Laser dosimetry planning tool for colonoscopic tumor resection

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ABSTRACT

Gastrointestinal tumoral pathologies are quite common nowadays. Diseases such as gastric antral vascular ectasia (GAVE) or actinic proctitis may require endoscopic surgery. Argon Plasma Coagulated (APC) or radiofrequency are usually employed. However, they present disadvantages, such as the reduced treated area, magnetic resonance incompatibility, or an uncontrolled ablation depth.

Optical surgery could avoid these problems and contribute to a better and controlled treatment result, either ablative or coagulative, in a minimally invasive, non-contact and non-ionizing way. The treatment area could also be increased by adequate optical fiber probe design. In this work laser surgery is analyzed for resection of colonic tumors. A Monte Carlo model is employed to study optical propagation, and an optical ablation approach allows the estimation of the resected volume. The ablation approach is based on plasma-induced ablation, particularly taking into account the free-electron density generated in the tissue by the pulsed optical source. Several wavelengths, radii and malignant tissue types are considered, either healthy, adenomatous or even coagulated tissues. Optimum source parameters as a function of tumor geometry can be estimated for treatment planning.

Keywords: Laser surgery, Plasma-induced ablation, Colonic tumor, Tissue coagulation

1. INTRODUCTION

Gastrointestinal tumors are quite common nowadays in clinical praxis [1]. Gastric antral vascular ectasia (GAVE), actinic proctitis or colon cancer are usually treated by Argon Plasma Coagulation (APC), radiofrequency (RF) or electro-ablation. However, they present disadvantages, such as a reduced treatment area, Magnetic Resonance incompatibility or the lack of a precise control of the affected volume [2].

Endoscopic laser surgery provides an advantageous alternative to the previously mentioned approaches in colonic tumor resection. The use of lasers provides selective ablation of polyps with an additional hemostatic effect in the surrounding tissue, and also tissue coagulation of hemorrhagic lesions. Broader areas of the colon can be treated simultaneously. The effects of the laser on the tissue are strongly dependent on several laser parameters. This dependency involves mainly optical propagation and tissue ablation. The analysis of those effects for particular laser and tissue parameters is required in order to adequately plan the treatment procedure. The relationship between laser parameters and the desired effects requires an adequate analysis of all the processes involved. Otherwise the patient could suffer from insufficient therapeutic results that could even lead to tumor relapse or colonic perforation. Some previous approaches were applied to dermatology [3] and gastric malignancies [4].

In this manuscript laser surgery colonoscopic process is studied. Optical propagation is considered by means of a Monte Carlo three-dimensional approach. The optical ablation procedure is taken into account by means of the main mechanism of plasma-induced ablation and ablation threshold. The analysis is extended to several laser wavelengths and irradiated areas. Results show clear differences in the ablation volume, which are critical for an appropriate treatment. This analysis could be employed in clinical practice to obtain the optimal laser beam parameters to treat a certain type of colonoscopic pathology.

Next section presents the fundamentals of the optical propagation and ablation approaches. Section 3 applies the procedure to colonic tissue and show the main results. Section 4 contains the conclusions of the work.

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2. OPTICAL DISTRIBUTION AND PLASMA-INDUCED ABLATION

The model for 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 [5]. 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.

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

There are several ablation approaches ranging from mechanistic models to heuristic models, such as the blow-off or stationary state models [6]. 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.

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

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 [7]. 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.

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

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

3. APPLICATION TO COLON TISSUES

Several pathologies may affect the colon, such as colorectal cancer, polyps, ulcerative colitis, diverticulitis or irritable bowel syndrome [1]. Depending on the pathology, even a segment of the colon may be removed [2].

The model described in section 2 is applied to healthy and adenomatous colon. Several laser parameters and tissue geometries are considered. Laser wavelengths of 415, 530, 630 and 1064 nm are analyzed. The location of adenomatous tissue, with variable thickness of 0.1, 0.05 and 0.01 cm, is varied from the tissue surface to 0.2 cm in depth.

Table 1 shows the minimum laser energy required for resecting a 0.1 cm thickness tumor located at different depths for each considered wavelength.

Table 1. Minimum laser energy (J) for resecting a 0.1 cm thickness tumor at different depths.

	Location			
λ (nm)	**0.01 cm**	**0.04 cm**	**0.08 cm**	**0.1 cm**
1064	0.17	0.2	0.22	0.23
630	0.17	0.25	0.32	0.35
530	0.15	0.5	0.9	1.5
415	2	3.2	5.8	7

As it can be appreciated in Table 1, further depth tumor locations require increasing laser energies, as expected. Regarding the influence of wavelength, radiation at 1064 nm needs less energy to reach deeper tumors, as its penetration depth is longer. This is coincident with the fact that that wavelength is located inside the therapeutic window.

A representation can be made for a colon tumor of 0.1 cm thickness located at 0.1 cm depth for laser energies previously calculated in Table 1. Figure 1 shows the results. In the graphs of Figure 1 the ablation area is represented in a plane where the x axis corresponds to the radial direction, and the y axis corresponds to depth. Laser radiation is impinging at position (0,0) (upper left corner of each graph).

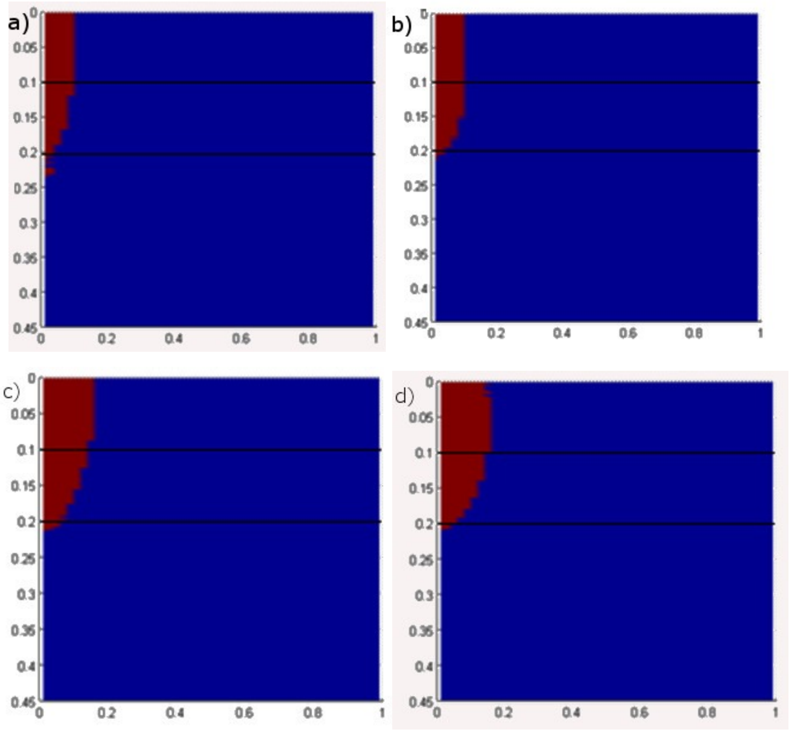

Figure 1. Ablation area (red) of colon tissue with different laser wavelengths: a) 1064 nm, b) 630 nm, c) 530 nm, d) 415 nm. Axes are in cm. Tumor location is delimited by two horizontal black lines.

The results in Figure 1 show that the whole tumor thickness is ablated at each wavelength when employing the adequate laser energies of Table 1. A further analysis can be made with any particular tumor geometry or laser parameters.

4. CONCLUSIONS

Gastrointestinal tumors, such as Gastric antral vascular ectasia (GAVE), actinic proctitis or colon cancer are usually treated by Argon Plasma Coagulation (APC), radiofrequency (RF) or electro-ablation. However, they present disadvantages, such as a reduced treatment area, Magnetic Resonance incompatibility or the lack of a precise control of the affected volume. Endoscopic laser surgery provides an advantageous alternative to the previously mentioned approaches in colonic tumor resection. In this work we proposed a laser dosimetry tool, based on optical propagation and plasma-induced ablation models, in order to delimitate the ablation area. Tumor geometry and laser parameters can be varied, so the optimal laser source for the particular pathology and patient can be found. This tool could be relevant in medical praxis planning.

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