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# Analysis of radiative signals from normal and malignant human skins subjected to a short-pulse laser

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ABSTRACT

Responses from a normal skin and a malignant human skin subjected to a low power short-pulse laser are studied. Temporal variations of transmittance and reflectance that carry the signature of the skin conditions are analyzed. The normal skin is modeled based on the anatomical details available in the literature. The malignant skin represents commonly found skin lesions, viz., non-melanoma and cutaneous melanoma. Optical properties of the skin such as the absorption and the scattering coefficients cover various lesions, and they are within the therapeutic optical window of 600–1300 nm wavelength. Scattering is modeled using Henyey–Greenstein phase function. The transient radiative heat transfer equation is solved using the modified discrete ordinate method.



## 1. Introduction

In the recent past, consideration of thermal radiation in the characterization of optically participating media, such as tissues, has been explored by many investigators [1–6]. Several facts that are not revealed at normal spatial and temporal scales are understood well when these are investigated at lower scales. For example, with $l$ as the characteristic length of the system and $c = 3 \times 10^8\ \mathrm{m\ s^{-1}}$ as the speed of light, the temporal changes in transmittance and reflectance are not revealed if the radiative transport process is investigated at time scales $O(l/c) = 10^{-6}$ s or higher [7]. This is true whether the medium is under the influence of radiation for a short or a long duration. However, if the observation time is lowered to $10^{-9}$ s or lower, temporal changes in transmittance and reflectance become evident [7]. Further, if the incidence of the radiation source is also of the order of $O(10^{-9}\ \mathrm{s})$ or lower, the temporal distributions of the reflectance and transmittance are more distinct. This is for the fact that in the radiative transfer equation (RTE) the term $(1/c)(\partial I/\partial t)$, where $I$ is the intensity of radiation, can only be significant when the changes are investigated at time scales $O(10^{-9}\ \mathrm{s})$ or lower. This fact becomes a potential tool for characterizing an optically participating medium [1–7]. This attracted attention of many researchers towards the possible application of thermal radiation in characterizing biological tissues [1–6].

The properties for healthy and malignant tissues are different, since the cancer affected tissues exhibit a distinctive metabolic activities, compositions and growth of cells as compared to that of the normal tissue. Further, the properties and conditions of the tissues keep on changing with different growth phases of malignant cells. Thus, tissues having different optical properties yield different temporal variations of the transmittance and the reflectance when subjected to an external radiation source. Temporal variations in the transmittance and the reflectance carry the signature of the tissue, and reveal its physiological state. Thus, for an optically participating human skin the optical window between 600 and 1300 nm is of particular importance to optical detection of cancer. Since light in this wavelength regime scatters through several centimeters of tissues before being extinguished. One such observation by Anderson and Parrish [8] showed that 1% of light can even penetrate the entire human chest at 605–850 nm wavelengths. The detailed information on human skin optical properties can be obtained from [8–14].

In the literature, some works pertaining to the study of temporal variations of transmittance and reflectance from optically participating medium are available [1–7]. Not specific to any tissues and malignancies, these studies are of general nature. A good amount of literature pertains to the applications of various

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**Nomenclature**

| | |
|---|---|
| $c$ | speed of light |
| $g$ | asymmetry factor |
| $G$ | incident radiation |
| $I$ | intensity |
| $I_b$ | blackbody intensity |
| $I_d$ | diffuse intensity |
| $l$ | length |
| $L$ | order of approximation for Legendre polynomial $P_L$ |
| $M_\theta$ | number of discrete points over complete span of polar angle |
| $n$ | refractive index |
| $q$ | radiative heat flux |
| $r$ | position |
| $s$ | geometric distance in the direction $\hat{s}$ of intensity |
| $S$ | source term |
| $t$ | time |
| $t_p$ | pulse width |
| $t_c$ | cut-off period |
| $T_p$ | time period of the pulse train |
| $V$ | volume of cell |
| $Z$ | physical thickness |

*Greek symbols*

| | |
|---|---|
| $\delta$ | Dirac-delta function |
| $\mu$ | direction cosine |
| $\lambda$ | wavelength |
| $\kappa_a$ | absorption coefficient |
| $\sigma_s$ | scattering coefficient |
| $\beta$ | extinction coefficient |
| $\tau$ | optical thickness |
| $\theta$ | polar angle |
| $\phi$ | azimuthal angle |
| $\Omega$ | direction $(\theta, \phi)$ |
| $\Delta\Omega$ | solid angle $(\sin\theta d\theta d\phi)$ |

*Subscripts*

| | |
|---|---|
| $c$ | collimated |
| $d$ | diffuse |
| $i$ | incident |
| $max$ | maximum value |
| $med$ | medium |
| $N$ | north |
| $P$ | cell center |
| $S$ | south |
| $ref$ | reflectance |
| $t$ | total |
| $tr$ | transmittance |

*Superscripts*

| | |
|---|---|
| $m$ | index for discrete directions |
| $*$ | non-dimensional parameter |

*Abbreviations*

| | |
|---|---|
| CM | cutaneous melanoma |
| DOM | discrete ordinate method |
| HG | Henyey–Greenstein |
| MDOM | modified discrete ordinate method |
| NBCC | nodular basal cell carcinoma |
| RMC | reverse Monte Carlo |
| RTE | radiative transfer equation |
| SCC | squamous cell carcinoma |
| SNR | signal to noise ratio |

numerical radiative transfer methods, such as the Monte Carlo method [15,16], the discrete ordinate method (DOM) [7,17], the discrete transfer method (DTM) [7,18], the finite element method (FEM) [19,20] and the finite volume method (FVM) [7,21] to this class of problems. Some experimental and numerical studies pertaining to the interaction of short pulse laser light with inhomogeneous tissue phantoms [3,22], turbid medium [23], superficial skin models [24], normal human skins [25] and normal human breast [26] are available. The previous studies on skin melanoma and benign skin lesions are on active mode of thermal imaging [27] and on pulsed terahertz imaging [28,29], which has been proved to be a potential non-invasive approach. Similarly, few important investigations deal with the thermally induced skin injury [30] due to laser interaction, eye treatment using laser [31], thermally induced damage during retinal laser surgery [30,32], estimation of thermal load on eye using IR-thermogram [33] and on skin burning due to external thermal load [34]. However, to the best of the knowledge of authors there is no study reported on the skin with and without malignant lesions, and for various types of malignancies therein when subjected to short pulse laser. The present work, therefore, aims at the study of temporal variations of transmittance and reflectance of a biological tissue with and without malignancy, when subjected to short-pulse laser. In general, the radiative signatures due to laser-tissue interaction convey important information about in-vivo changes in tissue properties as well as tissue conditions, and can be quantified using a sensitivity study. Moreover, these output radiative signatures are different for different grades and types of cancers. Thus, the variation in radiative signatures, due to the changes in properties and conditions (i.e., grades/growth of cancer) can be a means to understand any anomalies, and is, therefore, a potential dynamic technique for early detection and staging of skin cancer. According to the guidelines given by American Joint Committee for Cancer Staging, the increase in skin cancer thickness/volume is regarded as the best predicator for cancer staging [35]. Similarly, Clark *et al.* [36] and Breslow [37] described the prognostic relationship between the depth of penetration of skin cancer from epidermis into the dermis/subcutis and the survival expectancy. In view of the above details, present study considered a model for the human skin cancer with different growth stages (varying thickness) of lesion within the normal skin.

The motivation behind this work is to perform modeling based feasibility study to quantify the effectiveness of short-pulse laser for early detection and staging of skin cancers. It is a well-known fact that, at present in most clinical settings, detection of subsurface cancer at an early stage is a formidable challenge. It often involves multiple biopsy trials to identify the types and grades. The detection and staging of skin cancer using short-pulse laser based modality is a novel approach, since this will enable quick access of firsthand information without undergoing unnecessary biopsy trials. This article performs an extensive modeling and sensitivity study in order to materialize the argument described above. The present study is a part of the comprehensive research effort to device an approach to detect as well as stage skin cancer noninvasively.

In the present work, commonly found skin abnormalities, viz., non-melanoma and melanoma skin cancers are considered. The skin is modeled according to the available anatomical details, and the optical properties of the malignancies in the skin are considered as reported in the literature. Temporal distributions of transmittance and reflectance resulting from the incidence of laser source having pulse-width of the $O(1.0 \times 10^{-9}\,\text{s})$ and the $O(1.0 \times 10^{-12}\,\text{s})$ are analyzed. Transient RTE is solved using the modified DOM (MDOM) [38].