Fiberoptic laser angioplasty probe with optical steerability

D.A. Christensen*, D.L. Decker-Dunn*, and G.M. Vincent†

*Dept. of Electrical Engineering
University of Utah, Salt Lake City, Utah 84112 USA
†Depts. of Medicine, University of Utah and LDS Hospital
Salt Lake City, Utah 84143 USA

ABSTRACT

We have designed and bench tested an optically steerable fiberoptic probe for use in laser angioplasty. The unique feature of this design is the use of a gradient-index (GRIN) lens attached to the distal end of a seven-fiber bundle. By selecting which fiber of the bundle is illuminated by the source, the radiation pattern from the probe's tip may be steered either straight ahead or off-axis in one of six angularly biased directions. The probe may also be used to collect scattered light (for example, fluorescence) for the purpose of detecting the spatial distribution of the plaque on the vessel's walls.

1. INTRODUCTION

The tip design for laser angioplasty delivery probes has seen several stages of improvement in the past few years[1-4]. The early flat fiber ends have been augmented by optically absorbing hot tips, optical spherical tips, lenses, and mutifiber designs. This paper descibes a seven-fiber probe with attached GRIN lens which has the capability of directing the light in one of seven selectable directions, depending upon which fiber is optically active. The ability to direct the beam has the potential of providing a more specific therapy beam to the plaque, thereby reducing the risk of overexposure and perforation of normal wall. Moreover, the beam selectivity is valid during the receiving mode as well, so the probe may potentially be used for spatial imaging of the plaque location when used in conjunction with one of the fluorescent techniques currently being studied by several investigators.

2. TIP DESIGN

The GRIN lens is characterized by a parabolic index of refraction n(r) which decreases as the square of the distance r from the optical axis:

$$n(r) = n_0[1-Ar^2/2]$$

where n_0 is the refractive index at the center axis of the lens and A is the radial gradient coefficient. This lens performs the same optical functions (e.g., focussing and collimation) as a standard spherical lens, but has the advantages of cylindrical shape, flat faces (for ease of attachment to fibers) and a very small size. The GRIN lens (from Nippon Sheet Glass) used in our prototype probe is 1 mm in diameter and has a length of 3.1 mm. This length was chosen in combination with a radial gradient of $A=0.499\ mm^{-2}$ in order to provide a "quarter pitch" lens. For such a lens, the rays from a point source positioned at one face of the lens will be collimated as they exit the opposite face, analogous to the situation of a point source located at the front focal plane of a standard thin spherical lens.

Figure 1 shows the GRIN lens attached to the end of the seven-fiber probe. Figure 2 illustrates how the beam pattern is laterally directed by the choice of the illuminating fiber. If the center fiber is selected, the beam is directed forward; if one of the six surrounding fibers is chosen, the beam

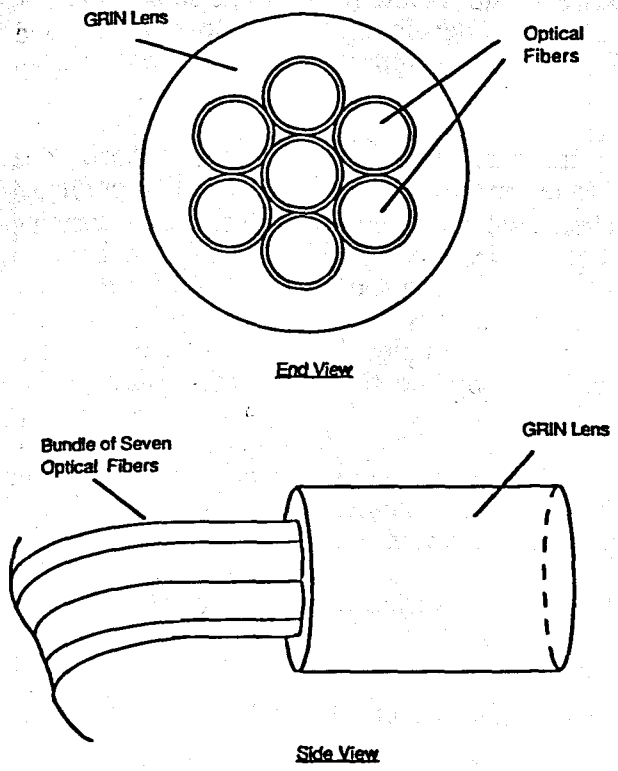

Fig. 1. Gradient index (GRIN) lens attached to seven-fiber probe.

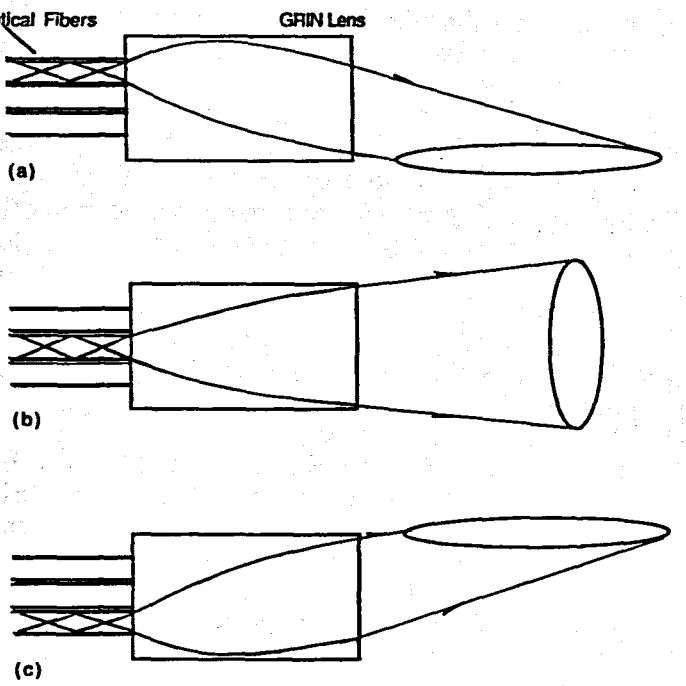

Fig. 2. Beam patterns through quarter pitch lens: (a) from top fiber, (b) center fiber, (c) bottom fiber.

is tilted off-axis. Figure 2 also illustrates the rational for employing a quarter pitch lens. It is important for the lens to transform the spatially confined cone of rays exiting the fiber faces into a broader, quasi-collimated beam in order to optimize the illumination patterns on the arterial wall.

The fibers chosen are step-index, hard-clad silica core fibers from Ensign-Bickford. The core (200 μm) and clad (230 μm) diameters yield a high core-to-clad ratio, important for minimizing the overall diameter of the bundle to approximately 700 μm. This bundle diameter fits well (optically and physically) within the 1 mm diameter of the GRIN lens. The fibers' large numerical aperture (NA=0.37) results in an appropriately large beam area at the vessel wall, giving good coverage without excessive overlap between beams, as shown next.

3. BEAM PATTERNS

A computer program was written to predict the theoretical illumination patterns by tracing rays from the fiber faces through the parabolic index lens to the site of the vessel wall[5]. Some of the optical parameters considered were: fiber core location and size; fiber numerical aperture; a possible gap between the fiber faces and the entrance face of the lens; the GRIN lens length, diameter and index profile; diameter of the lumen of the vessel; and refractive index of the fluid filling the vessel lumen. Various choices of these parameters were then analyzed to determine which combination gave the optimum beam patterns, i.e., complete coverage without excessive overlap. The fiber and lens components described in the previous section were, in fact, chosen as a result of this computer optimization procedure.

Figure 3 shows the theoretically determined power contour patterns for some adjacent beams as seen on the vessel wall, assuming the optical components descibed above. Both on-axis and off-axis beams are shown. Note the good circumferential coverage, with only modest overlap between spots.

Irradiation patterns were then experimentally measured in a bench test using these same components, for both on-axis and off-axis beams, for comparison to the theoretically predicted patterns[5]. Figure 4a shows one experimental off-axis beam pattern, which was obtained by scanning a 400 μm collection fiber over a curved plane located at the simulated position of a 2 mm diameter arterial wall. This plot may be compared with the theoretical pattern shown in Fig. 4b for the same conditions. Note that the position of the maximum intensity (4.5 to 5.0 mm from the end of the lens) is approximately the same in both plots. However, the experimental plot shows a beam spread that is about 10% longer (axial length ≈ 10 mm) than predicted by the theory, perhaps due to lens imperfections.

All of the above tests were performed in air for experimental convenience. When water (or clear plasma) is assumed to fill the lumen of the vessel, the theoretical beam patterns change somewhat. For example, for the off-axis pattern the point of maximum intensity moves to a location 5.5 mm from the end of the lens (as compared to 4.5 to 5.0 mm in air) and the axial length is increased to about 12 mm (as compared to 10 mm in air). The beams also overlap more in area. However, the patterns still give the desired coverage and selectivity.

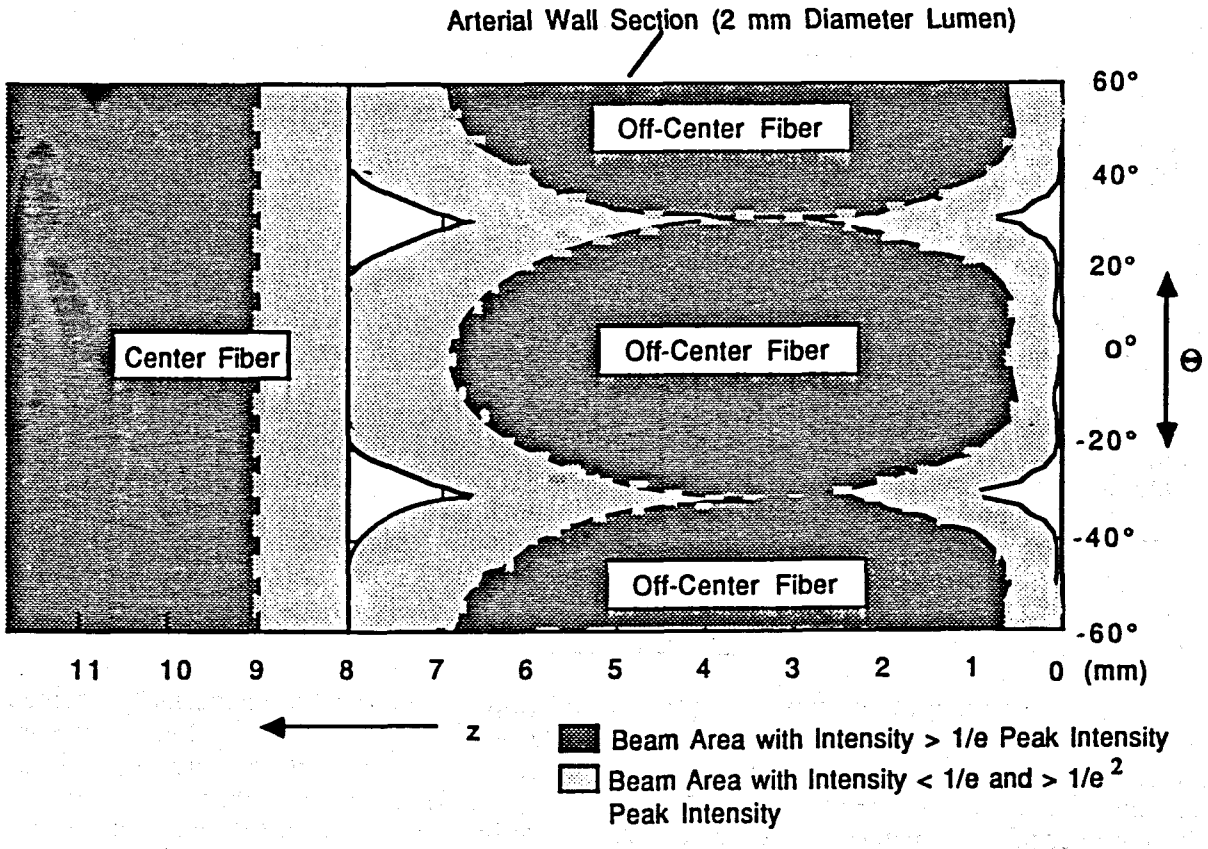

Fig. 3. Theoretical irradiation patterns from three off-center fibers and the center fiber showing the degree of coverage and lateral overlap on the arterial wall.

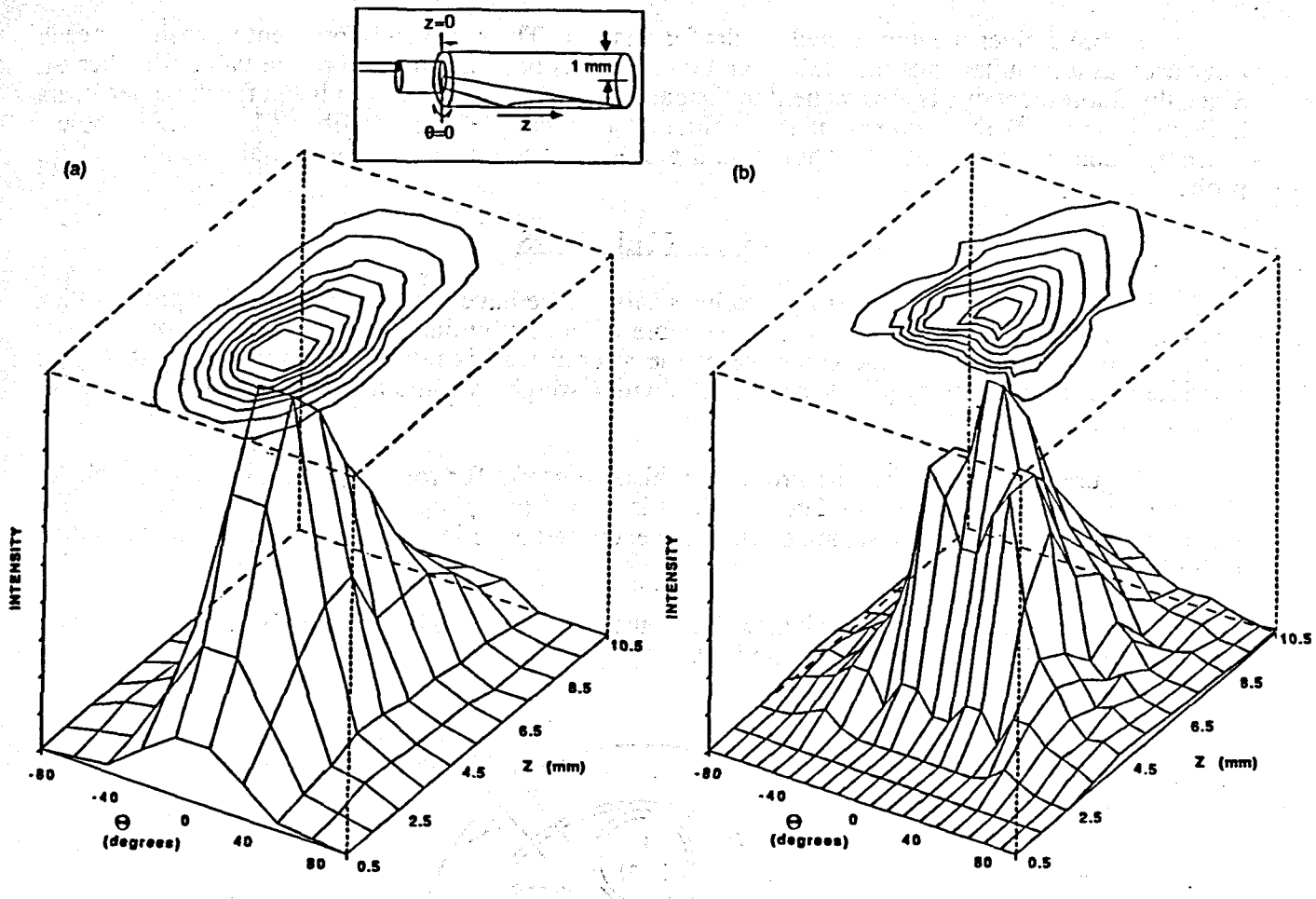

Fig. 4. (a) Experimental irradiation pattern from an off-axis fiber as measured at position of arterial wall (see inset for measurement geometry).

(b) Theoretically predicted pattern for the same conditions.

4. FLUORESCENT DETECTION

To test the concept of detecting a spatially confined fluorescent object, we fabricated a seven-fiber probe to the above specifications and used it in a bench test with a target solution of the fluorescent dye Nile Red (0.636 mg Nile Red in 2 ml DMSO). We placed a small capillary tube (ID = 1.68 mm, OD = 2.0 mm) filled with this solution along the side of the probe, with the nearest fluorescent surface located approximately where a 2 mm diameter vessel wall would be relative to the lens end. The tube was always located opposite off-axis fiber #1 and had a intercepting area about the same size as the beam pattern from fiber #1; this placed the solution directly in the path of the transmission pattern of fiber #1 (and, by reciprocity, in the reception pattern of fiber #1), but on the edges or outside the patterns from the other fibers. The tube was kept at this location for the duration of the test. Each fiber was then illuminated with the 514.5 nm line from an argon ion laser, and the fluorescent intensity coupled back into that same fiber at a peak wavelength of 610 nm was detected with a beamsplitter/monochromator arrangement.

Figure 5 gives the normalized results for this test. The received fluorescent intensity for each fiber used as a simultaneous transmitter and receiver has been normalized to the value for fiber #1. Since the fluorescent dye is always held in the pattern of fiber #1, the values listed for the other fibers indicate how much the patterns of these fibers "cross couple" that of fiber #1 (in a fluorescent excitation and reception sense). Thus, Fig. 5 provides an indication of the spatial resolution of the probe.

5. CONCLUSIONS

By employing a computer ray-tracing analysis, we have designed a multifiber probe with a quarter pitch GRIN lens which has six selectable off-axis illumination directions and one on-axis beam. Figure 3 shows that the coverage of the arterial wall is relatively complete, so it may be possible to treat an arbitrary plaque distribution with a weighted combination of laser powers via the various fibers of the probe.

Figure 5 indicates that the probe may also be useful for rough spatial diagnosis of plaque distributions through fluorescent detection (if it is shown that plaque is fluorescently unique). The received fluorescence may be separated from the exciting power in each fiber by either beam splitters or 3 dB couplers.

The ray tracing program will also allow other lens/fiber combinations to be analyzed if further modifications to the beam patterns are desired.

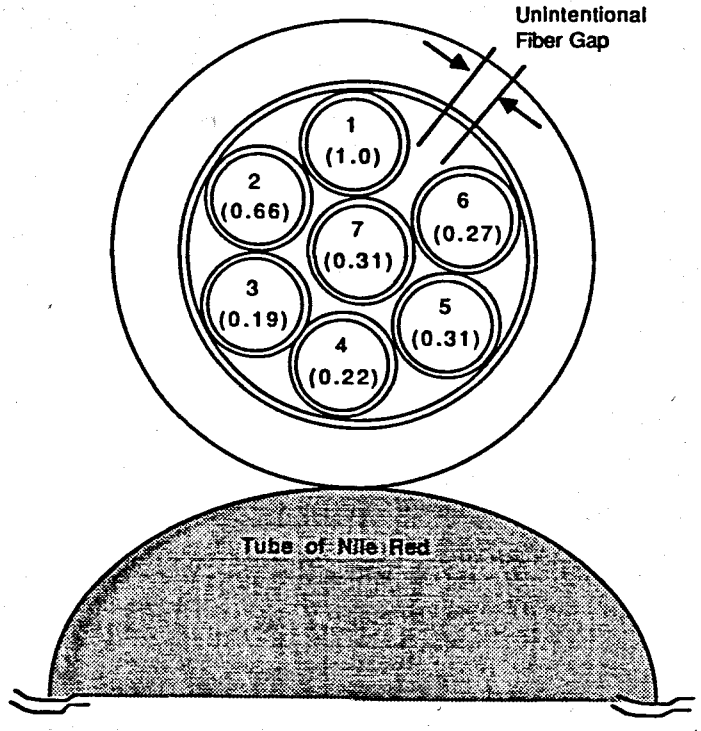

Fig. 5. Received fluorescent power (normalized to the power for fiber #1) when each fiber is individually illuminated and collection is by that same fiber. Dye tube is held at a constant location opposite fiber #1.

6. ACKNOWLEDGEMENTS

This work was funded by the Utah Laser Institute, the University of Utah School of Medicine, the Veterans Administration Medical Research Program, the SDIO/MFEL Research Program, and the LDS Hospital.

7. REFERENCES

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