Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2016 February ; 9689: . doi:10.1117/12.2208126.

Laser Treatment of Female Stress Urinary Incontinence: Optical, Thermal, and Tissue Damage Simulations

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Abstract

Treatment of female stress urinary incontinence (SUI) by laser thermal remodeling of subsurface tissues is studied. Light transport, heat transfer, and thermal damage simulations were performed for transvaginal and transurethral methods. Monte Carlo (MC) provided absorbed photon distributions in tissue layers (vaginal wall, endopelvic fascia, urethral wall). Optical properties (n, μ_a, μ_s, g) were assigned to each tissue at $\lambda=1064$ nm. A 5-mm-diameter laser beam and power of 5 W for 15 s was used, based on previous experiments. MC output was converted into absorbed energy, serving as input for ANSYS finite element heat transfer simulations of tissue temperatures over time. Convective heat transfer was simulated with contact cooling probe set at 0 °C. Thermal properties (κ, c, ρ) were assigned to each tissue layer. MATLAB code was used for Arrhenius integral thermal damage calculations. A temperature matrix was constructed from ANSYS output, and finite sum was incorporated to approximate Arrhenius integral calculations. Tissue damage properties (E_a, A) were used to compute Arrhenius sums. For the transvaginal approach, 37% of energy was absorbed in endopelvic fascia layer with 0.8% deposited beyond it. Peak temperature was 71°C, treatment zone was 0.8-mm-diameter, and almost all of 2.7-mm-thick vaginal wall was preserved. For transurethral approach, 18% energy was absorbed in endopelvic fascia with 0.3% deposited beyond it. Peak temperature was 80°C, treatment zone was 2.0-mm-diameter, and only 0.6 mm of 2.4-mm-thick urethral wall was preserved. A transvaginal approach is more feasible than transurethral approach for laser treatment of SUI.

Keywords

coagulation; incontinence; laser; Monte Carlo; simulations; thermal remodeling

1. INTRODUCTION

1.1 Female SUI and Conventional Treatments

Over 6.5 million women in U.S. suffer from stress urinary incontinence (SUI) [1]. Only ~200,000 women (3%) have surgery (e.g. Burch open colposuspension, sub-urethral sling, urethral bulking agents) [2]. The need for general anesthesia, long recovery time, incisions,

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potential treatment failures with future pregnancy, and procedural morbidity are reasons for patient hesitation to have surgery. The remaining 97% of women use disposable absorbable products to cope with symptoms [3]. There is a role for a non-surgical method which improves patient quality of life if treatment is rapidly performed, has minimal morbidity, and short recovery. Non-surgical treatments (e.g. Kegel exercises, biofeedback, pelvic floor stimulation) are limited by burdensome compliance and treatment requirements and issues of efficacy and durability. Most patients do not select any nonpalliative treatment. For most incontinent women, treatment selection is driven by desire for minimally invasive therapy, and expectation is improvement in quality of life, with few patients expecting a cure. Patients would prefer minimally invasive therapy which safely improves their quality of life rather than more invasive treatment even if it has high probability of cure.

1.2 Alternative Radiofrequency Thermal Treatment of Female SUI

Radiofrequency (RF) energy has been used for transurethral thermal shrinkage and micro-remodeling of submucosal collagen in bladder neck and proximal urethra, with success rates up to 80% [4,5]. The ability of RF micro-remodeling to improve patient quality of life is proven. However, RF heating is limited by a rapid, $1/r^4$ decay, in penetration depth. Current RF devices require needles inserted into submucosal tissue for thermal remodeling, and saline irrigation for cooling of vaginal mucosa. Thus, RF therapy is more invasive than desired by SUI patients.

1.3 Laser Treatment of Female SUI

Lasers have been used for sub-ablative rejuvenation of atrophic vaginal tissue in post menopausal women, and for treatment of female SUI [6–8]. Short-term studies appear most promising for vaginal rejuvenation, but also show improvements for SUI. However, the laser wavelengths (2.94 and 10.6 μm) are limited to an optical penetration depth of only 10's μm 's and thermal treatment zone < 0.5 mm. Furthermore, vaginal mucosa is not primarily collagen. Therefore, we hypothesize that subsurface laser thermal remodeling specifically targeting endopelvic fascia may produce improved thermal tissue remodeling results for SUI compared to treatment of the vaginal wall.

Preliminary studies in our laboratory have showed that subsurface thermal denaturation of a variety of tissues can be achieved using a deeply penetrating laser wavelength and applied cooling, while preserving up to 1–2 mm of tissue surface from thermal necrosis [9,10]. Thus, vaginal mucosa may potentially be preserved while submucosal tissue is thermally remodeled, using an endoscopic laser probe with cooling for minimally invasive treatment of SUI. For SUI treatment, the goal is to thermally remodel and tighten endopelvic fascia without damaging adjacent tissue layers (e.g. urethra or vaginal wall). The thickness of the vaginal wall, endopelvic fascia, and urethral wall measure about 2.7, 4.3, and 2.4 mm, respectively [11,12]. Therefore, the objective of our computer simulations is to determine whether a “transvaginal” approach can preserve the vaginal wall while treating the endopelvic fascia, or alternatively, whether a “transurethral” approach can preserve the urethral wall while treating the endopelvic fascia.

2. METHODS

2.1 Monte Carlo Light Transport Simulations

A Monte Carlo (MC) program was adapted to simulate distribution of photons absorbed in the tissue layers [13]. One million photons were used to achieve sufficient distribution of photons in tissue with each simulation taking ~ 10 min. A previously reported convolution program was used to fit results to an actual laser beam of known power, profile, and beam diameter [14]. A complete set of values for tissue layer optical properties, including refractive index (n), absorption coefficient (μ_a), scattering coefficient (μ_s), and anisotropy factor (g), was compiled from the literature (Table 1) based on the Nd:YAG laser wavelength used in our previous experimental results.

2.2 Heat Transfer Simulations

Temperature simulations were conducted using finite element software (ANSYS 14.5). A heat transfer model was imported from MC model dimensions with mesh of 350×350 elements ($28.5 \times 28.5 \mu\text{m}$). Tissue layers were represented in the mesh using thermal properties (Table 1). Absorption data from MC simulations was convolved and converted into input of heat transfer model to simulate heat created by laser irradiation. The initial tissue temperature was 35°C (308 K) with contact probe cooling temperature set to 0°C (273 K).

2.3 Arrhenius Integral Thermal Damage Simulations

A standard Arrhenius integral model was employed to predict and characterize thermal injury using known values from the literature. A single damage parameter, $\Omega(t)$, quantified thermal damage to the tissue (Eq. 1):

$$\Omega(t) = A \int_0^{\tau} \exp\left(-\frac{E_a}{RT(t)}\right) dt \quad (\text{Eq. 1})$$

$$\text{Damage} (\%) = 100 (1 - \exp(-\Omega(t))) \quad (\text{Eq. 2})$$

In Eq. 1, A (s^{-1}) is frequency factor determined by experimentally derived constant; τ (s) is total heating time; E_a (J/mol) is activation energy of transformation, also an experimentally derived constant (Table 1), R (8.32 J/K mol) is universal gas constant, and $T(t)$ is absolute temperature of tissue in Kelvin. From Eq. 1, damage probability can also be expressed as % damage (Eq. 2). Damage probability is 0% when $\Omega(t) = 0$, and at 63.2%, $\Omega(t) = 1$. Damage rate increases exponentially when temperature exceeds T_{crit} . Both Ω and Damage (%) were computed for the tissues.

Monte Carlo, heat transfer, and thermal damage simulations were conducted to compute thermal damage based on optical, thermal and damage parameters for the tissues (Table 1).

Due to limited availability of damage parameter data, vaginal wall was modeled as smooth muscle, endopelvic fascia as collagen, and urethra as aorta tissue.

3. RESULTS

3.1 Transvaginal Approach

During Phase 1, MC simulations predicted that the majority of energy (62%) is absorbed by the vaginal wall, 37% of energy is absorbed in the endopelvic fascia, and 0.8% of energy is deposited in the urethral wall beyond (Figure 1).

During Phase 2 (heat transfer simulations), 15 s of pre-cooling at 0 °C was applied to the tissue model prior to laser irradiation at 5.0 W for 15 s. After 15 s of laser irradiation, the internal tissue temperature in the simulation reached 71°C (344°K) at the boundary between vaginal wall and endopelvic fascia (Figure 2). Therefore, applied cooling of tissue surface is critical for transvaginal treatment of SUI. After laser irradiation, laser probe was removed and 15 s of post-operative tissue cooling was performed with temperature decreasing to 42.8°C (316°K).

In Phase 3 (tissue damage simulations), temperature data was converted into % tissue damage using the Arrhenius integral. The treatment zone is 0.8-mm-diameter, and a 2.4-mm-thick surface tissue layer, with almost entire (2.7 mm) vaginal mucosa is preserved (Figure 3).

3.2 Transurethral Approach

The transurethral approach was also simulated, where laser irradiation propagated from the urethra to endopelvic fascia and then to the vaginal wall in reverse order from the previous transvaginal approach. The laser parameters used were also 5 W for 15 s. For this approach, 82% of energy is absorbed in urethral wall, only 18% energy is absorbed in endopelvic fascia, and 0.3% deposited in the vaginal wall beyond it (Figure 4). The peak temperature reaches 80 °C in the urethra, and only 0.5 mm of surface tissue out of entire 2.4-mm-thick urethral wall is preserved (Figure 5).

4. DISCUSSION

The transurethral approach to laser treatment of female SUI was sub-optimal. Even with ideal parameters, including probe cooled to 0 °C and 5 mm diameter laser spot, thermal damage to the urethral wall still occurred. Such parameters are not realistic due to size limitations (< 6 mm-OD) of the endoscopic probe for urethral insertion. Thus, experimental results may be even worse than simulations predict. The coolant setting of 0 °C in the simulations is also overly optimistic compared to 7 °C achieved during our previous experiments with other tissues.

Simulations for transvaginal approach predicted that the vaginal wall is preserved, due to deeper light penetration (and deposition of energy in endopelvic fascia layer), and applied cooling of the vaginal wall. A transvaginal approach also allows use of a larger endoscopic probe capable of achieving a laser spot diameter and coolant temperatures simulated here.

Recently, a transvaginal approach with ruler markings for precise insertion and rotation of endoscopic probe has been utilized for laser vaginal resurfacing and SUI clinical applications, so this approach is feasible [8].

5. CONCLUSIONS

Computer simulations suggest that a transvaginal laser based approach to thermal remodeling of endopelvic fascia and minimally invasive treatment of female stress urinary incontinence is more feasible than transurethral approach.

Acknowledgments

This research was supported by NIH (1R15DK099774). C.-H. Chang received travel grants from SPIE and CBES at UNC-Charlotte. Luke Hardy received a travel grant from McKay Dept. of Urology at Carolinas Medical Center.

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Figure 1. MC simulations for transvaginal approach: (A) 2D spatial output of MC simulation of photon distribution; (B) 1D spatial absorbed energy distribution along central axis of laser radiation.

Figure 2.

Heat transfer simulations for transvaginal approach: (A) 2D temperature distribution (depth x width) after 15 s laser irradiation; (B) 2D temperature distribution after 15 s postoperative cooling time period.

Figure 3.

Arrhenius integral output showing thermal damage plotted as (A) % damage and (B) damage parameter, Ω . Almost entire 2.7-mm-thick vaginal wall is preserved using a transvaginal approach.

Figure 4. MC simulations for transurethral approach: (A) 2D spatial output of MC simulation of photon distribution; (B) 1D spatial absorbed energy distribution along central axis of laser radiation.

Figure 5.

(A) Temperature distribution after laser irradiation for 15 s; (B) Arrhenius integral output showing undesirable damage to urethra. Only 0.5 mm of 2.4-mm-thick urethral wall is preserved from thermal damage during transurethral approach.

Table 1

Optical, thermal, and damage parameters for computer simulations of transvaginal and transurethral laser therapy. A laser wavelength of 1064 nm, incident power of 5.0 W, spot diameter of 5.0 mm, and irradiation time of 15 s was used.

Optical Properties (Phase 1: Monte Carlo)	Vaginal Wall	Endopelvic Fascia	Urethral Wall
Absorption coefficient (μ_a) cm^{-1}	0.43	0.35	0.5
Scattering coefficient (μ_s) cm^{-1}	21.6	484	239
Anisotropy Factor (g)	0.9	0.9	0.9
Index of Refraction (n)	1.38	1.39	1.39
Tissue Thickness (mm)	2.7	4.3	2.4
References	[11,12,17]	[11,12,15,18]	[11,12,16]
Thermal Properties (Phase 2: Heat Transfer)	Vaginal Wall	Endopelvic Fascia	Urethral Wall
Thermal Conductivity (κ) W/m-k	0.54	0.47	0.46
Specific Heat (c) J/kg-k	3655	3200	3306
Density (ρ) kg/m^3	1088	1085	1102
References	[15]	[15]	[19]
Damage Parameters (Phase 3: Damage Integral)	Vaginal Wall	Endopelvic Fascia	Urethral Wall
Frequency factor (A) s^{-1}	5.73×10^{34}	1.61×10^{45}	5.60×10^{63}
Activation energy (E_a) J/mol	2.40×10^5	3.06×10^5	4.30×10^5
T_{crit} ($^{\circ}\text{C}$)	88.0	80.4	78.9
References	[15]	[15]	[15]