm² with an average deviation of 5% for an input power of 100 mW, in excellent agreement with the average irradiance of 92 mW/cm² with 6% average deviation predicted from the numerical simulation.

Light was confined in the uncoated lightpipe by total internal reflection (TIR): the rays that hit the glass–air interface with an angle greater than the critical angle were totally internally reflected inside the lightpipe with 100% efficiency. Since the device is to be used in the oral cavity and has as its primary purpose to limit irradiation of healthy tissue, it is necessary to avoid leakage of light from the lightpipe by adding an appropriate coating; the efficiency of the resulting device is expected to be lower than the TIR device because of reflection losses. The final device was entirely coated with the reflective coating, with the exception of the output window of 6.8 mm × 6.8 mm, as shown in Fig. 3(b).

The comparison between the numerical simulation and the experimental measurement for an input power of 100 mW is shown in Fig. 5. The experimental average irradiance of 76 mW/cm² with an average deviation of 5% on the 25 mm² target matched the average irradiance of 73 mW/cm² with an average deviation of 6% calculated with the numerical model and amply satisfied the PDT illumination requirements of an average irradiance of at least 50 mW/cm² with an average deviation well below 10%.

4. Discussion

The lightpipe device presented in this paper was designed to deliver uniform illumination to a flat treatment field of 25 mm². Within this area, a lesion of any shape can be treated by applying a local mask at the output of the device. Further developments will address bigger treatment fields: for some locations in the oral cavity this could be obtained simply by scaling up the dimensions of the lightpipe, but for less accessible locations a different design may be needed; in any case, a local masking will be added to conform to the geometry of the lesion. Eventually, we envision a family of devices to be developed to treat different sizes of lesions in different locations within the oral cavity, such that an entire toolkit will be available from which the physician can pick the appropriate device and tailor the treatment for each case.

It may be noted that as this technology is translated to the clinic to treat bigger fields, the lightpipe device being scaled up to a bigger dimension will result in a lower average irradiance if the input power is maintained constant: in this case, it might be preferable to avoid applying the reflective coating to the lightpipe and consider instead a TIR device of the kind of Fig. 3(a), with appropriate packaging to avoid light leakage to the oral cavity; the higher efficiency of the TIR device would be beneficial to cases in which the average irradiance is critical due to bigger treatment fields.

The efficiency of the current device is mainly limited by the transmission of the Lambertian diffusing film placed at the input of the lightpipe: in order to maximize the uniformity at the target, we have used a Lambertian diffuser with a transmission of 60%, resulting in an

efficiency (calculated as the ratio between the lightpipe output and input flux) of 32%. For situations in which maximizing the efficiency of the flux transfer from the source to the target is critical, a diffusing film with a higher transmission but lower angular range could be envisioned. It is also possible to remove the diffusing film at the input of the lightpipe altogether. The simulation results for the lightpipe device in the absence of a diffuser, shown in Fig. 6, present, as expected, a significant increase in the overall efficiency of the device to 72% between output and input. The average irradiance on the 25 mm² target was calculated to be 168 mW/cm², while the average deviation of 7% still nominally satisfied the requirements of uniformity wanted for this device. Although this configuration produced a hot spot in the irradiance, we envision that it could be blocked with an appropriate mask if desired or reduced by a modification of the design. The choice regarding the presence and properties of the diffusing film will be driven by the specific application and its flux transfer efficiency requirements.

5. Conclusion

We designed and fabricated a compact lightpipe device for delivery of photodynamic therapy to the oral cavity that greatly reduces the irradiation of healthy tissue, offering potential for improvement of the current treatment procedure. We reported in simulation an average irradiance of 73 mW/cm² with 6% average deviation over a 25 mm² treatment field for an input power of 100 mW, which was validated in an experiment that delivered an average irradiance of 76 mW/cm² with an average deviation of 5%. The efficiency of the lightpipe, calculated as the ratio between the flux at the input and at the output of the device, is 32% using a Lambertian diffusing film at the input of the lightpipe. It is also possible to remove the diffusing film and still produce an illumination distribution that meets the uniformity requirements, thus obtaining an efficiency of 72%. The choice of whether to use the diffusing film or not will be driven by the flux transfer efficiency requirements of the specific application. The device presented falls into a larger family of devices targeted for significantly different sizes and shapes of lesions. The next development of this device will be packaging for entering preclinical trials.

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Fig. 1.

(Color online) (a) LightTools model of solid reflective lightpipe device designed to deliver uniform illumination to oral cavity. The overall length of the device was 4.6 cm. (b) Map of the irradiance obtained on a $6\text{ mm} \times 6\text{ mm}$ area at 1 mm from the output window. The 25 mm^2 target is represented by the square outline. The simulation was run tracing five million rays, with a peak statistical error of 2%.

Fig. 2.

(Color online) (a) Average irradiance and (b) average deviation obtained with a vertical and horizontal displacement of the fiber with respect to the input face up to 1 mm.

Fig. 3.

(Color online) BK7 lightpipe prototype, tested in two configurations: (a) Mylar reflective coating applied only to the 45° mirror while the rest of the lightpipe was left uncoated; (b) lightpipe device entirely coated with the exception of the output window.

Fig. 4. (Color online) (a) Numerical simulation and (b) experimental data of the irradiance obtained at a distance of 1 mm from the output window for the uncoated lightpipe of Fig. 3(a). The square outline represents the 25 mm² target area.

Fig. 5. (Color online) (a) Numerical simulation and (b) experimental data of the irradiance obtained at a distance of 1 mm from the output window for the final lightpipe device of Fig. 3(b). The square outline represents the 25 mm² target area.

Fig. 6. (Color online) Numerical simulation of the irradiance obtained at a distance of 1 mm from the output window for the lightpipe device of Fig. 1(a), for which the diffusing film at the input of the lightpipe was removed. The square outline represents the 25 mm² target area.