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Comparison of Four Lasers ($\lambda = 650, 808, 980, \text{ and } 1075 \text{ nm}$) for Noninvasive Creation of Deep Subsurface Lesions in Tissue

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Abstract

Lasers have been used in combination with applied cooling methods to preserve superficial skin layers (100's μm 's) during cosmetic surgery. Preservation of a thicker tissue surface layer (millimeters) may also allow development of other noninvasive laser procedures. We are exploring noninvasive therapeutic laser applications in urology (e.g. laser vasectomy and laser treatment of female stress urinary incontinence), which require surface tissue preservation on the millimeter scale. In this preliminary study, four lasers were compared for noninvasive creation of deep subsurface thermal lesions. Laser energy from three diode lasers (650, 808, and 980 nm) and a Ytterbium fiber laser (1075 nm) was delivered through a custom built, side-firing, laser probe with integrated cooling. An alcohol-based solution at -5°C was circulated through a flow cell, cooling a sapphire window, which in turn cooled the tissue surface. The probe was placed in contact with porcine liver tissue, *ex vivo*, kept hydrated in saline and maintained at $\sim 35^\circ\text{C}$. Incident laser power was 4.2 W, spot diameter was 5.3 mm, and treatment time was 60 s. The optimal laser wavelength tested for creation of deep subsurface thermal lesions during contact cooling of tissues was 1075 nm, which preserved a surface layer of $\sim 2 \text{ mm}$. The Ytterbium fiber laser provides a compact, low maintenance, and high power alternative laser source to the Neodymium:YAG laser for noninvasive thermal therapy.

Keywords

ablation; infrared; lesions; subsurface; thermal

1. INTRODUCTION

Active cooling methods are currently used in dermatology to preserve the skin surface during cosmetic laser procedures, including skin resurfacing, hair removal, and treatment of vascular birthmarks. These technologies include both contact cooling (e.g. cold water, sapphire window) and non-contact cooling (e.g. cold air, cryogen spray). In dermatology, the tissue structures of interest for laser therapy are usually superficial, requiring preservation of only a thin layer of tissue (e.g. epidermis and papillary dermis), measuring about 200–400 μm .

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The ability to preserve the tissue surface to a depth on the order of a few millimeters during laser therapy may result in development of noninvasive laser procedures beyond cosmetic surgery. Our laboratory has previously demonstrated creation of deep subsurface thermal lesions in a variety of tissues using both non-contact and contact cooling techniques [1,2], with the ultimate goal of developing new noninvasive laser therapies in urology. Several applications of potential interest in urology that may benefit from this approach include treatment of female stress urinary incontinence and male sterilization [3]. The objective of this study was to compare four lasers spanning the optical window in the visible to near-infrared spectrum for noninvasive creation of deep subsurface thermal lesions.

2. METHODS

2.1 Laser Parameters

Four lasers were compared (Figure 1), including a 7 W, 650 nm diode laser (Modulight, Finland), 30 W, 808 nm laser (Apollo Instruments, Irvine, CA), 50 W, 980 nm diode laser (Edwards Life Sciences, Irvine, CA), and 50-W Ytterbium fiber laser (IPG Photonics, Oxford, MA). Laser energy was coupled into a custom-made laser probe using a 100-mm-FL lens and a 600- μm -core, 0.39 NA fiber optic patch-cord (M29L05, Thorlabs, Newton, NJ). The probe was assembled using lens tubes with 12.7-mm-ID, housing the optics, including a lens for collimating laser beam and mirror for 90° delivery. The comparative wavelength study was limited by power output through probe for 650 nm laser. An incident laser power of 4.2 W and 5.3 mm spot diameter (19.0 W/cm²) was used for all four lasers. Laser power was calibrated using a power meter (EPM2000, Molelectron, Portland, OR). The Gaussian laser beam was measured using an IR beam analyzer (Pyrocam III, Spiricon, Logan, UT) and razor blade scan (Figure 2).

2.2. Cooling Probe

The cooling element of the laser probe consisted of a recirculating chiller (T255P-D5, Thermotek, Carrollton, TX). A coolant (25% ethylene alcohol / 75% water by volume) flowed at a rate of 12.7 ml/sec through the flow cell and allowed the chiller to operate at -5°C. The custom-built flow cell consisted of aluminum housing with a sapphire plate mounted at its surface (Figure 3). Coolant flowed through a circular channel around the circumference of the flow cell, while an 8-mm-diameter aperture in the center of the flow cell provided a window for transmission of the laser energy through the transparent sapphire plate. The sapphire plate temperature measured -2°C, and provided a thermally conductive medium for contact cooling of the tissue surface. A hot plate maintained the tissue temperature at approximately normal body temperature (~35°C) as monitored by a microthermocouple.

2.3 Tissue Preparation

Liver tissue was chosen for these preliminary experiments because gross thermal lesions in liver are easily observed immediately after the procedure. Fresh samples of porcine liver tissue were obtained from a slaughterhouse (Animal Technologies, Tyler, TX), refrigerated, and then used within 24 hours. Tissue samples were cut into similar cylindrical dimensions (5.4 cm diameter by 2.5 cm thickness) using a cookie cutter mold, and then placed in an

aluminum dish on the hotplate (Figure 3). The tissue was bathed in physiological saline to keep it hydrated during the procedure.

2.4 Statistical Analysis

After the procedure, gross and histologic examination were used to measure liver lesions. Lesion dimensions and thickness of preserved surface tissue layer were measured, with mean $\pm$ standard deviation (S.D.) recorded.

3. RESULTS

Table 1 summarizes the thermal lesion dimensions with four lasers studied. For the 650 nm wavelength, no surface tissue was preserved, while for the 808 and 980 nm wavelengths only a small tissue layer of $\sim 300\ \mu\text{m}$ was preserved. No lesions were observed for the 1075 nm wavelength at 4.2 W, presumably due to the significantly deeper optical penetration depth at this wavelength. Therefore, a small power escalation study was conducted, until an optimal result of $\sim 2\ \text{mm}$ of tissue was preserved above the thermal lesion, at an incident laser power of 5.2 W for 60 s. Further power escalation studies using 7.2 W for 15 s yielded similar results, so shorter procedure times are feasible (Figure 4).

4. DISCUSSION

The majority of therapies utilizing lasers in conjunction with applied cooling techniques preserve a thin layer (200–400 μm) of tissue during cosmetic dermatological laser procedures. However, the ability to preserve a thicker tissue layer (several mm's) by optimization of laser/cooling parameters may lead to new noninvasive laser applications in other surgical fields as well. For example, in urology, development of a noninvasive laser vasectomy preserving the scrotal skin ($\sim 1\ \text{mm}$ thick) may eliminate fear of bleeding, pain, and infection associated with conventional nascalpel vasectomy. Also, endoscopic laser treatment of female stress urinary incontinence which preserves the vaginal mucosa (2–3 mm thick) during thermal remodeling of the endopelvic fascia may be less invasive than current conventional surgical sling and RF procedures.

Four lasers spanning the optical window in the visible to near-IR spectrum were tested for producing deep subsurface thermal lesions in porcine liver tissue, ex vivo. The surface tissue was not preserved at the 650 nm wavelength, and preserved tissue layers for the 808 and 980 nm wavelengths were superficial. Only the 1075 nm wavelength preserved a thick tissue surface layer of $\sim 2\ \text{mm}$. These results are consistent with other previous reports which measured the optical properties of liver tissue in the visible and near-infrared spectrum for potential photodynamic therapy (PDT) and laser interstitial thermal therapy (LITT) applications [4–6]. However, this study provides a comprehensive wavelength comparison for deep subsurface thermal lesion generation in tissues using red and near-IR lasers in combination with contact cooling methods.

5. CONCLUSIONS

The optimal laser wavelength tested for creation of deep subsurface thermal lesions during contact cooling of tissues was 1075 nm, which preserved a surface layer of ~2 mm. The Ytterbium fiber laser provides a compact, low maintenance, and high power alternative laser source to the conventional Neodymium:YAG laser for noninvasive thermal therapy.

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Figure 1. Images of the four compact, tabletop lasers used in this study. (a) 650 nm, 7 W diode laser; (b) 808 nm, 30 W diode laser; (c) 980 nm, 50 W diode laser; (d) 1075 nm, 50 W Ytterbium fiber laser.

Figure 2.

Spatial beam profiles for lasers measured using a razor blade scan. (a) 650 nm; (b) 808 nm; (c) 980 nm; (d) 1075 nm.

Figure 3.

- (a) Experimental setup showing probe, hot plate, thermocouple system and tissue sample;
(b) Close-up view of laser probe, including flow cell, and coolant tubes. An optical fiber (not shown here) connected the laser to the probe.

Figure 4.

Representative gross images of thermal lesions produced in liver tissue, ex vivo, using 650, 808, 980, and 1075 nm lasers. The 1075 nm laser images are shown for optimized laser parameters during power escalation studies (7.2 W, 15 s).

Table 1.

Comparison of lesion dimensions for four laser wavelengths tested ($P = 4.2$ W, Spot = 5.3 mm, $t = 60$ s).

Lesion Characteristics	650 nm	808 nm	980 nm	1075 nm *
Preserved Surface Tissue Layer (mm):	0.0 ± 0.0	0.3 ± 0.2	0.3 ± 0.3	1.9 ± 0.5
Lesion Width (mm):	5.3 ± 0.2	3.9 ± 0.6	4.4 ± 0.3	3.0 ± 0.3
Lesion Depth (mm):	2.9 ± 0.5	2.3 ± 0.4	3.7 ± 0.6	2.5 ± 0.2
Lesion Area (mm ²):	12.2 ± 2.7	7.3 ± 1.9	12.9 ± 2.2	6.0 ± 1.0
Sample size (N):	8	6	8	5

* The 1075 nm wavelength results were for an incident laser power of 5.2 W for 60 s during power escalation studies.