High Intensity Illumination from Small Fibers for In-Vivo Medical Lighting

James Hermanowski
Nathaniel Group, Inc.
101 Panton Road
Vergennes, VT 05491

Abstract

There is a continuous drive to reduce the size of imaging systems for medical applications. Smaller size imaging systems reduce the impact of its introduction into the body and allow for the exploration of ever smaller cavities. This work will explore a novel illumination system and its potential application for in-vivo medical imaging.

I. Introduction

Illumination systems have been used in medical applications for many years to help image inside body cavities (eye, ear, nose, throat, heart, colon, etc.); assist in the placement of internal medical devices; even to perform work such as ablate unwanted or diseased tissue as in laser eye surgery or laser atrial fibrillation treatment. The use of in-vivo illumination sources for medical applications has expanded recently to even more revolutionary technologies including spectrophotometry, fluorescence analysis, near infrared lipid core plaque detection and optical coherence tomography. Light delivery for in-vivo use is primarily through optical fibers. The intrinsic physical characteristics of optical fiber combined with its versatility and wide availability make it an attractive technology for biomedical applications.

The ultimate goal for medical illumination is to deliver enough radiation of the desired wavelength/s to a desired location through as small a channel as possible or through no channel at all. It is not enough to deliver the radiation. In addition, consideration must be given to extraction of the delivered radiation when it is necessary, as in the case when it is used for imaging, analysis, or as a near infrared sensor. The delivered radiation must make a round trip path first to illuminate the object, then to collect the reflected light for imaging purposes. After visualizing the object, other radiation e.g. a laser, may be used to deliver energy for ablation or other work. Furthermore, it is desired that the return path have the same diameter as the supply path or even that the return path is the same physical path as the supply path.

The size and properties of the optical fiber must be considered. Millimeter sized fibers are easy to handle and work with but would be too large when used within certain body parts, for example a human eye, and can contribute to leakage of vitreous humour from an eye, or more generally, longer healing periods or higher risk of infection. Other fiber properties to be considered include:

Single or multi-strand fiber/s
Coherent or incoherent fiber bundle
Single or multimode fiber core
Fiber material (e.g. plastic or glass)
Fiber construction (e.g. jacket or not)
Fiber length
Bend radius
Transmission properties
Biocompatibility
Power handling capability
Intended use of the fiber/application
Allowable/unacceptable fiber defects
Cost (including disposal or reuse cost)

II. Geometry of Illumination in Small Fibers

Some medical devices such as hypodermic needles, catheters, suture wires and certain ophthalmic instruments use a gauge number as a measure of outside diameter of the object. Various needle/catheter lengths are available for any given gauge. There are several systems for gauging these devices, including the needle wire gauge in the United States which is derived from the Stubs Iron Wire Gauge for wires. Alternatives include the French Catheter Scale system, among others. Other devices report diameter using millimeters. Optical fibers are primarily manufactured using millimeter units. Table 1 show the relationships between the common needle wire gauge which is used for some optical fibers, its outer diameter in inches and millimeters, fiber area and finally the relative optical power density. Relative power density represents the power density if 1 watt of light were coupled into an optical fiber of the specified outer diameter. As expected, the energy density increases as the fiber diameter decreases. For reference, some manufacturers specify fused silica fibers capable of 1000 W/mm^2, whereas the author has measured damage to plastic optical fibers at levels as low as 5 W/mm^2.

TABLE 1. Fiber Properties

Fiber (Needle[1]) Gauge	Diameter (in)	Diameter (mm)	Area (mm^2)	Relative Power Density (W/mm^2)
20	**0.036**	**0.908**	**0.648**	**1.5**
23	**0.025**	**0.641**	**0.323**	**3.1**
25	**0.020**	**0.514**	**0.208**	**4.8**
27	**0.016**	**0.412**	**0.134**	**7.5**
31	**0.013**	**0.260**	**0.053**	**18.8**
32	**0.009**	**0.235**	**0.043**	**23.1**
34	**0.007**	**0.184**	**0.027**	**37.5**

III. Key Requirements for Medical Illumination

The general requirements for medical illumination are consistent with illumination needs for industrial applications. These include requirements for sufficient intensity to image the object of interest through a small optical fiber and shape control of the light that is created so it overlays the area to be imaged without creating shadows. The imaged area may not necessarily be directly at the end of the optical fiber. In many cases, the best view of the object of interest will be from the side of the endoscope necessitating both an angled image sensor and light source. Finally, the color or color accuracy of the illumination is often important in facilitating human or machine interpretation of the images.

There are additional, special requirements that must be considered for medical applications. These include integration with a specialized medical device such as a catheter or endoscope; addressing safety issues; and maintaining visibility under adverse operating conditions where blood or body fluids could interfere with function.

TABLE 2. Key Medical Illumination Requirements

General Requirements	**Value / Purpose**
High intensity light	Maintaining usable light through a sub-millimeter optical fiber
Direction of illumination	To match imaging optics which sometimes view at angles
Shadow control or removal	Illumination uniformity from viewer perspective
Lensing	Diffuse light, focused, macroscopic, wide angle, zoom
Color	Balanced color for clear images
Medical Requirements	
Dose control	Tissue, eye protection from excessive radiation
Integration with catheter/endoscope	Addresses specialized medical requirements for form, fit
Visibility	Preventing blood and fluids from degrading images
Specialized color control	Color tuning to discriminate between tissue, blood, other
Additional function	Ablate, cut, heat, react, ability to analyze tissue for disease, e.g. via fluorescence or spectroscopy

IV. Functions of Light

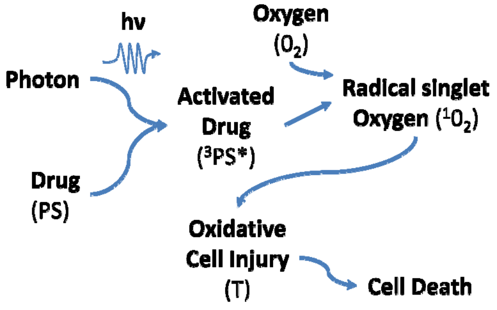
It can be challenging to position an illumination and imaging system in the vicinity of the object or tissue to be viewed. In the case of atrial fibrillation surgery, a catheter is fed through the venous system to the heart, piercing the heart wall to reach the desired chamber and ultimately the correct heart vein. Once there it is highly desired and advantageous to use light to do more than illuminate the object or tissue. Radiation in the form of visible light, infrared, or ultraviolet wavelengths can be used to do work. In some procedures, the delivered radiation can be used to assist in the diagnosis of disease using fluorescence or spectroscopy, to cut diseased tissue for removal, to ablate stones, to initiate a reaction between a therapeutic molecule and its target reaction site or to provide physically based phototherapy.

Viewing tissues using white light is effective in detecting many lesions and the general health of the tissue. In contrast, conditions such as some bacterial infections, lipid plaque detection, precancerous conditions, and subtle inflammatory conditions are difficult to visualize under white light. Consequently, while the object of interest is made visible for examination it is highly desired and advantageous to also collect analytical information for deeper analysis.

Spectroscopy or fluorescence visualization can be used to provide more detailed information to the physician. The spectroscopic technique looks for differences between the incident radiation on an object and the detected radiation from that object. For example, narrow band green radiation (545nm) when incident on tissue will reflect green while blood or blood vessels will reflect a darker brown.

Fluorescence imaging techniques utilize a property that some materials exhibit. Fluorescence occurs when a surface absorbs radiation of one wavelength, converts some portion of that radiation to a slightly longer wavelength and then re-emits the longer wavelength. For example, when normal oral cavity tissues are illuminated with violet light (405 nm) they emit fluorescence that appears light blue. The effect is small but can be noticeable and help discriminate between healthy tissue and tissue with underlying problems.

Photochemotherapy or photodynamic therapy involves a combination of the administration of a sensitizing agent followed by the action of light on tissues in which the photosensitizer is localized. Ample illumination through small optical fibers is one of the limiting factors of this promising technique.



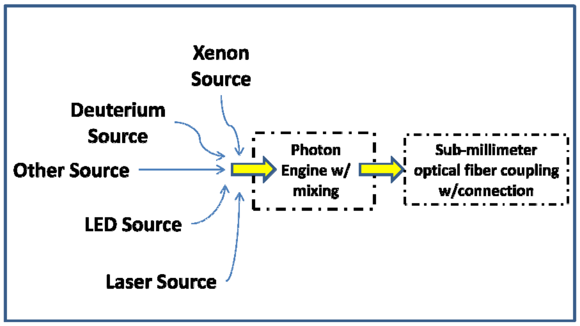
Type II reaction of energy transfer from the photosensitizer (PS) in its triplet state (^{3}PS*) to molecular oxygen (O^2). Oxygen radicals ($^1O^2$) are injuring cellular targets (T) causing cell death.

Figure 1. One principle reaction process flow of photochemotherapy treatment of cancer.

Physical phototherapy normally involves the use of infrared radiation to penetrate deep within tissue to deliver heat and stimulate blood vessel expansion. Often infrared (IR) radiation is used because it can penetrate through tissues easily. IR lasers are a preferred embodiment allowing large doses to be delivered in short times and controlled positioning of the therapy.

V. Small Optical Fiber Illumination Combined with Imaging Systems

A new approach has been developed to couple radiation from a variety of sources into sub-millimeter optical fiber for medical and industrial applications. The patent pending technology, developed by Nathaniel Group, Inc. (NGI), allows the integration and mixing of multiple sources into an optical fiber including infrared (IR), white light, ultraviolet (UV), and solid state sources. The flexibility of the system allows the optimum source or sources to be selected for each application. For example, a xenon source for general illumination can be combined with the stable UV output from a deuterium lamp for semi-quantitative spectroscopy; or solid state LED sources can be combined for general illumination and fluorescence imaging with an infrared laser source for ablation, allowing the visualization, analysis and removal of diseased tissues.



Hyperion™ Small Optical Fiber Illumination

Figure 2. Schematic of sub-millimeter optical fiber illumination system.

Table 3 shows the measured lumen and radiometric output of a Hyperion™ 300 Small Optical Fiber Illumination system from NGI configured for medical and industrial applications and compares it to other fiber illumination sources on the market. The data from the Hyperion source was measured for white light in both lumens and milliwatts at the distal end of a 1 meter fiber connected to the source. The Hyperion was in a configuration optimized for coupling radiation into optical fibers ≥0.5mm, yet the data demonstrates exceptional performance for fiber diameters down to 170 microns.

Table 3. Measured optical output from Hyperion™ 300 Small Optical Fiber Illuminator

	Lumen Output	milliWatts (mW)	Lumen Output (typical competitor)
0.170 mm Plastic Fiber	**19**	63	4
0.250 mm Plastic Fiber	**76**	349	6
0.350 mm Plastic Fiber	**137**	404	10
0.500 mm Plastic Fiber	**254**	811	14

Further work combined the light source with two different imaging systems to determine if the light output delivered from the Hyperion 300 would be sufficient for imaging purposes.

Figure 3 shows the imaging capability achieved when the Hyperion light source is combined with a 1mm sized NanEye video chip at various working distances. The image chip was capable of producing images showing the pixilation of the printed target without any adjustment of the lens (fixed lens system). The light source ran at small fraction of its available power output, yet a bright spot remained at the center of the image even after various adjustments.

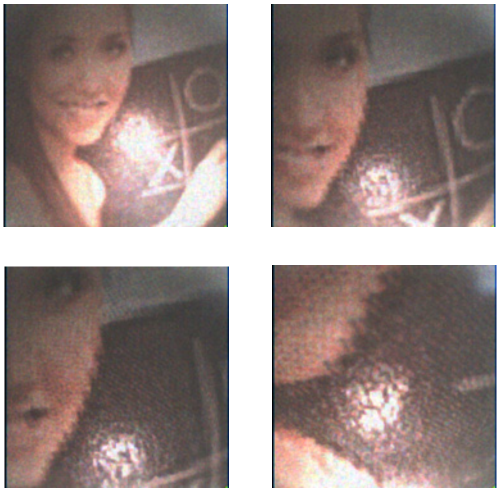


Figure 3. Printed color resolution target imaged using 1 millimeter size video camera and Hyperion light source at various working distances from 30mm to 5mm

Next, the light output was made very diffuse and used to illuminate a laceration on human skin. Although the image appearance is much improved, there remained a bright spot in the center.

Figure 4. Image of human skin with laceration using NanEye camera and Hyperion light

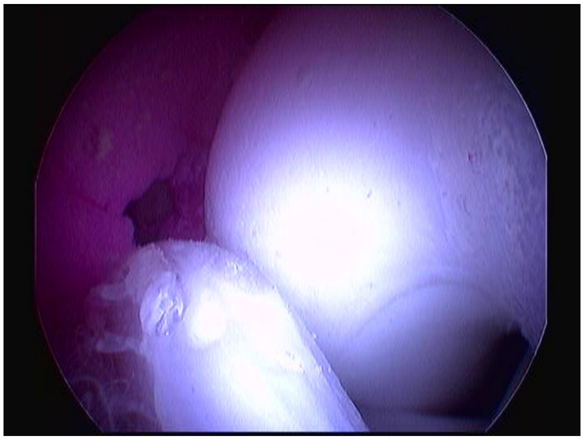


Figure 5. High resolution image of artificial knee joint using illumination through 400µm fiber.

Figure 6a.

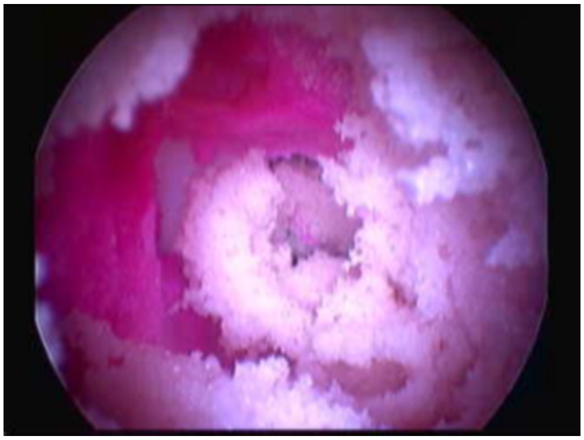


Figure 6b.

Figures 6a and 6b are high resolution images of artificial knee tissue using illumination through 400µm fiber.

Figures 5, 6a and 6b are images of an artificial knee taken using a three sensor high resolution color camera in conjunction with an arthroscopic endoscope and a Hyperion 300 small fiber light source delivering light through a 400 micron fiber. The images are frame grabs from the video produced during the experiment. The light source setup demonstrates the deep cavity illumination

VI. Summary and Conclusions

There is a continuous drive to reduce the size of imaging systems for medical and industrial applications. Smaller sized imaging systems allow the exploration of ever smaller cavities and reduce the impact on living organisms. A unique new small fiber illumination light source was studied to determine its capabilities as an illuminator for sub-millimeter optical fibers, more specifically plastic optical fibers which are readily available and inexpensive.

Lumen and radiometric measurements of the Hyperion light source showed performance ranging from 4.75 to 18 times better than other systems.

The light source was coupled with two imaging systems. The first imager was a NanEye ultra-small 1mm x 1mm, 250 x 250 pixel sensor from Awaiba. Images generated were not limited by the illumination source which ran at a fraction of its output power.

The second camera consisted of a three sensor high definition camera. The target consisted of an artificial knee illuminated through a 400 micron fiber. The resulting images captured from the video were crisp and well illuminated while a significant output power remained available from the light source.

In summary, the light source exhibited the type of performance necessary to significantly reduce the diameter of an optical fiber used for illumination in medical and industrial applications. In fact, the illumination source delivered enough light to allow a smaller imaging fiber to be used. The performance exceeded expectations, especially when using the smallest available fiber at 170 microns diameter which makes it interesting for ophthalmic and minimally invasive surgical applications.

REFERENCES

[1] A. Dietze, “Preclinical evaluation of photochemical treatment on rheumatoid arthritis and soft tissue sarcomas”, Institute for Cancer Research at the Norwegian Radium Hospital, November 2004.

[2]Micro-incision vitrectomy surgery: A paradigm shift in modern vitreoretinal surgery. Proceedings of 7th EURETINA Congress, May 2007.

[3] A. Mendez, “Medical applications of fiber optics: Optical fiber sees grows as medical sensors”, OptoIQ, January 1, 2011.

[4] E. Pinet and C. Hamel, “True challenges of disposal optical fiber sensors for clinical environment,” Third European Workshop on Optical Fibre Sensors, EWOFS 2007, Naples, Italy.

[5] R. Schwarz, W. Gao, C. Weber, C. Kurachi, et al, “Noninvasive evaluation of oral lesions using depth-sensitive optical spectroscopy,” Cancer 2009; 115:1669-79, April 2009.

[6] D. Roblyer, R. Richards-Kortum, “Optical Diagnosis for early detection of oral cancer,” ADHA Access, 22-25, January 2010.

[7] D. Javier, N. Nitin, D. Roblyer, R. Richards-Kortum, Journal of Nanophotonics, Vol. 2, 023506, April 2008.

The author would like to thank Jeff Cogger at Nathaniel Group, Inc. for mechanical designs and data collection.