Journal of the Optical Society of Korea, Vol 5, No. 2, June 2001, pp. 33-36

Measurement of Spatial Resolution in Fiber-optic Image Guides

Bongsoo Lee*

School of Biomedical Engineering, Konkuk University, Chungju 380-701, KOREA

(Received June 21, 2000)

Common methods of determining the spatial resolution of fiber-optic image guides are by measuring the diameter of individual microfibers or by the use of a resolution test target. However these methods cannot provide enough information of spatial resolution in ultrathin fiber-optic image guides. In this study, a simple method to measure the modulation transfer function (MTF) of an image guide was developed. The MTFs of ultrathin image guides with 3 and 4 μm diameter were measured by examining transmitted sharp edge image. This method should be especially useful for measuring spatial resolution of ultrahigh resolution image guides with less than 5 μm diameter microfibers because their spatial resolution cannot be determined by individual microfiber diameter due to crosstalk and leaky ray phenomena.

OCIS codes : 110.2350, 110.4100, 110.3000, 100.6640.

I. INTRODUCTION

Fiber-optic image guide contains a large number of single optical fibers to allow the direct transmission of optical images. There are many parameters which can have an effect on the image quality in fiber-optic imaging system. These parameters can be divided into three main categories [1]. The first category includes the structural parameters such as fiber diameter, fiber spacing between core center to center, the irregularity of fiber shape, imperfections and fiber length. The second category includes the material parameters such as numerical aperture of the fiber and attenuation coefficient. The last category includes system parameters such as the numerical aperture of the light source and its wavelength.

Although all these parameters are important to characterize the image quality of the fiber-optic system, it is difficult to characterize all these parameters separately [2]. Therefore, there are a few methods to assess the overall image quality of the fiber-optic imaging system by measuring spatial resolution and contrast. The spatial resolution is defined as an ability to distinguish or separate two small objects placed close to each other and the image contrast is the relative difference in image brightness between the object and its background.

In particular, the spatial resolution or the amount of image detail in the fiber-optic imaging system is mainly determined by the diameter of the individual microfibers. The theoretical maximum resolution of fiber-optic image guide can be estimated by the following Eq. [3]:

$$\frac{1}{3d} \leq p \leq \frac{1}{2d} \tag{1}$$

where p (lp/mm) is the resolution in terms of the number of line pairs per millimeter and d (mm) is the diameter of the individual fiber in millimeters. There is another simple method to measure spatial resolution of fiber-optic image guides using a test target [4]. One end of image guide is brought into full contact with the target and illuminates the target from behind with a light source. The resolution can be decided simply by group numbers.

However, in the case of high resolution image guides which have microfibers less than 5 μm, it is very difficult to characterize the spatial resolution of image guides simply by microfiber diameter or group number because there are well-known phenomena such as crosstalk and leaky rays which can affect the image quality of the fiber-optic imaging system. The fiber-optic image can be blurred by mode coupling due to crosstalk between cores, which deteriorate the resolution [5,6] and the propagation of a leaky mode across the bundle also plays a significant role in dropping the resolution of the fiber-optic imaging system [7].

Therefore, the modulation transfer function (MTF) measurement that is applicable to evaluate the image quality is required to obtain spatial resolution of fiber-

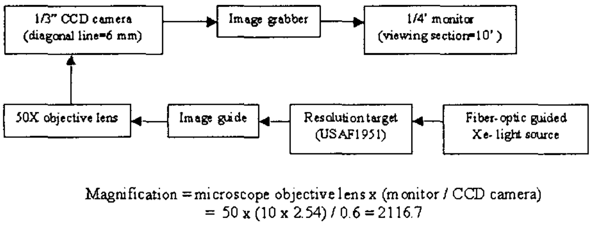

FIG. 1. Edge response function measurement setup.

optic image guides with less than 5 μm microfibers. MTF represents the transformation of the point spread function in the fiber-optic image. In this study, the MTF of the image guide was obtained by measuring the edge response function (ERF) of the sharp edge image through the image guides with the diameter of 3 and 4 μm microfibers, respectively.

II. THEORY

The spatial resolution of an imaging system can be defined by its point spread function (PSF). However, it is difficult to determine the PSF because an infinitesimal point object cannot be produced. To relieve those technical difficulties of measuring PSF, the line spread function (LSF) is used.

The LSF is a one-dimension representation of the two-dimensional PSF. The LSF can be obtained with an infinitesimal line source, rather than an infinitesimal point aperture in the PSF. The width of the line source should be sufficiently narrow so that its finite extent does not contribute to the width of the image. The LSF can be obtained by using the edge response function (ERF) of a sharp edge of an object which transmits light only on one side of itself.

$$LSF(x) = \frac{d}{dx}[ERF(x)] \tag{2}$$

The Fourier transform of the derivative of the ERF yields the MTF in one dimension.

$$\begin{aligned} F\left[\frac{d}{dx}[ERF(x)]\right] &= F[LSF(x)] \\ &= \int_{-\infty}^{\infty} LSF(x)\exp(-2\pi iux)dx \\ &= \int_{-\infty}^{\infty}[\int_{-\infty}^{\infty} PSF(x,y) \\ &\quad \times \exp(-2\pi iux)dy]dx \\ &= \{\int_{-\infty}^{\infty}[\int_{-\infty}^{\infty} PSF(x,y) \\ &\quad \times \exp[-2\pi i(ux+vy)]dy]dx\}_{v=0} \\ &= F[PSF(x,y)]_{v=0} \\ &= MTF(u,0) \end{aligned} \tag{3}$$

There is a relationship of three functions which can yield the MTF.

$$\int_{-\infty}^{\infty} PSF(x,y)dy = LSF(x) = \frac{d}{dx}[ERF(x)] \tag{4}$$

III. EXPERIMENTAL AND RESULTS

The edge response functions (ERF) of the transmitted image through the fiber-optic image guide are measured as shown in Fig. 1. As a sharp image, the USAF 1951 resolution target is used. A light source (Xe light source, ILK-5, Olympus Inc.) illuminates a sharp edge placed in direct contact with the polished surface of the image guide. The surface of the fiber-optic image guide must be polished to within a few microns of surface roughness.

The output image from the proximal end of a 310 mm long image guide is read out by a 50X magnifying lens and a high resolution charge coupled device (CCD) camera system whose images are acquired by a Mac based frame grabber. The magnification factor of the system is 2117 as shown in Figs. 1, 2 and 3 show the output image of the sharp edge transmitted by a Sumitomo image guide made of 4 μm and 3 μm diameter step index microfibers. The ERF is the spa-

FIG. 2. The output sharp edge image of an image guide with average 4 μm diameter microfibers.

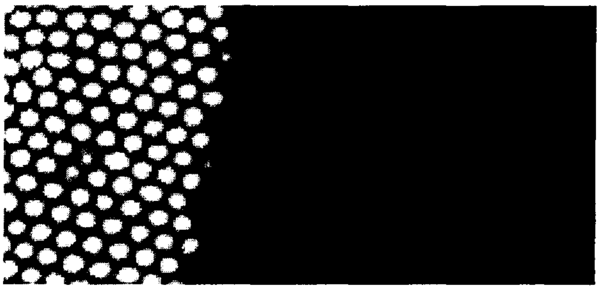

FIG. 3. The output sharp edge image of an image guide with average 3 μm diameter microfibers.

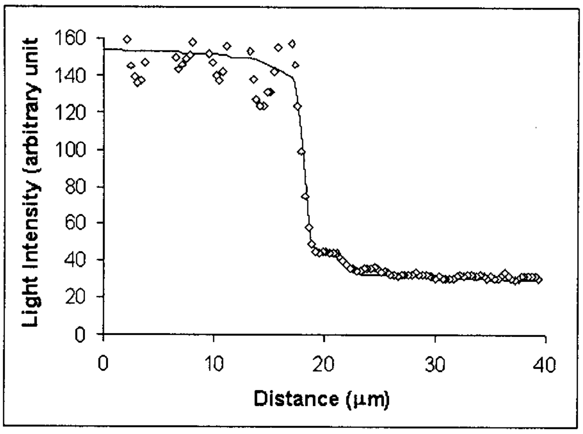

FIG. 4. The measured edge response function of an image guide with 4 μm diameter microfibers.

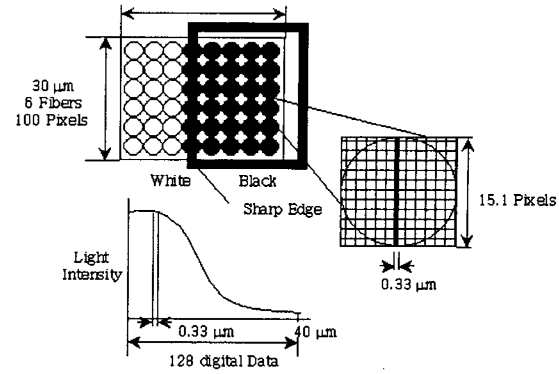

FIG. 6. The method for obtaining the digital data from captured sharp image.

tial intensity distribution across the image of an infinitely sharp edge. Figs. 4 and 5 show the measured ERFs of the 4 and 3 μm microfiber diameter step index image guides, respectively.

In the Figs. 4 and 5, a sharp change in the light distribution can be observed corresponding to the edge of the object. Systematic fluctuation in the light intensity over distances of a few microns can also be observed corresponding to light transmission through individual or small groups of fibers.

The digital data corresponding to Figs. 4 and 5 are used for the analysis of modulation transfer functions (MTF). Each of these sets of data are taken by averaging light intensities over a "swath" of fibers comprising 8 fibers by about 10 fibers in the case of the 4 μm diameter fibers and correspondingly by more for the smaller diameter fibers.

Fig. 6 shows how to obtain the digital data from the sharp edge image when the diameter of each fiber is 5 μm. The pixel size of the measuring system is 0.33 × 0.33 μm^2 that which can resolve the image of the high resolution (3,4 μm) image guide. All 8-bit digital data (128 gray levels) are obtained from averaging about 100 pixel values. Thus, a 4 μm microfiber is mapped by 12.1 × 12.1 image pixels. The modulation transfer function (MTF) of the image guide is obtained from the Fourier transform of the line spread function (LSF) which is the derivative of the edge response function (ERF) as given in Eq. 4.

The ERFs are obtained from the solid lines in the Figs. 4 and 5. The solid lines are best fits from the measured data. The resultant MTFs of the step index image guides with different microfiber diameter, i.e. 3 μm and 4 μm are shown in Fig. 7.

IV. CONCLUSION

Usually, the spatial resolutions in fiber-optic imaging systems are determined by crude methods such as measuring the diameter of individual microfibers or determining group number using resolution targets.

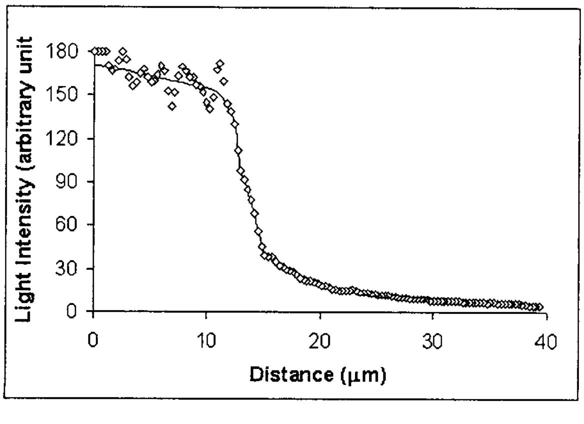

FIG. 5. The measured edge response function of an image guide with 3 μm diameter microfibers.

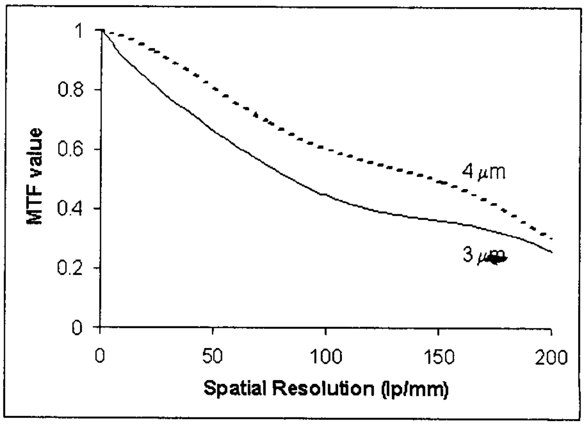

FIG. 7. The modulation transfer function of image guides with 3 and 4 μm diameter microfibers.

However, in the case of ultrathin fiber-optic imaging systems, those crude methods are no longer effective because of crosstalk and leaky ray phenomena. In this study, an exact method to measure MTF of ultrathin fiber-optic imaging systems is developed and the MTFs of step index image guides with 3 μm and 4 μm microfibers are measured. These image guides can be used for ultrathin endoscopes such as angioscopes, ophthalmic endoscopes and needlescopes. To develop these kinds of ultrathin endoscopes, MTF measurement in fiber-optic image guides is essential to examine their spatial resolutions.

It is reported that the spatial resolution of the step index image guide is limited to 5 μm, and the MTF value is lowered as the microfiber diameter decreases below 5 μm [8]. This study also shows that the image guide with 4 μm diameter microfibers has higher spatial resolution than that with 3 μm diameter microfibers as shown in fig. 7. This result shows why MTF value is required for the measurement of spatial resolution of ultrathin image guides with less than 5 μm microfiber.

*Corresponding author : bslee@kku.ac.kr.

REFERENCES

[1] B. Lee, Ph.D. dissertation, University of Florida, 95 (1999).

[2] N. S. Kapany, *Fiber optics: Principles and applications*, (Academic Press, New York, 1967).

[3] F. Suzuki, Proc. SPIE 1592, 150 (1991).

[4] L. Huang and U. Osterberg, Proc. SPIE 2536, 480 (1995).

[5] A. Komiyama and M. Hashimoto, Electron. Lett. **25**, 1105 (1989).

[6] S. Yamaguchi, A. Shimogima, and T. Hosono, Electro. Comm. Japan, Part 2, **72**, 51 (1989).

[7] R. Conde, C. Depeursinge, O. Coquoz, and F. Taleblou, Proc. SPIE 2084, 87 (1994).

[8] T. Tsumanuma, K. Tanaka, S. Chigira, K. Sanada, and K. Inada Opt. Fib. Medicine 3, Proc. SPIE 906, 92 (1988).