Analysis of radiation parameters to control the effects of Nd:YAG laser surgery on gastric malignancies

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ABSTRACT

Endoscopic laser surgery provides an advantageous alternative to Argon Plasma Coagulation, endoscopic tweezers or electro-ablation in gastroenterology that facilitates a selective ablation of stomach tumors with an additional hemostatic effect in the surrounding tissue. This coagulation effect can also be employed for the treatment of gastric ulcers. It is mandatory to control the laser parameters regardless of the desired effect, either cancerous tissue ablation or coagulation to prevent ulcerous bleeding, in order to avoid stomach wall perforation or an insufficient therapeutic outcome. Dosimetric models constitute an attractive tool to determine the proper light dose in order to offer a customized therapy planning that optimizes the treatment results. In this work, a model for Nd:YAG laser surgery is applied to predict both the coagulation zone in gastric ulcers and the removal in adenocarcinomas under different laser setups. Results show clear differences in the effective zone of the gastric malignancy affected by both coagulation and ablation. Therefore the current model could be employed in the clinical practice to plan the optimal laser beam parameters to treat a certain type of pathologic stomach tissue with variable morphology and without risk of perforation or undertreated parts.
Keywords: laser surgery, ablation, coagulation, adenocarcinoma, gastric ulcer

1. INTRODUCTION

Incidence and mortality data in gastric malignancies provided by the National Cancer Institute (National Institutes of Health) estimates a total of 22220 new cases of stomach cancer and 10990 deaths in the United States during 2014. The epidemiologic study reveals that adenocarcinoma accounts for 90% to 95% of all gastric malignancies [1]. As an alternative to Argon Plasma Coagulation, endoscopic tweezers or electro-ablation, which are routinely employed in the Marqués de Valdecilla University Hospital (Spain), endoscopic laser surgery facilitates a selective ablation of this type of tumors with an additional hemostatic effect in the surrounding tissue. This coagulation effect can be also employed for the treatment of gastric ulcers. Triggering the desired effect in the target zone avoiding an undesired stomach wall perforation will strongly depend on the type of tissue and laser energy deposition. For this purpose, dosimetric models constitute an attractive tool to determine the proper light dose to treat a certain amount of tissue or, in other words, to plan a customized surgery that yields a good therapeutic outcome [2]. In this work, a model for Nd:YAG laser surgery is applied to predict both the coagulation zone in gastric ulcers and the removal of adenocarcinoma. Section 2 presents the fundamentals of the model that is applied to obtain the treatment zone in both gastric malignancies in section 3. Finally section 4 includes the conclusions of the work.

2. FUNDAMENTALS OF THE MODEL

The model for Nd:YAG laser surgery includes three dimensional optical propagation as well as a particular plasma-induced ablation approach. The Radiation Transport Theory (RTT) provides the distribution of light in a three-dimensional tissue [3]. The basic light parameter is the specific intensity $I(r,\hat{s})$. The radiation is expected to be at point r, and to follow the direction $\hat{s}$. The scattering events are treated according to the scattering phase function $p(\hat{s}\cdot\hat{s}')$. Optical radiation comes from direction $\hat{s}'$ and is redirected to $\hat{s}$. The steady-state radiation transport equation without sources can be written as in (1), where μ_a and μ_s are the absorption and scattering coefficients, respectively.

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$$\hat{s}\cdot\bar{\nabla}I(r,\hat{s}) = -(\mu_a+\mu_s)I(r,\hat{s}) + \frac{\mu_s}{4\pi}\int_{4\pi} p(\hat{s}\cdot\hat{s}')I(r,\hat{s}')d\Omega' \quad (1)$$

There are several ablation approaches ranging from mechanistic models to heuristic models, such as the blow-off or stationary state models [4]. Steady-state heuristic models are valid for pulsed microsecond laser sources, and assume an energy density threshold for optical ablation. The main mechanism of the optical ablation we are dealing with is plasma-induced ablation, and therefore the description of the process requires the consideration of multiphoton ionization and ionization by light absorption. All these effects can be included in the rate equation (2) for the quasifree electron density $\rho(t)$, where η is the probability rate of cascade ionization, mp stands for multiphoton ionization, ch stands for chromophores absorption and g is the electron recombination rate [5].

$$\frac{d\rho}{dt} = \eta\rho + \left(\frac{d\rho}{dt}\right)_{mp} + \left(\frac{d\rho}{dt}\right)_{ch} - g\rho(t) \quad (2)$$

The expression (2) can be solved analytically with a simple 1D diffusion approach, and a threshold value can be fixed when life and diffusion times of the electrons are long compared with laser pulse duration, and multiphoton ionization is neglected. For a broader pulse duration range Loesel et al. proposed the ablation threshold model expressed in the rate equation (3), where $\tilde{\beta}$ is the reduced avalanche ionization, which takes into account inelastic collisions [6]. It can be solved analytically, and a threshold value for the fluence F_{th} can be obtained by (4), taking into account the initial electron density N_0, the threshold electron density N_{th}, the laser pulse duration τ and the time constants for inelastic collision τ_c and diffusion τ_d.

$$\frac{\delta\rho}{\delta t} = \tilde{\beta}\rho(t) - g\rho(t) \quad (3)$$

$$\eta \mathrm{F}_{\mathrm{th}} = \frac{1}{2}\ln\left(\frac{N_{th}}{N_0}\right) + \sqrt{\left(\frac{1}{2}\ln\left(\frac{N_{th}}{N_0}\right)\right)^2 + \frac{\tau}{2\tau_c} + \frac{\tau}{\tau_d}} \quad (4)$$

3. RESULTS AND DISCUSSION

The model previously described was applied to laser treatment of two gastric malignancies (gastric ulcers and adenocarcinoma). The optical distribution in both of them was obtained taking into account a Nd:YAG nanosecond pulsed laser at 1064 nm that impacts perpendicularly to the layered stomach tissue. The most superficial layer corresponds to the 1 mm *tunica mucosa* whose parameters are μ_a=2.8 cm^{-1} and μ_s=732 cm^{-1}, and the deeper one is the 1.2 mm *muscularis propria* layer, with μ_a=3.3 cm^{-1} and μ_s=29.5 cm^{-1}. The index of refraction and the anisotropy of scattering are 1.38 and 0.91 for the *tunica mucosa* and 1.39 and 0.87 for the *muscularis propia*, respectively. The ulcer affects to 1 mm depth of the stomach tissue and its optical properties were assumed the same as those of *mucosa*, whereas the adenocarcinoma extends to a depth of 0.8 mm and its optical properties are μ_a=0.1 cm^{-1} and μ_s=65 cm^{-1}, index of refraction 1.38 and anisotropy of scattering 0.9. Several Nd:YAG laser parameters such as the beam profile, the beam radius and the energy delivered were modified both to coagulate the ulcerous tissue and to remove the cancerous one. Under the first scenario, the coagulation threshold was set to 200 W/cm^2 whereas in the second one, the ablation threshold was 5 J/cm^2.

Figure 1 summarizes the coagulation depths reached for two different beam radius and two beam profiles when different powers are supplied. The cross section of the coagulated tissue volume is shown in Figure 2 when it is exposed to the 1 mm radius optical beam taking into account different powers. It can be clearly observed the influence of the beam profile in the coagulation extent. Attending to the results obtained for the 1 mm laser radius (graphic on the left), the election of a certain beam profile becomes increasingly important as the laser power is higher. In this case, for optical powers higher than 40 W, the Gaussian profile allows a deeper coagulation due to its particular energy distribution in the target tissue. Differences in the depth of the coagulation effect can also be checked for the 2 mm laser radius (graphic on the right in Figure 1). The laser beam profile affects the coagulation extent even for the lower powers employed in this case.

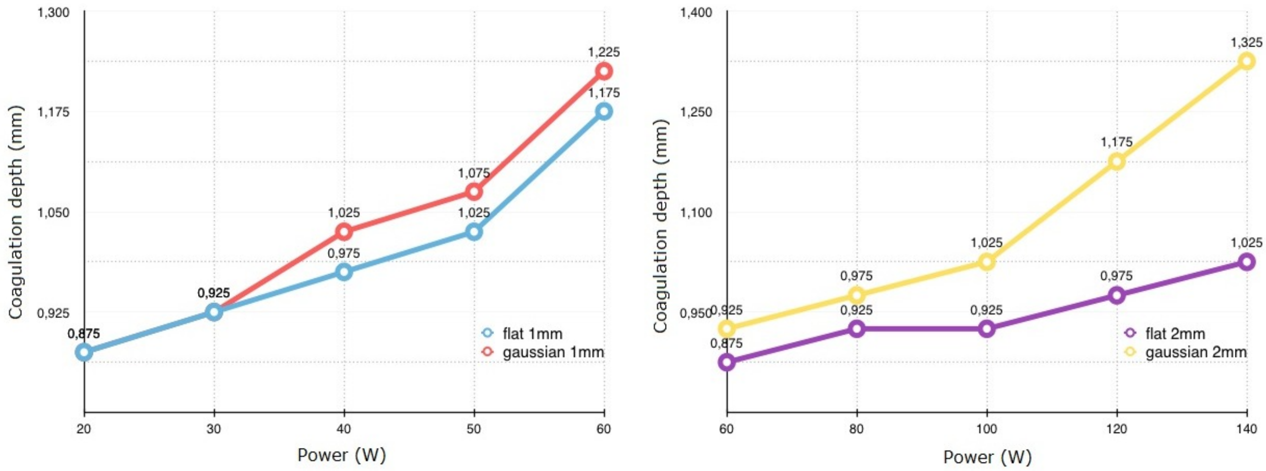

Figure 1. Coagulation depth in the gastric ulcer under Nd:YAG irradiation (beam radius 1 mm on the left, 2 mm on the right).

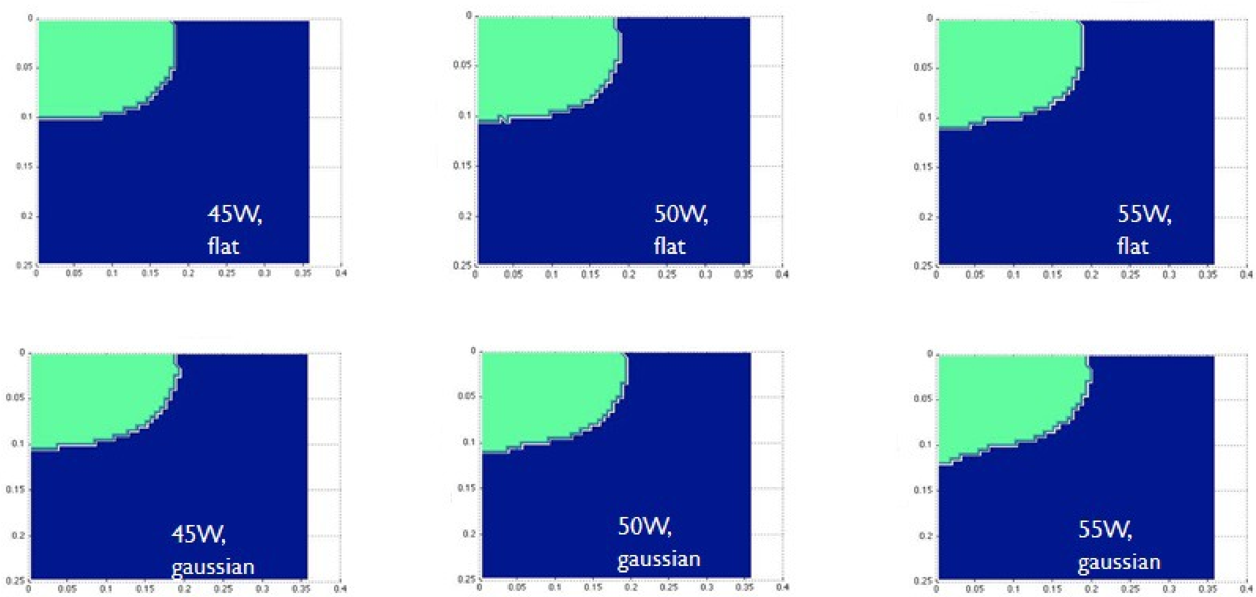

Figure 2. Coagulation area in the gastric ulcer under Nd:YAG irradiation with a 1 mm beam radius and different optical powers (x-axis is the radial component (cm) and y-axis is the depth in the target tissue (cm)).

The ablation crater produced in the stomach to remove the adenocarcinoma tumor is depicted in Figure 3. Nd:YAG laser radius was 2 mm. The upper graphics correspond to a flat beam that delivers 0.2 J (on the left) and 1 J (on the right), whereas the lower ones correspond to a Gaussian beam for the same energy delivery. As it can be observed, there is a strong dependence between the optical energy applied and the amount of cancerous tissue removal as well as different treatment effects depending on the laser beam profile under the same energy delivery. The optical beam radius effect on the ablation crater depth taking into account two beam profiles and different optical powers is depicted in Figure 4. As it can observed, under the same beam profile and optical power, the 1 mm radius beam produces a deeper ablation than the 2 mm beam radius. Therefore the optical beam radius should also be considered to provide an accurate adenocarcinoma removal.

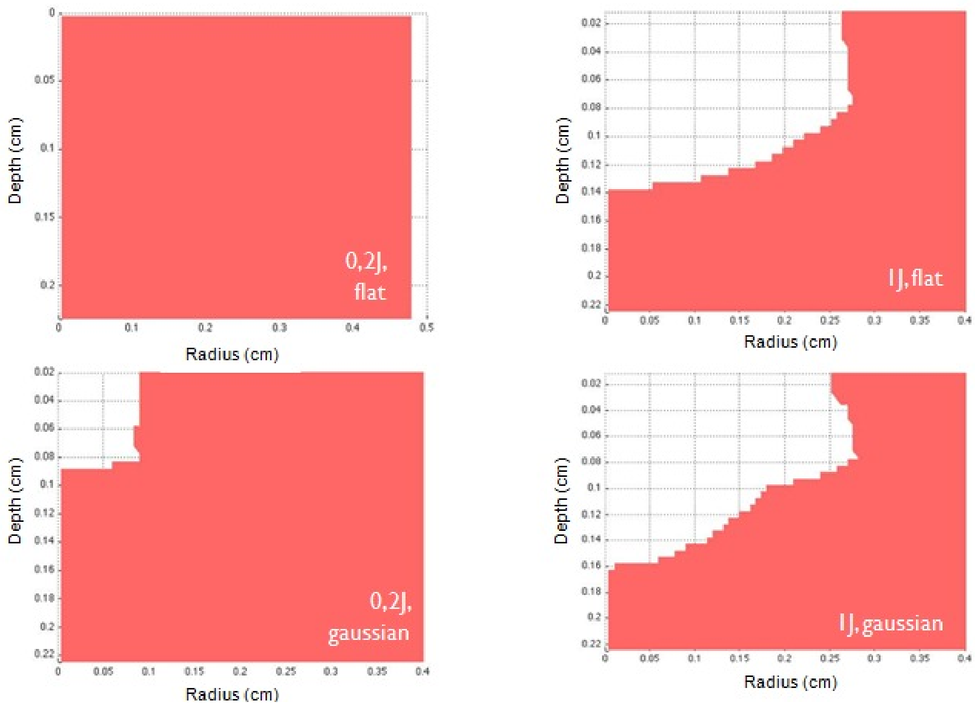

Figure 3. Ablation crater vs. depth and radial component in the stomach adenocarcinoma subjected to Nd:YAG laser (radius 2 mm) under different beam profiles (flat and Gaussian) and different optical energies.

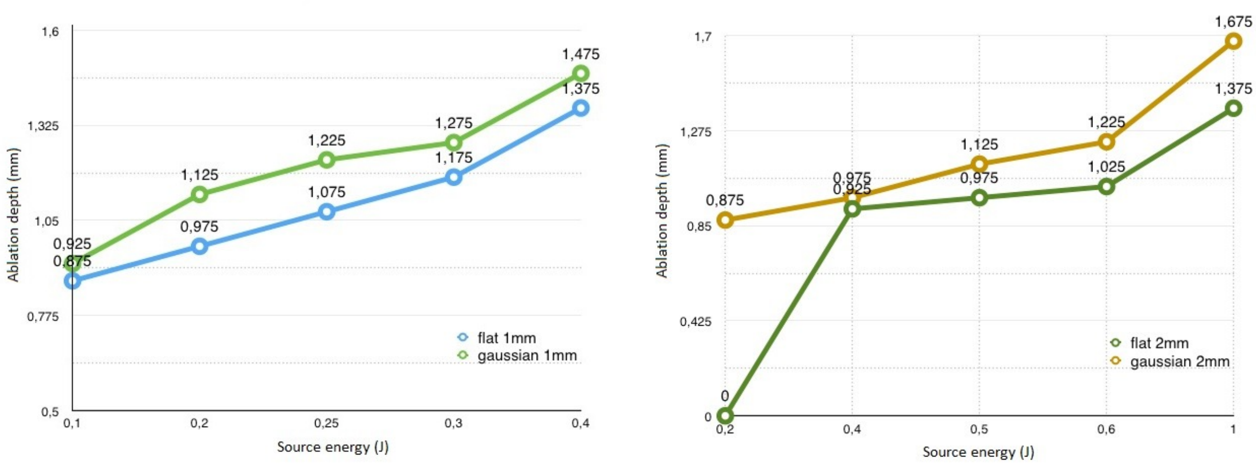

Figure 4. Ablation crater depth in the adenocarcinoma under Nd:YAG irradiation (beam radius 1 mm on the left, 2 mm on the right).

4. CONCLUSIONS

A complete model for Nd:YAG laser surgery was proposed and applied to predict both the coagulation of gastric ulcers and the removal of adenocarcinomas in the stomach wall under different laser setups. A clear dependence between laser parameters and treatment outcome was found in both cases. The results show the utility of laser surgery in gastric diseases, and allow a priori treatment planning taking into account both the tissue type and morphology and the optical source parameters. Therefore the Nd:YAG laser surgery model provides a clinical supporting tool to achieve the desired coagulation or ablation effect in the target zones avoiding an undesired gastrointestinal wall perforation.

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