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Pulsed Ho:YAG Laser Meniscectomy: Effect of Pulsewidth on Tissue Penetration Rate and Lateral Thermal Damage

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Background and Objective: Studies need to define the optimal parameters under which the holmium laser should operate for arthroscopic meniscectomy. This study was designed to analyze the effect of various Holmium wavelength pulsewidths on human meniscal tissue penetration rates and lateral thermal injury.
Study Design/Materials and Methods: Using a pulsed Holmium: YAG laser at a wavelength of 2.1 μm, the effect of various pulsewidths on tissue penetration rates as well as the degree of accompanying thermal damage in human meniscal tissue was evaluated in a specially designed jig. Holding the energy constant at 500 mJ per pulse, the pulsewidth was varied between 100 and 600 microseconds.
Results: Fiber penetration of meniscal tissue was found to be fastest at a pulsewidth of 250 microseconds. As the pulsewidth was increased or decreased around this number, the observed penetration time decreased, although no statistical difference was found. The size of the hole created was inversely related to the penetration time. Microscopic examination revealed zones of lateral thermal effect extending 800 μm from the ablation site.
Conclusion: No relationship between the pulsewidth and the lateral thermal effect could be found.

Key words: lateral thermal damage, meniscectomy, tissue penetration rate

INTRODUCTION

As technology improves, the range of clinical indications for lasers in orthopedics will continue to expand. One such area that has recently received a great deal of investigative inquiry is arthroscopic knee surgery. Lasers in arthroscopy have many potential advantages over conventional surgical methods. These include decreased iatrogenic trauma to articular cartilage caused by the use of cumbersome tools in the confined joint space, greater accessibility to difficult-to-reach areas, ability to coagulate and resect with one single instrument, less risk of instrument breakage, and improved contouring of the meniscal rim [6,8,10].

The best wavelength for partial meniscectomy is controversial. Between 1985 and 1988, Smith et al. [6] performed a clinical investigation using the CO_2 laser (10,660 μm) in arthroscopic knee surgeries. This led to its declaration as safe and effective by the FDA when used arthroscopically in the knee. Although the laser is capable of precision cutting with a minimal zone of tissue alteration, its major clinical limitation was the lack of fiber optic use. Arthroscopic use of CO_2 laser energy usually requires the cumbersome

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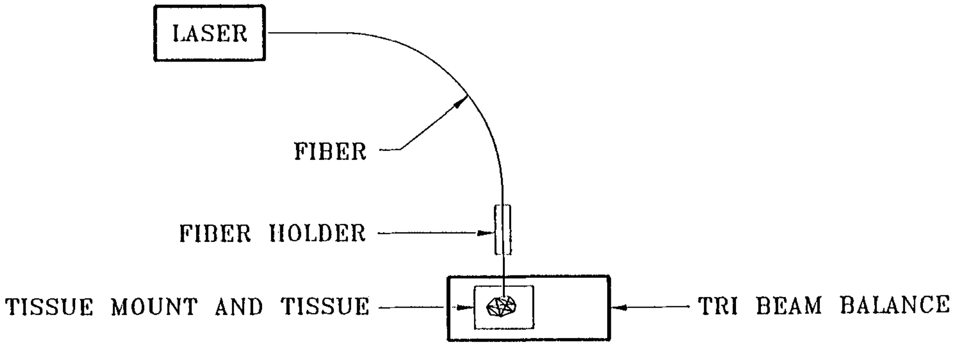

Fig.1. Fixture setup demonstrating penetration rate.

use of gas or air in the joint as opposed to the conventional wet environment [3,6].

The Nd:YAG (1.064 μm) was the next laser to be granted FDA approval for use in arthroscopy. In a preliminary study, Glick [4] found that the Nd:YAG laser was poorly absorbed by fibrocartilage and that the distance of lateral thermal effect was considerable. Miller et al. [5] have shown that the Nd:YAG laser, with an arthroscopic contact handpiece, can eliminate the previously reported problems. The major drawback to the use of this contact laser system is breakage of the tip and its limited life expectancy.

The clinical holmium laser (2,100 μm) has appeared recently with the FDA granting clearance for its use in arthroscopic surgery within the last 2 years. The main attraction of the holmium laser is its ability to cut and vaporize soft tissue like a CO_2 laser, with the added advantage of fiberoptic delivery in a fluid environment. Surgical precision and control are obtained with a bare optical fiber in a curved handpiece without the need for a sculpted fiber, sapphire, or quartz contact tip. These features make the Ho:YAG laser a useful tool in arthroscopic surgery.

Studies need to define the optimal parameters under which the Holmium laser should operate for arthroscopic meniscectomy. This study was designed to analyze the effect of various Holmium wavelength pulsewidths on human meniscal tissue penetration rates and lateral thermal injury.

MATERIALS AND METHODS

Fifteen fresh human menisci were obtained from a local tissue bank and immediately frozen. The menisci ranged from 19 to 68 years of age (mean 42 years of age). All specimens were warmed to room temperature in normal saline and sagittally cut into 10–12 pie-shape pieces of approximately equal 3–4 mm thickness. The tissue sample thickness was measured between two microscopic slides using a digital micrometer (accuracy ± 10 μm). For testing, all meniscal samples were placed in a specially designed fixture (Fig. 1), which controlled fiber alignment and applied force (10g). Samples were secured by pins, immersed in room temperature saline, and laser energy was delivered with the fiber perpendicular and in contact with the meniscal tissue section.

A pulsed Ho:YAG laser system (Trimedyne, Tustin, CA) with a 600-μm fiber was used in the free running mode. Keeping the frequency (5 Hz) and energy delivered constant (500 mJ), the pulsewidth was varied from 100 μs to 600 μs. The pulse-to-pulse energy variation was $< 5\%$. The energy fluence was held constant at 1,768 mJ/mm^2 (179 J/cm^2). Ten samples were evaluated at each pulsewidth. The time taken for tissue penetration by the laser fiber was recorded for each specimen.

Following laser exposure the hole diameter and distal crater diameter were measured by light microscopy (Zeiss, model 80). The tissue was fixed in 10% formalin, embedded in paraffin, sectioned parallel to the laser hole, and stained for histological examination using hematoxylin and eosin (H & E). The lateral thermal effect was quantified and the average ablation rate and rate of tissue penetration were calculated for each pulsewidth.

RESULTS

The observed penetration rates for all pulsewidths tested ranged from 83.3 to 105.7 μm/pulse (Table 1). The mean penetration rate for all sam-

TABLE 1. Statistical Results of Laser Penetration at Various Pulsewidths

Pulsewidth	Sample size	Mean penetration rate	Standard deviation	Sample variance	Mean hole diameter	Mean crater diameter	Mean lateral thermal damage
100	10	83.34	17.0	288.9	343	972	867
200	10	91.3	30.88	953.6	318	910	876
250	10	105.67	31.5	992.0	317	921	778
300	10	93.95	25.15	632.8	345	928	757
350	10	90.38	19.38	375.7	397	1014	810
400	10	85.66	24.61	605.9	400	973	803
500	10	89.1	34.64	1199.8	410	997	703
600	10	84.72	13.74	188.8	414	987	790

ples tested was 90.5 μm/pulse. Fiber penetration of meniscal tissue was found to be fastest (105.7 μm/pulse) at a pulsewidth of 250 microseconds, although this result was not statistically significant ($P > 0.05$) by analysis of variance (Fig. 2).

On gross examination, the laser created a cavity at the point of entry and exit from the tissue. Thermal change in the tissue of the crater was noted by a change in color from white to a yellow-brown color (Fig. 3). Hole size averaged 368 μm and crater size averaged 965 μm. The size of the channel created by the laser was inversely related to the penetration rate with the smallest size channel corresponding to the fastest rate of penetration, although these differences were not statistically significant.

With H & E stain, the thermal tissue change was characterized by disruption of collagen fibers and intense basophilic staining. There was an area of necrosis (<75 μm) at the laser tissue interface with a nonspecific extended area of thermal tissue alteration extending 800 μm from the ablation site (Fig. 4). No relationship between the pulsewidth and the lateral thermal effect was found.

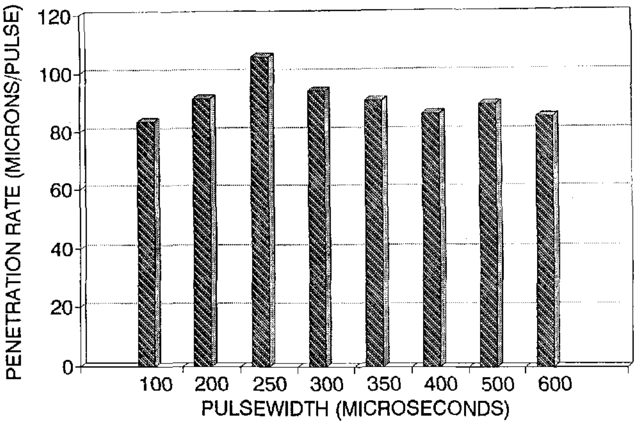

Fig. 2. Histogram of penetration rates vs. different pulse widths (0.5 J/pulse @ 5 Hz).

DISCUSSION

The use of controlled laser energy for photoablation in arthroscopic surgery of the knee has been intensively investigated in recent years. The two most extensively studied systems to date are the CO_2 laser and the Nd:YAG laser.

Since the initial work completed by Whipple et al. [8,9], then Smith et al. [6], the CO_2 laser system's popularity has decreased. One disadvantage to this laser's wavelength is the high absorption by water. To combat this, a gas or air arthroscopy medium rather than the conventional wet environment is desired.

The Nd:YAG system is absorbed much less by water than the CO_2 and can be used via a flexible fiber optic system during the conventional arthroscopic surgery. The Nd:YAG contact laser allows tactile feedback within the joint. The major drawback with this system in clinical use is breakage of the laser tips and the limited life of the probe.

The Ho:YAG laser's only recent attention in the field of orthopedics relates to the simple free beam "near contact" fiberoptic delivery system. The handpiece permits easy excision of intra-articular tissues. As laboratory and clinical trials illustrate the efficacy of this laser system for resection of meniscal tissue, there is a strong need to define the optimal parameters and the tissue effects of this laser.

The Holmium laser systems have been factory set at different pulsewidths ranging from 250

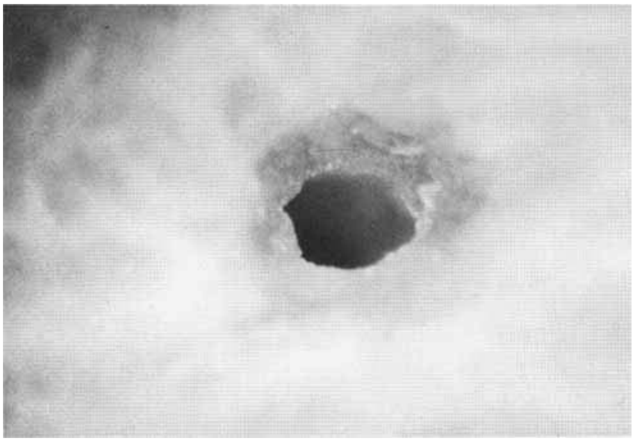

Fig. 3. Thermal change in tissue adjacent to laser hole.

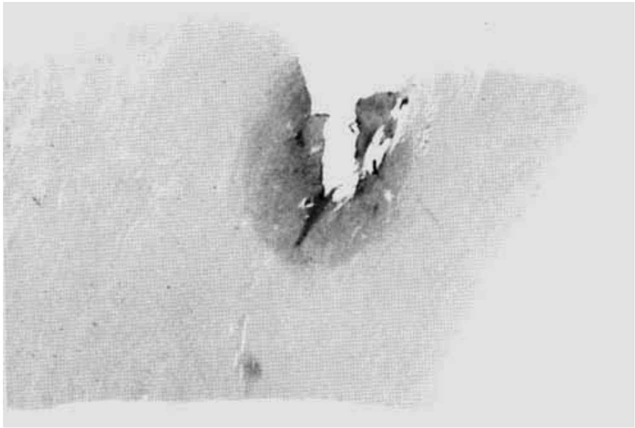

Fig. 4. Hematoxylin and eosin stain of thermal change in meniscal tissue.

μs to 350 μs. No scientific evidence is available to support using one specific pulsewidth for meniscectomy over another. This study showed a pulsewidth of 250 μm appeared to cut more quickly than the other pulsewidths, although quantitative measurements of ablation and penetration rates at other pulsewidths showed no statistically significant differences. This was consistent with the findings of Vari et al. [11] on bone tissue.

This study confirmed previous reports [7,10] showing the pulsed Ho:YAG laser delivered through a small diameter quartz fiber can quickly and effectively ablate human meniscal tissue with minimal thermal damage to the remaining meniscus. Unlike visible wavelength lasers, photothermal interactions with the holmium laser do not rely on hemoglobin or other tissue pigments for efficient heating of tissue. The water component of tissue is responsible for absorbing the 1,200 nm laser energy and converting it into heat [1]. The thermal relaxation time constant of hydrated tissue is ~ 150 milliseconds [2]. The pulsewidths studied varied from 100 to 600 microseconds, which was 250 times shorter at the longest pulsewidth (600 microseconds) than the thermal relaxation time constant for hydrated tissue. This allows tissue cooling to near baseline temperatures between pulses. The shortness of the delivered pulses in relation to the thermal relaxation time constant of tissue was responsible for the lack of difference in the degree of thermal damage imparted to the tissue. To see a difference in the degree of thermal damage, one would have to experiment with pulsewidths that are close to the thermal diffusion time constants of the tissue.

This study did not investigate the effect of repetition rate. If the pulses of laser energy delivered to the tissue, however short, were delivered at a high enough repetition rate to prohibit the tissue to cool to baseline temperatures in between pulses, one would encounter the phenomenon called thermal super position. This occurs when the tissue retains residual heat from prior pulses and accumulates heat causing greater thermal damage to the tissue. Two independent and mutually exclusive parameters must be controlled when deciding on clinical laser energy delivery. One is to keep the pulsewidth much shorter than the thermal relaxation time constant of the tissue (preferably 1/10th or less). The other is to keep the repetition rate low enough to maintain on interpulse period longer than the thermal relaxation time constant of the tissue. By keeping these two parameters under control, one can minimize the thermal injury imparted to the surrounding tissue.

This study's findings on the lateral thermal change using the Ho:YAG laser were higher than those reported by Trauner et al. [7] on porcine meniscal tissue and consistent with those reported by Vangsness et al. [10] on human tissue. Whether or not the observed lateral thermal tissue change is reversible through tissue repair mechanisms in the weeks following the initial insult is an area for subsequent study.

Although relatively new to the field of orthopedics, the Holmium laser is rapidly gaining support for its use in arthroscopic meniscectomy as well as other applications. The advantages of the Ho:YAG laser are its handheld flexible fiberoptic delivery system and its use in aqueous media. Clinical studies need to further define the efficacy of the Holmium laser for use in arthroscopic surgery. Future work needs to address the effects of different delivery rates and power densities of the Ho:YAG on meniscal tissue ablation and penetration rates.

In summary, we have shown that the Ho:YAG laser (2,100 nm) can quickly and precisely ablate meniscal tissue and that the rate of penetration is not dependent upon the laser's pulsewidth. Furthermore, lateral thermal change is minimal and showed no relation to these tested pulsewidths. The Holmium laser presently has design features that make it the current laser of choice for arthroscopic meniscectomy.

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