An Er:YAG Laser Endoscopic Fiber Delivery System for Lithotripsy of Salivary Stones

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Background and Objectives: Endoscopic applications of Erbium:YAG lasers are still very limited due to lack of appropriate fiber delivery capabilities. Recent reports on potential advantages of this laser for lithotripsy of ureteral stones prompted us to develop an Er:YAG fiber delivery system for endoscopic lithotripsy of salivary stones. We report on the development of this system and its clinical use on 17 patients.

Study Design/Materials and Methods: Ho:YAG and Er:YAG laser fragmentation performances were initially compared. Optimal laser parameters for lithotripsy of salivary stones were then established ex vivo using a commercial dental Er:YAG laser (Lumenis Opusdent 20). Metal hollow waveguides optimized for Er:YAG laser transmission were end sealed with a polished sapphire rod of 0.63 mm diameter and designed to adapt to the Opusdent laser and to a Storz sialoendoscope. The system was tested ex vivo for durability and clinical compatibility at input energies up to 700 mJ, 10–20 Hz. Following Helsinki approval the system was clinically tested on 17 patients with sialolithiasis.

Results: Lithotripsy threshold was around 80 mJ/pulse (26 J/cm²) while efficient fragmentation, with microscopic fragments, was observed at an output energy range of 150–300 mJ/pulse. At 10 Hz, fragmentation rates of about 1.8 mm³/second were achieved enabling lithotripsy of a 6 mm stone in about 2 minutes. Front surface damage to the sapphire rod occurred but did not contribute to significant loss in fragmentation efficiency. Of the 21 stones treated clinically, 5 were fully fragmented, 7 were prepared for extraction by mini forceps, and 9 were released from surrounding soft tissues for subsequent removal. Fifteen of the 18 treated glands returned to normal function without any symptoms.

Conclusions: The Er:YAG endoscopic delivery system described is a clinically viable and cost-effective device for a range of hard and soft tissue wet field applications accessible through rigid or semi-rigid endoscopes. Further improvements in the waveguide may allow access also through fully flexible endoscopes. Lasers Surg. Med. 00: 1–8, 2006. © 2006 Wiley-Liss, Inc.

Key words: erbium laser; hollow waveguides; infrared fibers; laser lithotripsy; sialolithiasis; sialoendoscopy

INTRODUCTION

Sialolithiasis (salivary gland stones) is the most frequently occurring of the diseases affecting the salivary glands. In post-mortem studies incidence was found to be 1.2% while in hospital admissions it is estimated to be 1 per 15,000 [1]. Sialolithiasis results in a mechanical obstruction of the salivary duct causing repetitive swelling during meals which can remain transitory or be complicated by bacterial infections [2]. The introduction of sialoendoscopy in the mid 90s has significantly improved the diagnosis and treatment of salivary gland inflammatory diseases yet the endoscopic removal of larger and impacted salivary gland stones remains challenging often requiring sialoadenectomy which is associated with the risk of facial paralysis [3–6] and requires general anesthesia and hospitalization. Although the patient can function without one of the glands it is involved with decreased secretion of saliva which creates dry mouth and potentially more dental caries. Extracorporeal shockwave lithotripsy is also used for treatment [7]. This technique requires several sessions at intervals of a few weeks. The remaining stone debris may function as the ideal nidus for further calcification and sialolithiasis recurrence. This technique creates potential risk to bones and teeth. The success rate is also rather low and does not pass 50% in the best cases [8]. It is much less effective for stones larger than 7 mm in diameter. Interventional Sialoendoscopy with a wire basket through a miniaturized endoscope was also carried out in the 90s. [9]. It has good success for the 1–3 mm diameter stones but majority of stones are 3–7 mm.

Endoscopic laser lithotripsy can potentially treat most cases of salivary gland stones with minimal complications while preserving a functional salivary gland. In urology the Holmium laser has become the gold standard for endoscopic lithotripsy with delivery of the energy through highly reliable, low OH Silica fibers with core diameters as small as 1–8, 2006.
as 200 microns [10]. Some successful attempts have been reported on the use of this laser for sialolithiasis, however, the smaller anatomy of the salivary ducts increases the risk to surrounding soft tissues [11–13].

Recent reports on the potential advantages of Erbium laser over Holmium laser in endourology [14,15] prompted us to investigate its use for sialolithiasis. According to these reports the Erbium laser is a more effective laser lithotriptor and is significantly safer to surrounding soft tissues both due to its higher absorption in water and soft tissues and to differences in the vapor bubble dynamics [16–18]. Endoscopic delivery of Erbium laser wavelengths is still technically challenging [19], however, sialoendoscopy, unlike endourology, does not require fully flexible delivery over long distances. A typical sialoendoscope (Fig. 1) is a semi-rigid endoscope with an operating channel of only 14 cm. Operating channel inner diameter is 1 mm.

We describe the development of an Erbium fiber delivery system for lithotripsy of salivary stones in a biocompatible, liquid environment; its comparison to the Holmium laser and our initial clinical experience with this new device.

MATERIALS AND METHODS

Sialolithiasis is usually managed by oral-maxillofacial surgeons who are already using Erbium lasers for a range of dental applications. We therefore attempted to develop our fiber delivery system for lithotripsy of salivary stones as an accessory to standard, commercially available Erbium dental lasers. We used a Lumenis Opusdent 20 Erbium laser which delivers up to 1 J/pulse, 20 Hz at a wavelength of 2.94 microns. Pulse durations are 250–300 μseconds. The laser beam is delivered to a detachable dental handpiece through a metal hollow waveguide with a 1 mm inner diameter. With the dental handpiece attached the beam may be delivered through short, straight or tapered hollow waveguides, or through short straight or tapered sapphire probes. We initially used these short sapphire probes to investigate sialolithiasis lithotripsy with this laser in a liquid environment and to establish optimal parameters for our endoscopic deliver system.

Human-extracted salivary stones were supplied to us by Prof. Nahlieli of the Barzilai Medical Center, Israel. These stones ranged in size from about 5 to 20 mm, were of different compositions, and of different shapes. Salivary duct calculi are composed mostly of calcium phosphate with traces of magnesium and ammonia with an organic matrix consisting of carbohydrates and amino acids [20]. Most stones are found in the submandibular gland. Hardness of salivary stones is generally similar to that of urinary stones, 85% of which are also composed predominantly of calcium compounds.

Extracted salivary stones were placed in a water container and irradiated in contact with a conical sapphire probe of 0.6 mm tip diameter. Energy settings, as measured in air with a thermopile power meter (Ophir Optronics, Jerusalem, Israel) were varied from 100 to 700 mJ/pulse at frequencies from 10 to 20 Hz. Threshold for effective stone fragmentation was observed at around 125 mJ/pulse while at 200 mJ/pulse fragmentation seemed rapid and well controlled with the probe in contact with the stone. At 200 mJ/pulse, 10 Hz, a fragmentation rate of about 1 mm³/second was measured. At these energy levels stone fragments had a dust-like appearance and were suspended in the water.

With increase of the energy to the 300–500 mJ level, larger stone fragments appeared. We therefore concluded that our fiber delivery system should be able to deliver 200–300 mJ/pulse to the stone, should be no more than 0.9 mm in outside diameter in order for it to pass through the sialoendoscope (Karl Store, Tuttingen, Germany) and should be bendable to a radius of curvature of at least 15 cm. Length of the operating channel of the sialoendoscope we used was 11.5 cm.

Based on these preliminary requirements we analyzed the commercially available flexible delivery technologies for Erbium lasers [21] which include: Sapphire fibers (Photran Poway, CA), Germanium oxide fibers (Infrared Fiber Systems, Silver Spring, MD), hollow silica waveguides (Polymicro Technologies, Phoenix, AZ) and metal hollow waveguides (Lumenis, Yokneam, Israel). The Sapphire fibers are available in a core-only configuration and would therefore suffer significant losses if surrounded by water. They are also limited in flexibility requiring diameters smaller than 600 microns for a radius of curvature of 15 cm, thus reducing energy damage threshold.

The Germanium oxide fibers are core/clad fibers, are highly flexible but lack the durability required for direct contact with the stone. They are also not biocompatible and are too expensive to be considered for a single use device. Hollow Silica fibers offer the required flexibility but were also found to be too fragile to withstand the impact of lithotripsy in contact with the stone. They are also excessively priced for this application.

We therefore concluded that the best approach would be a metal hollow waveguide since these are extremely durable, inexpensive, biocompatible, and can withstand high energies and powers. Hollow metal waveguides can be produced with low attenuation (<0.5 dB/m) and can be bent to a radius of curvature as low as 5 cm. Hollow waveguides must be hermetically end sealed for use in a water environment since even a small amount of water in the waveguide will
completely attenuate the beam. Silver hollow waveguides of 0.9 mm outer diameter and 0.13 mm wall thickness were prepared with an AgI internal dielectric coating using Croitoru’s single pair technique [22]. 99.9% pure silver tubes with a 20 RMS inner surface finish were used. The tube’s inner surface underwent chemical reaction with a solution of iodine dissolved in ethanol, resulting in a thin dielectric layer of AgI. Coating deposition time and iodine concentrations were adjusted to optimize transmission at around 3 microns. Polished Sapphire rods of 0.63mm diameter and 5 mm length were cemented at the tip of the waveguide using a biocompatible adhesive (Epotek 353 ND). A plano-convex ZnSe lens (II-VI Inc.) was designed to focus the 1 mm output aperture of the OpusDent fiber into our 0.63 mm waveguide which was mounted in a Luer/SMA connector to facilitate quick connection to both the Erbium laser and the sialoendoscope (Fig. 2).

To simulate clinical use, human-extracted salivary stones were tightly placed inside a 3 mm latex tube simulating a salivary duct. The sialoendoscope, connected to an endoscopic video camera, was passed down the latex tube and the fiber delivery system was then inserted into the working channel of the endoscope. Pressurized saline irrigation was connected to the endoscope.

FTIR transmission was measured for the Ag hollow waveguides with and without the Sapphire rod (Equinox 55; Bruker, Optics, Ettlingen, Germany) (See Fig. 3). Temperatures along the waveguide and at the distal end of the fiber probe were measured using a ThermaCam system (SC500, FLIR Systems, Danderyd, Sweden). The complete delivery system was then tested for functionality and durability under the simulated endoscopic conditions, and a comparison, on salivary gland stones, to a Holmium laser lithotripter was conducted. Resistance of the delivery system to autoclave sterilization and chemical disinfection was also tested. Finally, following Helsinki committee approval, human clinical cases were performed.

**RESULTS**

Silver hollow waveguides manufactured were first tested for transmission using the FTIR system (Fig. 3).
Transmission values measured at 2.94 μm were 85% for the 14 cm long probes, with the spectral graph indicating that additional few percent should be achievable with further optimization of the dielectric coating. Considering Fresnel reflection losses on the sapphire surfaces (13.4%) these are close to theoretical values possible.

The waveguides were then connected to the Opusdent system through the optical coupler designed and at these conditions a total transmission of 60% was consistently achieved. These lower transmission values were attributed to the larger numerical aperture of the beam from the laser system and possibly to absorption in the adhesive used to seal the sapphire rod.

In our system the ratio of focusing lens spot size and waveguide’s inner diameter was 0.65, which may also contribute to a small additional transmission loss [23].

The probes were inserted into the bent operating channel of the sialoendoscope but no additional bending losses were measured.

To test the fibers for autoclave sterilization and chemical disinfection, the proximal end of the hollow waveguide was sealed with a polyethylene cap. Several fibers were tested through two cycles of standard autoclave cycles (135°C, 30 min) and three cycles of chemical disinfection (Cidex, Advanced Sterilization Products, Irvine, CA). Fiber transmission was tested before and after the sterilization and disinfection processes and no degradation in transmission was detected.

The endoscopic simulation was used to determine optimal laser parameters, measure lithotripsy rates, and check fiber durability. With the sapphire tip in contact with the stone lithotripsy threshold was determined to be around 80 mJ/pulse (26 J/cm²). Efficient fragmentation, with microscopic fragments which remain suspended in the water, was achieved at an energy range of 150–300 mJ/pulse. Higher energies resulted in larger fragments (up to 0.5 mm) which no longer floated. Most fragmentation was carried out at 10 Hz since at higher repetition rates it was difficult to maintain a clear endoscopic view using the manually operated syringe irrigation system. At this repetition rate, stone fragmentation rates of about 1.8 mm³/second were achieved. A 6 mm stone required 2 minutes for complete fragmentation. With an improved irrigation system higher laser repetition rates and hence faster fragmentation should be achievable.

Following fragmentation of the first stones, front surface damage of the sapphire rod was detected (Fig. 4). This damage did not result in any catastrophic failure but gradually deteriorated total fiber transmission. This damage occurred only during lithotripsy with the stone in contact with the sapphire surface and did not occur when the laser was delivered without a stone in front of the fiber. It was therefore concluded to be surface pitting from stone fragments ejected during lithotripsy. Typical transmission loss was 30% following 5,000 pulses and 50% following 15,000 pulses. No fractures or disconnection of the sapphire rod from the waveguide occurred. It was therefore concluded that fiber durability, particularly if designed for single use, is sufficient to assure patient safety.

To further assure patient safety the temperature along the fiber was checked using the ThermaCam system (FLIR, Danderyd, Sweden) (Fig. 5). Since this system employs wavelengths in the range of 7.5–13 microns this test could only be conducted in air. It was assumed that temperatures with the fiber in the liquid environment can only be lower. With 100 mJ at the fiber output, 10 Hz and 30 seconds of continuous lasing the maximum temperature measured at the fiber tip was 45°C. Temperatures along the fiber were significantly lower.

Finally an ex vivo comparison to a Holmium laser lithotripter (Sharplan, Tel-Aviv, Israel) was performed. The Holmium laser was operated at 1 J/pulse, 10 Hz. Fragments were photographed with a digital camera, X-rayed, and compared to those of the Erbium laser stone fragments.

Holmium laser stone fragments were generally smaller than 1 mm but contrary to the suspended Erbium stone fragments, all sank to the bottom of the test basin indicating larger fragments (Fig. 6). Even when we lowered the Holmium laser energy to be close to the threshold for

![Fig. 4. Front surface damage of the sapphire tip following 5,000 pulses at 150–300 mJ/pulse. Small crater is seen on the right.](image)
fragmentation we still obtained fragments too large to float in the water.

CLINICAL TESTS

Helsinki committee approval was obtained to conduct human clinical trials at the outpatient facility of the Oral & Maxillofacial Department, Barzilai Hospital, Ashkelon, Israel.

The objectives of this open, phase I study were to evaluate the safety and effectiveness of this new endoscopic laser device for fragmentation of salivary stones as well as to evaluate its ease of use by a surgeon experienced in salioendoscopy, in a true clinical setting.

Patients were enrolled for the study based on the following criteria:

Inclusion criteria

1. Over 18 years old.
2. Suffers from “mealtime syndrome”— recurrent painful swelling of the affected salivary gland at meal-times.
3. 1–15 mm diameter stones located in the posterior third of the submandibular or parotid duct.
4. Patient understands and has signed the Informed Consent Form.

Exclusion criteria

1. Acute phase sialadenitis.
2. Patients on anti-coagulants.

Fig. 5. A: ThermaCam image of the fiber. Sapphire tip is marked with a rectangle. B: Maximum temperature versus time (seconds). C: Temperature profile along the fiber tip. [Figure can be viewed in color online via www.interscience.wiley.com.]

Fig. 6. Visual and X-ray images of the fragmented calculi. A: X-ray image of the calculus fragmented with Ho:YAG. A': Visual image of the calculus fragmented with Ho:YAG. B: X-ray image of the calculus fragmented with Er:YAG. B': Visual image of the calculus fragmented with Er:YAG.
3. Patients with cardiac diseases, kidney insufficiency, any malignancy or any steroid therapy.

4. Stones located in the distal third of the main salivary duct which may be removed by simple intra-oral incision.

The trial was conducted from November 2004 to March 2005 on 17 patients, 9 females 8 males, aged 11–72, with salivary stones of 1–15 mm in diameter located in the posterior part of the salivary ducts. Altogether 21 stones located in 18 glands, 16 submandibular and 2 parotid, were involved in the trial. Stone size and location were documented by plain radiographs, sialography, and high-resolution ultrasound prior to the procedure, immediately following the procedure (radiography only) and at 12 weeks post-op (Fig. 7). Videoendoscopy of the procedure (Fig. 8) was recorded and included a post-op view of the lumen in the area. Patients were followed up for lumen patency, symptoms of sialoadenitis, and any potential complications; immediately, at 4 weeks and at 12 weeks post-op.

All procedures were performed under local anesthesia in an ambulatory environment, using standard videosialendoscopy protocol. Under this protocol the orifice of Wharton’s or Stensen’s duct is first identified and a lacrimal probe gently inserted. Papillotomy is preferably performed with a CO₂ laser. Lacrimal dilators from 1 to 3 mm in diameter are then sequentially used for duct dilation. The rigid scope, connected to a video camera and monitor, is introduced with the help of isotonic saline irrigation. The salivary ducts are diagnosed and the stone is located. If no contraindications are detected, the fiber is inserted through the operating channel of the endoscope until its distal end is within the field of view of the endoscope. Actual laser irradiation is performed only under clear vision, when the fiber is seen to be in direct contact with the stone and tangential to the duct. Adequate irrigation is maintained throughout the procedure using an intravenous bag connected to the irrigation port on the sheath of the endoscope.

The fiber was connected to a standard Lumenis Opus 20, dental Erbium laser. Fragmentation usually began at a setting of 150 mJ per pulse and a pulse rate of 10 Hz.

While the initial plan was to attempt full fragmentation on all stones it was soon realized that due to anatomical and operational constraints, such as tortuous ducts or poor visibility, alternative techniques to assist in stone removal can be applied. Consequently three alternative methods were used depending on each individual case: total fragmentation, mostly for stones under 5 mm, creation of a traction point for mini forceps, and separation of surrounding soft tissues in cases of impacted stones.

Of the 21 stones treated 5 were fully fragmented, 7 stones of 5–7 mm were prepared for extraction by mini forceps, and 9 stones with diameters up to 15 mm were released from surrounding soft tissues for subsequent endoscopic or surgical removal.

Fifteen of the 18 treated glands returned to normal function without any symptoms while 2 non-functional glands remained non-functional but were completely asymptomatic.

No other complications have been noted during the 2–12 months follow-up so far.

DISCUSSION
The pulsed, free-running Erbium YAG laser emits a wavelength which coincides with the highest water absorption peak, thus rendering this laser unique char-

![Fig. 7. Pre- (A) and post- (B) operative sialogram showing endoscopic removal of submandibular duct blockage caused by stone (S).](image1)

![Fig. 8. Endoscopic view of salivary stone fragmentation. Sapphire tip (arrow) can be seen in the crater formed in the stone.](image2)
characteristics in a variety of surgical applications. In dermatology it is highly effective for removing thin, superficial sun damaged and aged skin layers [24]; in dentistry it has been accepted as the first “laser drill” capable of painless removal of both enamel and dentin [25]; in ophthalmology it has been shown to be effective in ablating the lens cortex without the heating associated with conventional ultrasonic phacoemulsification [26,27] and in eye surgery it is used for drilling 500–600 micron holes through the stapes bone footplate in a procedure called stapedotomy for the treatment of otosclerosis [28]. In most of these clinical applications the Erbium laser beam is delivered externally to the surgical site, using fibers, hollow waveguides, articulated arms or direct microscope coupling. In the ophthalmic application the beam is delivered into the eye through a fiberoptic microhandpiece based, for example, on a zirconium fluoride fiber connected to a quartz tip [29]. In all these applications the efficacy of the Erbium laser in precisely removing both soft and hard tissues with minimal, if any, surrounding thermal effects has been established yet it is still not implemented endoscopically due to lack of clinically practical delivery capabilities.

Fried [15] reviewed all the commercially available mid-infrared optical fibers and concluded that none of these fibers satisfies all of the criteria for endourologic use, including biocompatibility, chemical/mechanical durability, flexibility, high power transmission, and low cost. To overcome this limitation various research groups attempted to design hybrid fiber configurations. Yang et al. [30] reported on the design of a hybrid Germanium/Silica optical fiber assembly for endoscopic lithotripsy. While this configuration demonstrated a large improvement over the bare Germanium fiber and sufficient capabilities for contact soft tissue ablation through a flexible endoscope, damage thresholds in the range of 180 mJ for a straight, 425 flexible endoscope, damage thresholds in the range of capabilities for contact soft tissue ablation through a fiberoptic microhandpiece based, for example, on a zirconium fluoride fiber connected to a quartz tip [29]. In all these applications the efficiency of the Erbium laser in precisely removing both soft and hard tissues with minimal, if any, surrounding thermal effects has been established yet it is still not implemented endoscopically due to lack of clinically practical delivery capabilities.

From the work of Iwai it seems quite straightforward to replace the quartz sealing cap with a sapphire end-sealing cap, as reported above. Sapphire is a superior window material for this application in many ways. It has extreme surface hardness (Moh hardness 9), high softening point (1,800 C), high internal transmission at 2.94 µm, and high thermal conductivity. More so, it is biocompatible and inexpensive in the window shapes and sizes required. With a flat sapphire sealing cap we were able to effectively increase output energies to above 700 mJ, though in vivo clinical tests indicated optimal fragmentation energy range to be between 200 and 300 mJ per pulse. This corresponds to energy densities of about 65–100 J/cm², somewhat higher than 40 J/cm² found by Iwai to be a reasonable choice for calculus fragmentation.

CONCLUSIONS

The Er:YAG laser endoscopic fiber delivery system described above meets all of the clinical criteria required for lithotripsy as well as soft tissue, wet field, endoscopy through rigid or semi-rigid endoscopes. These capabilities were demonstrated in vivo in lithotripsy of salivary stones. The system has potential applications where ever precise endoscopic incision or ablation of hard or soft, particularly avascular, tissues is desired as long as access can be achieved through a rigid or semi-rigid endoscope. Examples include knee arthroscopy [32], percutaneous lithotripsy of renal stones and lower urinary tract lithotripsy. Further modifications in the metal hollow waveguide, such as use of a flexible metal tube internally coated with silver, may eventually allow delivery of Er:YAG lasers through fully flexible endoscopes for a whole range of clinical applications.

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