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Effect of Lithotripsy on Holmium:YAG Optical Beam Profile

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ABSTRACT

***Purpose*: To determine the effect of holmium:YAG lithotripsy on the optical beam profile.**

***Materials and Methods*: Beam profiles of the laser light from holmium:YAG optical fiber systems were characterized with a pyroelectric camera. Beam profiles were measured with 272-μm and 365-μm optical fibers both straight and bent to simulate lower-pole ureteronephroscopy. Struvite calculi were irradiated. Beam profiles and energy outputs were characterized for the fibers before and after ablation. Ablation crater geometry was characterized with optical coherence tomography.**

***Results*: Undamaged, straight fibers produced a near-Gaussian beam profile. Craters showed a similar near-Gaussian shape. Undamaged, bent 272-μm fibers produced a near-Gaussian beam but slightly flatter profile than the straight fiber. The bent 272-μm fiber transmitted 99% to 100% of the energy, similar to the 100% transmission of the straight fibers. After ablation, measured energy output dropped by 30% within 50 pulses at 0.2 J pulse energy. The damaged fibers produced irregular beam profiles with hot spots. Craters showed irregular contours.**

***Conclusions*: During Ho:YAG lithotripsy, the beam profile at the optical fiber tip approaches a Gaussian distribution. This shape corresponds to the crater produced on the stone surface. With further ablation, the beam profile becomes erratic and unpredictable, with loss of lithotripsy efficiency. The findings provide further insight into the photothermal mechanism of Ho:YAG lithotripsy.**

INTRODUCTION

THE HOLMIUM:YAG LASER is the intracorporeal lithotrite of choice for ureteroscopy.[1] Unlike other lithotripsy devices, which fragment stones in irregular fracture planes, the photothermal mechanism of Ho:YAG lithotripsy produces symmetric craters on the stone surface.[2–6] These craters increase in depth and width as pulse energy increases and retain their symmetric appearance regardless of stone composition.[7] Although fragmentation with a holmium laser may take longer than with other devices, holmium:YAG lithotripsy produces smaller fragments than other intracorporeal lithotripters.[8] Holmium:YAG lithotripsy may be advantageous for ureteronephroscopy, as optical energy may be delivered with small-caliber flexible optical fibers.[1,9,10]

Because lithotripsy requires efficient delivery of optical energy to the stone surface, optical fibers must function properly. Optical fiber damage during lithotripsy is associated with diminished lithotripsy efficiency.[5,11] In order to identify the mechanisms that lead to diminished lithotripsy efficiency, we studied the effect of lithotripsy on the optical beam profile. We also studied the effect of bending the optical fibers, such as occurs during lower-pole retrograde ureteronephroscopy, to determine the impact on optical beam transmission and beam profile.

MATERIALS AND METHODS

Cleaved optical fibers of 272-μm and 365-μm diameter (Slimline-200 and –365; Lumenis, Santa Clara, CA) were pol-

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ished using diamond lapping films with sequentially smaller grit sizes (minimum grit size 1 μm). After polishing of the fiber, the surface of the tip was examined under a microscope to confirm a smooth, flat, uniform surface.

The beam profile at the distal end of the optical fiber was imaged with a microscope objective (magnification 20, numerical aperture 0.4). The optical fiber tip was placed at the object plane of the microscope objective, and the magnified beam was viewed in the detector plane of the beam profiler (Pyrocam I; Spiricon, Logan, UT). The beam profiler was based on a pyroelectric detector array that was triggered by an external InAs photodiode (EG&G, Judson, PA). The acquired images were transferred to a personal computer equipped with a frame grabber.

Optical fibers were used to ablate calculi of >95% struvite composition. All calculi were cut with a dental diamond band saw and sanded to create a smooth, flat surface. The calculi were hydrated in deionized water for a minimum of 24 hours then placed in a water cuvette. The Ho:YAG laser (VersaPulse; Lumenis) was configured to deliver a pulse energy of 600 mJ at 6 Hz. After 167 pulses (100 J irradiation), the damaged optical fiber tip surface was reimaged with the beam profiler. The fiber was repolished and redamaged prior to each damaged profile measurement. The optical output of the fibers was measured using an energy detector (Molectron, Portland, OR) before and after ablation of struvite calculi up to 3500 pulses (600 mJ at 6 Hz). To avoid thermal damage to the energy detector, the laser energy was set at 200 mJ for a single pulse.

The beam profile was examined with the 272-μm optical fibers bent to simulate bending of a flexible ureteroscope. We made photocopies of 7F flexible ureteroscopes (models 11274AA, Karl Storz, Culver City, CA; URF-P3, Olympus, Lake Success, NY; 7325.172, Richard Wolf, Vernon Hills, IL; and DUR-8, ACMI-Circon, Stamford, CT) in maximally upward flexion and downward deflection with a 272-μm optical fiber through the working port. These copies were cut out and taped on more rigid card stock. The 272-μm optical fibers were taped to the photocopies to simulate the bent fiber in the ureteroscope. Each fiber was then aligned with the beam profiling system (above), and the beam profile was measured. The energy output was compared for straight and bent fibers.

The craters on the stone surface produced from Ho:YAG lithotripsy were characterized with optical coherence tomography. Craters were produced using both undamaged, polished fibers and damaged fibers. To create damaged fibers, polished, undamaged fibers were used to ablate calculi at 600-mJ pulse energy until a total of 100 J had been delivered. To compare the ablation volumes of craters produced from straight and bent fibers, the flat surfaces of plaster of Paris phantoms were irradiated with 500-mJ single-pulse energy. Ten ablation craters (ten phantoms) per cohort were characterized with optical coherence tomography and the volumes analyzed with unpaired *t*-tests.

RESULTS

The straight, undamaged fibers showed a near-Gaussian beam profile (Fig. 1). After 100-J stone ablation, the beam profile became erratic, with hot spots, irregular contours, and unpredictable profiles (Fig. 2). Damaged fibers produced different beam profiles in the various trials. During ablation, the measured output decreased approximately 30% within the first 50 pulses and stabilized thereafter (Fig. 3). With the fiber bent maximally, the beam profile flattened but still approximated a near-Gaussian profile (Fig. 4). Energy measurements from the straight fibers were 100% of the selected laser delivery energy. The energy measurements from the bent 272-μm fibers were 99% to 100% of the stated input energy. There were no detectable differences among beam profiles or energy outputs with fibers bent for the various ureteroscopy simulations. Optical coherence tomography images of craters produced with polished fibers were approximately Gaussian, grossly comparable to their beam profiles (Fig. 5). The craters from damaged fibers exhibited irregular contours with grossly less fragmentation than was obtained with the undamaged fibers. The ablation crater volumes of the straight and bent fibers were 0.038 ± 0.007 mm^3 *v* 0.044 ± 0.008 mm^3, respectively ($P = 0.11$).

DISCUSSION

The Ho:YAG laser emits optical energy in roughly a Gaussian distribution. The near-Gaussian beam profile grossly conforms to the measured crater shapes. Previously, we had speculated that the symmetric crater shapes were attributable to diffusion of thermal energy.[7] However, the current data demonstrate rather that the crater shape is affected by the beam profile: Ho:YAG lithotripsy produces symmetric craters because the beam profile is symmetric. The crater is deepest under the fiber center because fluence and energy density are greatest at this location. At the periphery of the fiber, fluence and energy density are weakest, so the crater depth is minimal. Higher pulse energy produces larger crater volumes as fluence and energy density increase at all points along the fiber tip. Crater geometries differ among fiber diameters, however, because of factors such as fiber acceptance angle and fiber diameter, as energy density and fluence diminish with a larger fiber diameter. Thus, the same pulse energy produces a deeper and narrower crater when using a small optical fiber and a more shallow and wider crater with a larger optical fiber.[12]

In contrast, after contact lithotripsy, the beam profile is changed dramatically and unpredictably. This finding is not unexpected, as fiber damage during lithotripsy causes microfractures of the optical fiber tip.[7,13] These fiber tip microfractures produce decreased collimation with less forward transmission of optical energy.[11] The decreased measured optical output was seen with the same (200-mJ) pulse energy input, implying that forward transmission of energy was decreased. The difference in the stated energy output and measured energy output is attributable to the irregular surface of the damaged fiber tip, which reflected and refracted optical energy in different directions, leading to noncollimated energy and energy scatter.[5] Thus, some of the energy is redirected elsewhere and not contributing to forward transmission directly under the fiber tip. Optical fiber tip damage is greater as pulse energy increases, particularly when it is >1.0 J. Calculus fragmentation efficiency diminishes for calcium stones at pulse energies >1.0 J.[11]

Ablation craters that correspond to beam profiles are further evidence of photothermal ablation caused by long-pulse (>250-

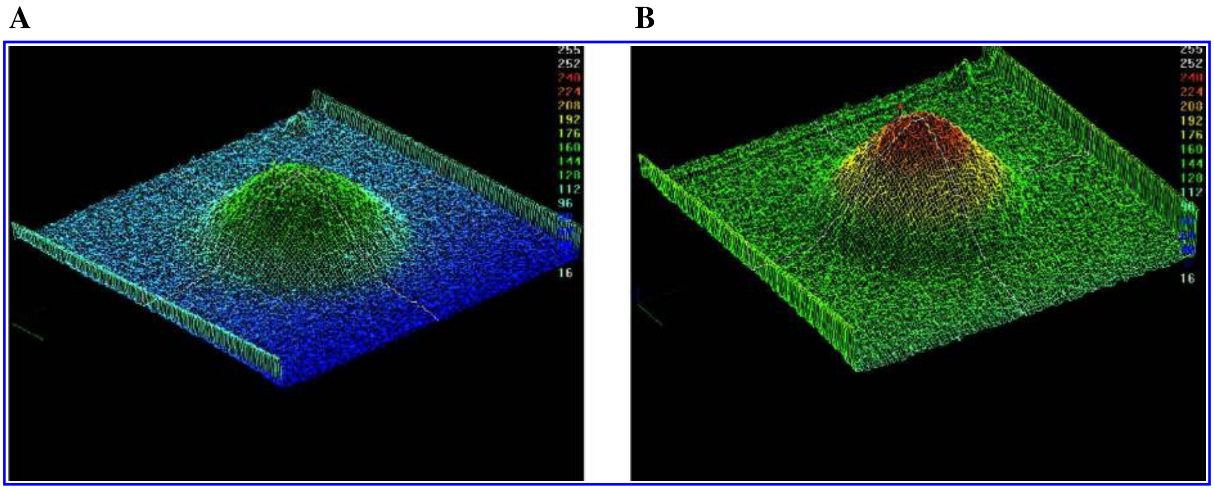

FIG. 1. Beam profiles of straight, undamaged, polished optical fibers. **(A)** The 365-μm fiber. **(B)** The 272-μm fiber. Both fibers provide near-Gaussian beam profiles.

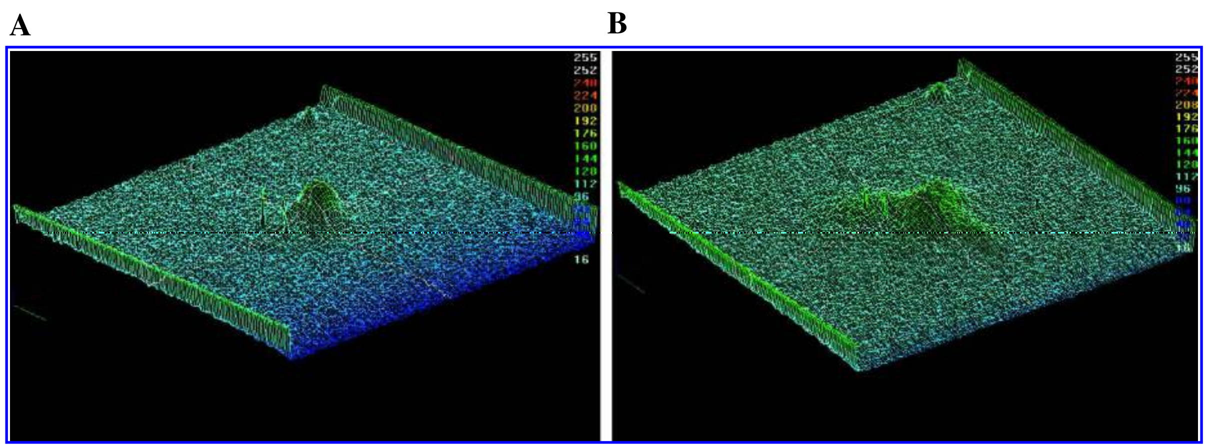

FIG. 2. Beam profiles of straight, damaged fibers. **(A)** The 365-μm fiber. **(B)** The 272-μm fiber. Both fibers exhibit irregular beam profiles, hot spots, and unpredictable irradiance contours.

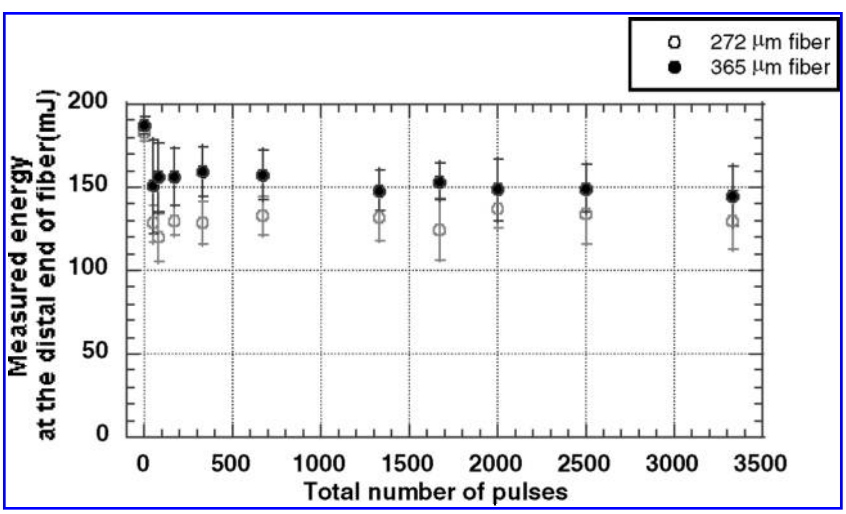

FIG. 3. Measured optical output during ablation. There is a rapid decline in measured energy forward of the optical fiber tip within 50 pulses, then relatively steady output of approximately 60% to 70% of stated pulse energy.

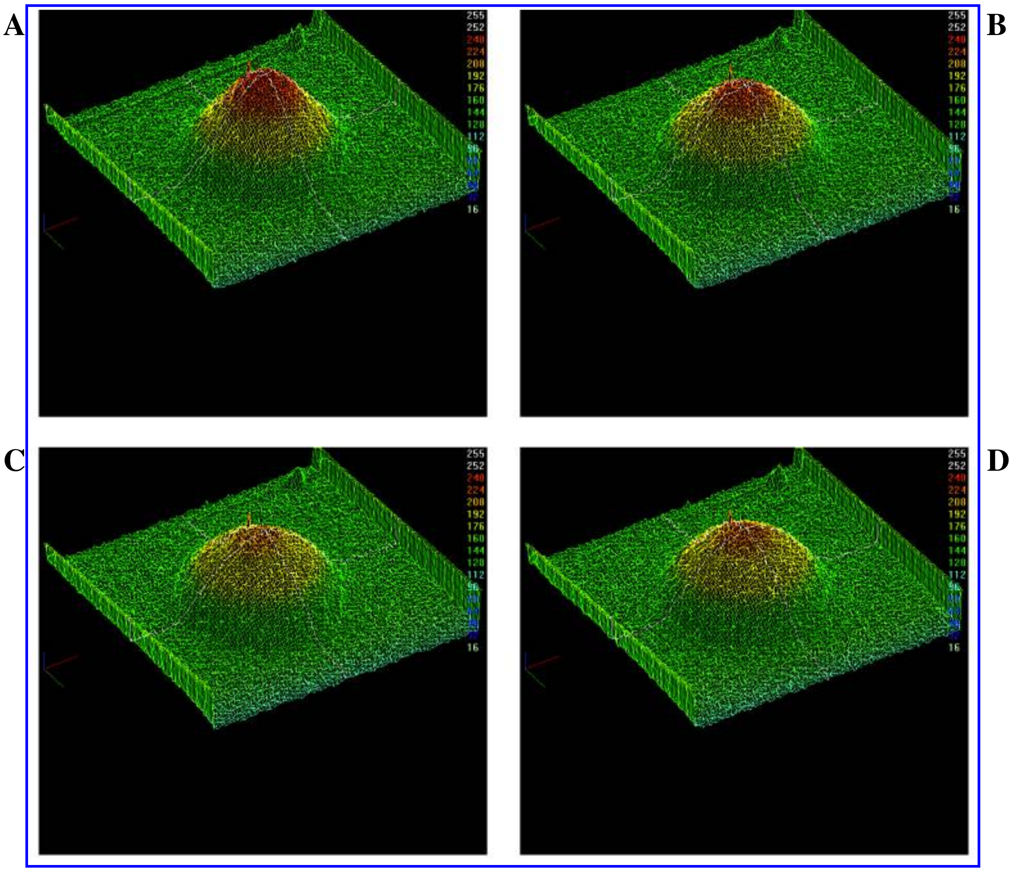

FIG. 4. When polished, undamaged 272-μm fiber is bent to simulate retrograde ureteronephroscopy, beam approaches Gaussian profile but is flatter than straight-fiber beam profiles. The beam profiles depict tallest, most narrow peak and near-Gaussian profile for straight fiber configuration (**A**). As fiber bending radius is tightened, there are progressively shorter and wider profiles for fiber in maximal angel bend (approximately 140°) bending radii of 2 cm (**B**), 1.5 cm (**C**), and 1 cm (**D**).

μsec) Ho:YAG irradiation.[2] In short pulse-duration lasers (<1 μsec), photoacoustic effects are maximal when vapor bubble geometry is largest.[3] We would expect that if Ho:YAG lithotripsy fragmented stones through photoacoustic mechanisms, the largest beam profile would translate into the largest vapor bubble, which in turn would produce the largest acoustic transient and an irregular fragmentation effect.[14] Instead, the largest Ho:YAG beam profiles produced symmetric, reproducible craters, evidence of a photothermal rather than a photoacoustic mechanism. In fact, an increase in Ho:YAG pulse energy produces an increase in the volume of these symmetric craters without evidence of fracture, findings that can be explained only by a photothermal mechanism.[12]

Clinically, the data raise the question whether urologists should cleave Ho:YAG fiber tips during prolonged lithotripsy cases. Alternatively, urologists might use a fiber for a set number of pulses before exchanging it for another fiber. The rationale is that either maneuver may yield more efficient lithotripsy.

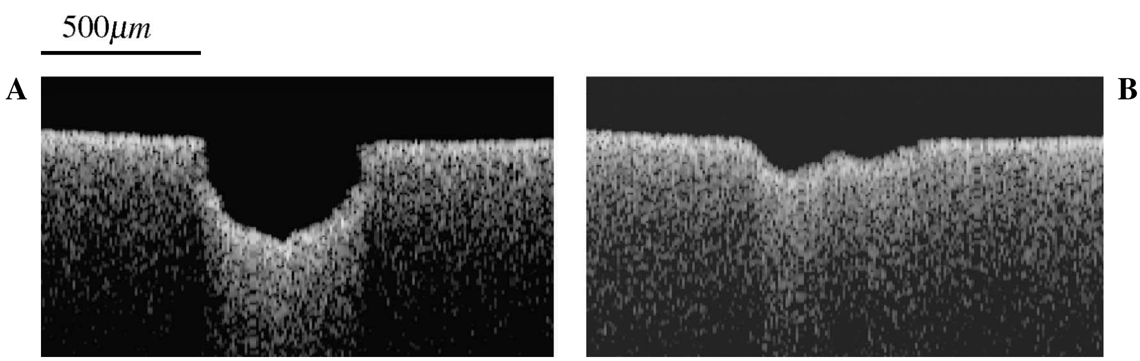

FIG. 5. Typical stone crater profiles measured with optical coherence tomography of struvite calculi after single-pulse (600-mJ) irradiation with 272-μm optical fiber. **(A)** Undamaged fiber produces crater profile similar to near-Gaussian beam profile. **(B)** Damaged fiber produces an irregular crater with grossly less ablation than is obtained with undamaged fiber.

At this point, however, we do not recommend either practice. Our data show clearly that fragment removal rates diminish after 50 pulses (roughly 5 to 10 seconds of lithotripsy at customary repetition rates) and thereafter remain stable at a diminished output. We assume it would take longer to repolish or exchange fibers intraoperatively, and even then, the urologist would have to repeat the maneuver every 5 to 10 seconds to ensure using a polished fiber. Enhanced optical fibers protected by a shield would seem a logical solution.

For all fibers bent similar to the manner used in lower-pole nephroscopy, the beam profile changed only minimally, with a slightly flatter distribution of optical energy. A minimal amount of energy, less than 1%, was lost in transmission in the bent *v* straight fiber. We infer that lower-pole retrograde ureteronephroscopy causes no significant laser leak to the ureteroscope and no significant change in the optical output or distribution of output. Anecdotally, we have experienced cases of lower-pole retrograde ureteronephroscopy in which optical energy damaged the inside of the ureteroscope. In this case, the fiber was damaged at the site of maximal ureteroscope deflection after firing of the laser. However, using the bending simulations and pulse energy of 0.6 J in this study, we were unable to reproduce fiber damage at the site of bending. It is unclear if higher pulse energies or greater bending (larger angle of deflection or smaller bending radius) might reproduce fiber damage from optical damage. It is nonetheless prudent to verify that optical fibers are intact prior to use. Urologists should confirm the integrity of the optical fiber by turning the tracer beam on high in a darkened operating room. Any bright spots along the fiber, except the tracer beam exiting the fiber tip, would indicate a fracture, and the fiber should be cleaved proximal to the fracture or discarded.

CONCLUSIONS

The beam profile during Ho:YAG lithotripsy approaches a Gaussian shape but becomes erratic with fiber damage after ablation. The altered beam profile yields less efficient lithotripsy.

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