Photochemistry and Photobiology, 2017, 93: 1509–1512

Measurement of UV Emission from a Diffusing Optical Fiber Using Radiochromic Film

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Received 3 April 2017, accepted 9 May 2017, DOI: 10.1111/php.12798

ABSTRACT

Analysis of the emission pattern from optical diffuser tips is vital to their usage in biomedical applications, especially as they find growing functionality beyond established phototherapy techniques. The use of ultraviolet radiation with diffuser tips increases the need to accurately characterize these devices, both for effective application and to avoid potentially dangerous exposure conditions. This study presents a new method to capture the diffusion pattern at a high resolution through the use of radiochromic film. The film is positioned in a cylinder around the diffuser, light is emitted from the diffuser onto the film and the film expresses a color change relative to the exposure amount. The resulting emission map shows the distribution of power from the diffuser in all direction. This method, which is both quick and inexpensive, generates high-resolution data much simpler than previously published works which required precise goniometric positioning.

INTRODUCTION

Optical fibers are routinely used for basic life science research as well as biomedical diagnosis, therapy, monitoring and surgery (1). Specialized fibers have been created to address numerous applications. One of the most prominent applications has been to use a fiber to transmit optical power and then emit the light from the sides of the fiber so it acts as an extended emitting optical source, also known as a diffuser. Diffusers are widely used for applications such as photodynamic therapy, interstitial laser coagulation and interstitial laser hyperthermia (2). Up to this point, optical diffusers have been primarily used with wavelengths in the visible range. However, with recent interest in ultraviolet (UV) radiation for various biomedical applications, ranging from sterilization (3–6) to excimer lasers for cutting or ionizing molecules (7), the widespread usage of diffusers with these wavelengths is imminent.

A critical factor in using optical diffusers is the light distribution characteristic (8). The user of the fiber needs to be aware of the intensity and direction that light is emitted from the diffuser to ensure proper interaction with the surrounding media. This issue is especially important for diffusers used with UV radiation, more so than with visible light, as the radiation can cause molecular damage (7). For example, short wave UV (UVC), with wavelengths between 200 and 280 nm, can cause photokeratitis (9) and skin cancer (10). Fully characterized diffuser fibers are necessary to ensure proper scientific evaluation and for decisions on their eventual use in biomedical applications.

A number of methods for optical diffuser measurement have been published. Most of these techniques utilize a goniometer setup with computer-controlled motors to move a sensor around a diffuser in a defined trajectory while recording data. Some methods employed the goniometer along with a silicon photodiode (2,8,11) or CCD cameras (12,13). Alternative published methods for diffuser characterization include using a video camera to analyze a rotating fiber (14) and measuring the emission indirectly by recording a fluorescent reaction (15). It is important to note that all of these methods produced measurements of relative intensity emitted from the device; an integrating sphere was used in some cases to capture the full intensity of light emitted (12). Additionally, the resolution of many of these measurements was limited by the accuracy of the goniometric setup, such as the use of linear motors with steps of 1 mm and sampling frequencies which generated angular resolutions of approximately 3° (8).

To the best of our knowledge, almost all of the work in measurement of optical diffusers up to this point has been limited to visible light. The one published work we have found which directly measured UV light from a diffuser tip was by Shangguan *et al.*, who utilized an isotropic fiber optic detector connected to a power meter to measure transmission of 365 nm light from a diffuser in the center of an angioplasty balloon (12). However, the UV diffusion characterization was minimal because the tip was simply moved to 16 different positions around the diffuser as a check of results obtained with a CCD camera. The aforementioned published diffuser measurement methods could likely be extended to the UV range by adapting hardware such as using UV-sensitive photodiodes and CCDs, but the systems would still require a complicated goniometric setup.

We describe here a new method of characterizing diffuser tips using UV-sensitive film. This method obviates the need for a complex and expensive goniometer setup and detection system and provides higher resolution results. As an example of its use, we provide for the first time the full characterization of UV diffuser tips. As UV diffusers grow in use, these methods will be important to assess both the efficacy and safety of these tools.

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MATERIALS AND METHODS

Measurement setup. The key in measurement of the total radiant power from the diffuser was positioning of the UV-sensitive film to surround the diffuser. To achieve this we constructed an acrylic jig to hold both the diffuser tip and a piece of film in a cylinder surrounding the tip, as shown in Fig. 1. The holder piece was a 12.7 mm thick piece of acrylic with a #60 (1.016 mm) hole drilled entirely through and a 19.05 mm diameter hole counterbored approximately 6 mm deep. The fiber to be measured was pushed through the hole and suspended in free space. The UV-sensitive film was rolled into a 19.05 mm diameter cylinder, with the active region facing inward toward the fiber and placed in the counterbored hole to hold it in position. An additional piece of UV-sensitive film was attached with adhesive tape to the top of the cylinder to enclose the diffuser tip, therefore capturing power emitted out of the distal end of the tip. There was no film placed around the region where the tip passes through the acrylic but this area is minimal and has little effect on the measurement of the total radiant power from the diffuser tip. A measurement was taken by emitting UV from the diffuser tip for adequate time to observe exposure across the film surface; in this work we exposed for 300 s. Multiple fibers were characterized with this method and a representative sample has been shown in the results.

Film properties. The UV-sensitive film used in this study was a specialty order from Ashland Specialty Ingredients (Bridgewater, NJ) referred to as unlaminated Gafchromic EBT3 (Product Code 849952). This specialty film is essentially one-half of the regular Gafchromic EBT3 film; it is simply a 14 μm thick active layer on top of a 125 μm polyester substrate. The active layer contains a proprietary mixture of active material, marker dye, stabilizers and other components. In our previous work, we reported on the utility of this film for UV exposure measurement (16). The film showed a response to exposures from wavelengths ranging from 207 nm to 328 nm and exhibited a dynamic range extending up to as high as 100 mJ cm^{-2}. The film is extremely sensitive, with radiant exposures in the range of μJ cm^{-2} detectable for 222 nm light. Our previous work also showed that the film has a wavelength dependent response, thus it is important to calibrate with a source emitting a spectrum that matches the analyzed light source. The film has a high spatial resolution with the ability to resolve features to at least 25 μm. The polyester layer is blocking to UV radiation so the active region must be oriented toward the source for accurate measurement. When the film is radiated on the side with the active region it exhibits a nearly ideal cosine response like other radiochromic films (17, 18).

Film calibration. Calibration of the UV-sensitive film was performed through a series of exposures using an excimer lamp (High Current Electronics Institute, Tomsk, Russia) with a krypton–chlorine (Kr-Cl) gas mixture emitting principally at 222 nm. A custom bandpass filter (224NB7, Omega Optical, Brattleboro, VT), CWL of 224^{+2}_{-1} nm and FWHM of 7^{+2}_{-1} nm, was used with the Kr–Cl lamp to isolate the 222 nm peak. Optical power measurements were performed using an 818-UV/DB low-power UV-enhanced silicon photodetector with an 843-R optical power meter (Newport, Irvine, CA). A range of radiant exposures, from 3.6 μJ cm^{-2} up to 281.6 mJ cm^{-2}, were performed on the film to define a response curve. The exposure film and corresponding response curves for all three color channels of each film are shown in Fig. 2.

Film analysis. Films were scanned as 48 bit RGB TIFF images at 150 dpi using an Epson Perfection V700 Photo flatbed scanner (Epson, Suwa, NGN, Japan). The image files were processed using custom software developed by Alves *et al.* (19) which improves on multichannel methods (20) using robust optimization for dose calculation. The resulting file, with each pixel value equal to the radiant exposure value in mJ cm^{-2}, was imported into MATLAB (MathWorks, Natick, MA). The 150 dpi image has pixel dimensions of 169 μm × 169 μm. Each pixel exposure value was multiplied by the area of the pixel and then divided by the length of the exposure, resulting in the radiant flux each pixel was exposed to. The total radiant power output by the diffuser tip was calculated by summing the power over the area of exposed film.

Diffuser properties. The UV diffuser analyzed in this study was a custom piece produced by Molex, LLC. (Phoenix, AZ). The diffuser tip is 5 cm long and has a diameter of 1 mm. The 1 mm diameter portion extends back from the diffuser region an additional 1 cm where it is fused with a solarization resistant multimode fiber. The fiber has a numerical aperture of 0.22 and is comprised of a 400 μm diameter deep UV glass core, a doped silica cladding with an outer diameter of 440 μm, and a polyimide coating for a total outer diameter of 480 μm.

Laser properties. A compact solid-state UVC laser module with 222 nm emission wavelength was supplied by SHARP Laboratories of Europe (Oxford, United Kingdom), a subsidiary of SHARP Corporation (Osaka, Japan). The laser beam was focused directly into the polished end of the fiber attached to the diffuser using a 6 mm diameter UV fused silica plano-convex lens with 10 mm focal length (LA4280, Thorlabs, Inc, Newton, NJ). We measured the optical power into the diffuser fiber to be approximately 12 μW.

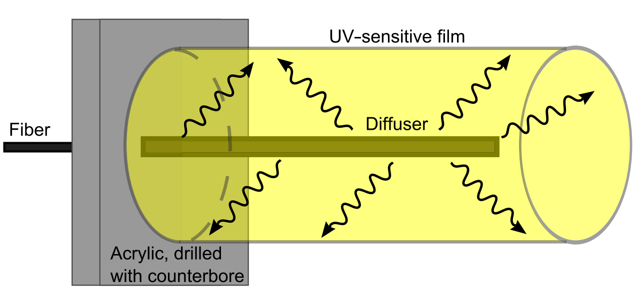

Figure 1. A drawing of the measurement setup shows the position of the optical diffuser within the cylinder of UV-sensitive film. The fiber enters into the cylinder through a piece of acrylic which both suspends the fiber and holds the film in place. A piece of film also encloses the distal end of the cylinder. The diffuser emits photons in all directions which are recorded as a color change in the film.

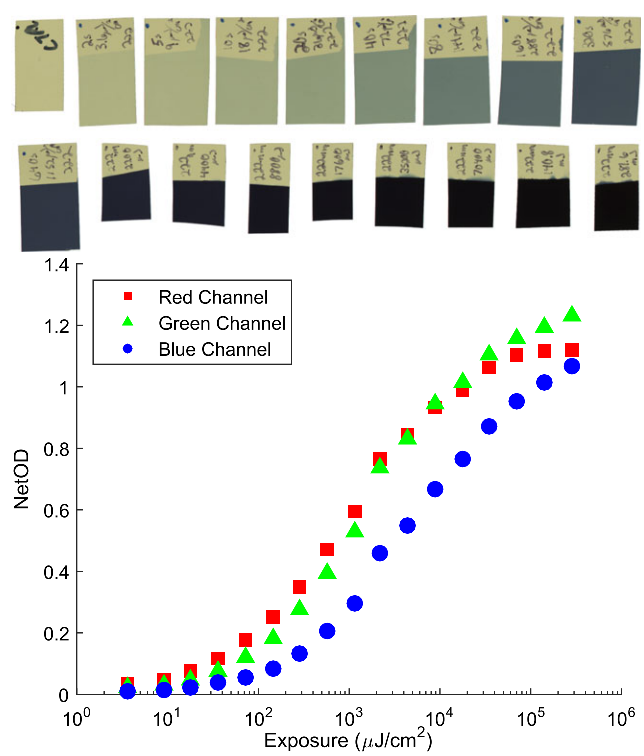

Figure 2. A set of calibration films is shown along with a graph of the color change in the film for each exposure. An unexposed piece of film is at the top left of the two rows of increasing exposures, which range in value from 3.6 μJ cm^{-2} up to 281.6 mJ cm^{-2}. Color change is noted as the net change in optical density from the unexposed piece of film (netOD) for each color channel. All three color channels are used jointly to determine the exposure level for a given color change.

RESULTS AND DISCUSSION

An example of the total power distribution from a test diffuser is shown in Fig. 3 along with the original scanned image of the analyzed films. The main piece of film, which was wrapped in a cylinder around the diffuser, is accompanied by a smaller piece of film which was placed on the end of the cylinder. Together these films show the power distribution coming out of the diffuser tip. The sum of the power over this surface area is 9.43 μW. The loss of power from the 12 μW aimed into the fiber is likely due to imperfect optical focusing into the fiber and losses from transmission through the fiber itself.

Figure 3 contains high-resolution data on the distribution of power out of the fiber. The power map exhibits areas along the fiber which emit UV at approximately twice the intensity observed over the majority of the surface. The map also shows that while the diffuser is 5 cm long the output loses uniformity outside of approximately the middle 80% of the length. Based on the diameter of the film cylinder, 19.05 mm, and the dpi of the scanned image, 150 dpi, the angular resolution for this result is approximately 1° around the circumference of the fiber. To the best of our knowledge, the ability to characterize diffuser fibers to this level of detail has never been demonstrated, especially in the UV range. The high-resolution data on the emission profile of UV diffuser tips are a significant improvement over previous attempts at characterizing diffusers using goniometric methods.

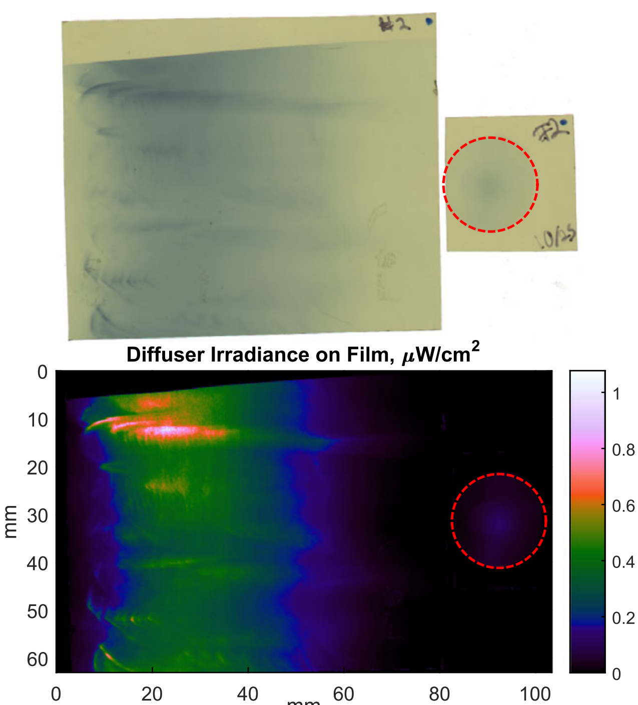

Figure 3. Scanned images of the films used for an example diffuser characterization include a rectangular piece which was rolled to create the cylinder and a piece which made the end face. The film is shown after exposure to UV radiation from a diffuser for 300 s. The exposure at each pixel was calculated from the calibration curve to create the power map shown below the scanned image. The summation of this power distribution gives the total power emitted from the diffuser. A dashed red circle was added to the film image and the power map to indicate the region which formed the end face of the cylinder. The power map for this diffuser clearly shows differences in exposure properties for the entire length of the diffuser. While a perfect cylinder would unroll to a rectangular shape our result is slightly tapered. This taper indicates that the cylinder had a larger diameter at the distal end of the fiber. The difference in diffuser to film distance does alter the total power distribution map shown on the film but the effect is minimal and overall negligible for diffuser assessment.

It is important to note that the power map was at a distance of approximately 9.5 mm away from the diffuser; examination of the angular distribution of power requires the cylinder size for accurate calculation. A power map taken closer to the fiber would show higher intensities but the resolution of the distribution would be lower. However, measurements of total power out of the tip are immune to variations in the film cylinder size; a smaller radius will produce higher intensity in a smaller area but a larger radius will return lower intensity over a larger area. Thus, it is important to choose a film cylinder size that is aligned with the goals of the experiment if distribution data are to be examined. Additionally, if distribution data are required then care should be taken to maintain the film at a consistent distance away from the tip. The example power distribution shown in Fig. 3 is not perfectly rectangular; this tapered shape indicates the cylinder had a larger diameter at the distal end. As the difference in diameter of the cylinder is minimal this likely had a negligible effect on the overall visualization of the power distribution. The total power output calculation was not changed due to this misalignment.

In our previous work with this film (16), we demonstrated maximum sensitivity in the UVC range but then dropping off significantly at UVB and longer wavelengths. This film worked well in this application as our light source was in the UVC range so it could be accurately calibrated, but it is important to note that these methods could be applied more generally given a suitable film was available. It is also important to note that this film allowed us to measure the absolute power emitted from the diffuser tip. This is in contrast to previous works characterizing diffusers which only reported relative intensities. The absolute power distribution data eliminates the need for expensive equipment, such as an integrating sphere, to fully examine the performance of the diffuser.

CONCLUSION

Overall, the methods presented here are an immense improvement in optical diffuser characterization techniques. The advantages of film analysis, including low cost, minimal processing, high spatial resolution and high exposure sensitivity, are showcased with this novel application area of diffuser intensity measurement. These measurements are especially notable with the added difficulty of performing measurements in the deep UV range. We believe these methods will become indispensable as the prevalence of UV diffuser tips rises with their expanded use in biomedical and other scientific applications.

Acknowledgements—This work has been supported by Columbia-Coulter Translational Research Partnership 9/1/15–8/31/16 “Ultraviolet Laser Sleeve” grant to Drs. Spotnitz and Andreas Hielscher. We are thankful to Dr. Karl Welna, Dr. Tim Smeeton and SHARP Laboratories of Europe for assistance with the UVC laser module.

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