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Sensitivity analysis to optical properties of biological tissues subjected to a short-pulsed laser using the time-dependent radiative transfer equation

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ABSTRACT

Visible and near-infrared spectral range of light can be used for estimating the optical properties of a biological tissue in a non-invasive way starting from its response to an external light stimulus. A forward model based on the time-dependent radiative transfer equation, that accurately describes light propagation through such media, is considered and solved with a finite-volume method for the discretization of the spatial domain. Results in terms of fluence and of reflectance at the illuminated transparent or semi-transparent wall for liver and skin tissues subjected to a collimated short-pulsed near-infrared laser are presented and discussed. A sensitivity analysis of the reflectance in the time domain to the four optical parameters of the model shows that only two of them can be estimated: the asymmetry factor of the Henyey–Greenstein phase function as well as either the refractive index or the scattering coefficient of the tissue. The reduced model can be used to invert the experimental reflectance measured assuming the signal over noise ratio of the detector known in the corresponding non-invasive detection technique.
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1. Introduction

The cancer is a major cause of death; it affects approximately ten million people in the world. This disease can cause physiological changes that affect the optical properties (scattering, absorption, refractive index, etc.) of biological tissues. Therefore, medical imaging techniques to diagnose cancer tumors early, efficiently and non-invasively have become major public health and economic issues related to costs sometimes very high for cancer treatments. To this end, Diffuse Optical Tomography (DOT) is designed for spatially reconstructing the optical properties of biological tissues, through measurements carried out by an external sensor, with a radiative transfer model in the visible or near-infrared spectral range [1–41]. It consists in illuminating a tissue sample with a short-pulsed laser and to analyze the information conveyed by the backscattered light (reflectance) at the wall of the tissue to detect the possible presence of cancer tumors. Biological tissues scatter strongly light as cells are commonly made of many different structures (such as cores and mitochondria). Moreover, they absorb light because of their content in hemoglobin, melanin and water. Light can penetrate the tissues up to a depth of a few centimeters in the spectral range which is considered to be the therapeutic window (located between 600 and 900 nm), where the absorption of tissues is minimal. The present study is devoted to a sensitivity analysis to optical properties of biological tissues subjected to a short collimated Gaussian

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Nomenclature

c	speed of light in vacuum, m s^{-1}
D	medium
E	energy, J
e_y	height of the laser beam, m
e_z	width of the laser beam, m
g	asymmetry factor of the Henyey–Greenstein scattering phase function
l_x	thickness of the medium, m
l_y	height of the medium, m
l_z	width of the medium, m
l_{tr}	mean free path of the photons ($=1/\mu_{s\lambda}^*$)
m	time iterations number to reach the steady state
n	refractive index
$\overrightarrow{n}$	outward pointing unit surface normal vector
$\overrightarrow{Q}$	fluence vector, W m^{-2}
Q_{inc}	radiance integrated over all incoming directions, W m^{-2}
Q_{obs}	reflectance, W m^{-2}
$\overrightarrow{r}$	position vector, m
S	source term, W m^{-2}
S^*	scaled sensitivity coefficient, W m^{-2}
S_j^*	scaled sensitivity vector, W m^{-2}
S_{ij}^*	scaled sensitivity matrix components, W m^{-2}
t	time, ps

Greek symbols

β	exact parameters vector
∂D	boundary of medium
δ	Dirac delta function
ψ	radiance, W m^{-2} sr^{-1}
Δt	time step, s
$d\Omega$	solid angle, sr
η	efficiency
μ_a	absorption coefficient, m^{-1}
λ	wavelength, nm
$\overrightarrow{\Omega}$	direction vector
Φ	scattering phase function, sr^{-1}
μ_t	extinction coefficient ($=\mu_a+\mu_s$), m^{-1}
μ_s	scattering coefficient, m^{-1}
μ_s^*	reduced scattering coefficient ($=\mu_s(1-g)$), m^{-1}
ρ	reflectivity
τ	optical thickness ($=\mu_t l_x$)
Θ	angle between the incoming and the scattering directions
Υ	incoming intensity of the pulse, W m^{-2}

Subscripts

back	backscattered
c	collimated
crit	critical
d	diffuse
ext	outside
inc	incoming direction
λ	monochromatic
obs	observed
r	relative
ref	reflected

Superscripts

T	transpose of a matrix

time pulsed laser (of the order of picoseconds) using an accurate model of light propagation based on the time-dependent radiative transfer equation (TRTE). In real applications, it should be noted that the time-dependent [1,5,6,8–10,18,19,22] or frequential [14,16,17,20,21,25,28,31–34] techniques, compared to the continuous technique [11–13,24,35–39] that has commonly been used, offer the advantages of providing more informations and a very high level of sensitivity. Also, it is more advantageous to obtain solutions directly in the time domain because, firstly, the radiance at arbitrary time values can be easily evaluated and, secondly, possible artifacts introduced by the Fourier transform can be avoided. Thus, it seems more interesting to use the TRTE for modelling. The paper is divided into three main parts. First, a study of the effect of the structural parameters to the outputs of the radiative model, the reflectances, for two types of different tissues, namely liver and skin are made. Second, a study of a more realistic model (plane laser beam impacting a wall ten times larger than its thickness) allows us to calculate the order of magnitude of energy that can be recovered on the illuminated wall of the tissue. This reflectance, that depends on the optical properties of tissue, can be measured by a sensor. It could allow the detection of a possible cancer tumor. In a third part, a sensitivity analysis and a study of the condition number of the scaled sensitivity matrix is made and allows determining the independent parameters. This is an essential step in the design of a non-invasive technique to quantitatively estimate one or more parameters of a cancer tumor, assuming the signal over noise ratio of the detector known. The last section reports our conclusions and suggests further developments for this work.

2. Modelling of light propagation through biological tissues

2.1. Configuration of the physical model

We studied a biological tissue such as liver and skin with optical properties listed in Table 1. The tissue has been illuminated with a short pulsed laser in the NIR (Near InfraRed) spectral range, at 850 nm for the liver and 830 nm for the skin.

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