Monte Carlo Simulation of Spectral Reflectance Images of Human Skin with Embedded Lesions

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Abstract: This study applies Monte Carlo simulation to model the spectral images of skin lesions in the visible and near-infrared ranges. By simulating the spatial distribution of backscattered light, we analyze the correlation between its optical properties and spectral features.

1. Introduction

The Monte Carlo (MC) method is a well-established computational technique for modeling light transport in turbid biological tissues, including human skin. Recent advances in biomedical optics and computational modeling have improved the accuracy and efficiency of MC simulations, enabling detailed analysis of photon interactions in multilayered skin structures. These simulations are essential for medical imaging, optical diagnostics, and non-invasive skin cancer detection [1,2].

One of the most critical applications of MC-based modeling is the identification of skin lesions through their color and spectral signatures, particularly for detecting tumors like malignant melanoma. This aggressive skin cancer exhibits distinct optical properties due to variations in melanin concentration, absorption, and scattering. By simulating photon transport, MC models help analyze backscattered light from different types of skin lesions, supporting advanced diagnostic techniques such as diffuse reflectance spectroscopy (DRS), hyperspectral imaging, and multispectral analysis [3].

The optical properties of skin, including absorption, scattering, and anisotropy, influence its color and spectral characteristics. While benign nevi generally exhibit uniform spectral signatures, malignant melanoma often presents irregular absorption patterns due to abnormal melanin distribution and increased vascularization. MC modeling allows for characterization of these variations, providing estimations for non-invasive means of differentiating malignant and benign lesions.

This study applies Monte Carlo simulations to investigate photon transport in human skin with embedded lesions, correlating their spectral features with optical properties. By improving lesion differentiation, this approach contributes to the advancement of non-invasive skin tumor detection techniques.

2. Methods

1.1. Monte Carlo simulation algorithm

Monte Carlo simulation for photon propagation in turbid media involves simulating photon trajectories as they scatter and get absorbed in the medium. Optical properties such as absorption μa, scattering μs, and anisotropy factor affect photon trajectories in skin tissue. Let us assume that light rays are incident perpendicularly to the skin surface. The photons enter the skin and then propagate in different directions. Some of them will be absorbed and scattered, and small portion will be back-scattered from the skin. These photons produce a 2-D energy distribution, which can be observed as an intensity image from the skin surface. Any structural changes like embedded nevi will affect intensity distribution. The successive steps of MC simulation algorithm [4] can be explained as follows:

1. The start of the simulation consists in launching multiple photons from a light source into the simulated scattering volume. The initial direction of each photon is defined as perpendicular to the skin surface (Z=0) and the photon's position is randomly distributed along the skin surface (X-Y). The initial weight of every photon equals 1.
2. The second step is adding boundary conditions which consider the size of environment, thickness of skin layers and location of the lesion within the skin structures (X-Y-Z position).

3. Next step is to determine the distance traveled by the launched photon packet before interaction. This distance is called the mean free path and is calculated using a random number and the Beer-Lambert law. A highly absorbing medium will result in very short mean free paths, while a diluted medium will allow photons to travel much further before interaction. During an interaction event, a portion of the light may be absorbed while the rest of the photon packet will be scattered. In this step, the weight of each photon is reduced by a factor $\mu a / (\mu a + \mu s)$.

4. A new direction of propagation is defined for the scattered light. This is determined by two random numbers and the scattering Henyey-Greenstein phase function [4].

5. While inside the simulated volume, the photon continuously repeats steps 2-4. This process stops as soon as the photon packet leaves the scattering medium, or its weight drops below threshold. A photon is considered detected if it crosses the surface from inner side of skin ($Z<0$). The energy distribution of back-reflected photons was calculated as the sum of photon weights in each XY grid position and can be visualized as normalized intensity map at the skin surface.

The simulated environment was a rectangular cuboid with a base size of 2x2 cm and infinite depth. Simulations were performed on laptop computer (Lenovo AMD Radeon 5 Pro, 16GB RAM, Nvidia Geforce-GTX 4GB GPU RAM), using custom developed Matlab software which was optimized for CUDA GPU processing. The calculation time of one billion photons at a particular wavelength takes ~2 hours.

1.2. The simulation of embedded skin lesions

Human skin consists of multiple layers, each with different optical properties. In this work we modelled skin as a two-layered turbid medium consisting of two layers. Optical properties of epidermis (upper layer) depend on melanin concentration and the layer thickness which was assumed as 0.1 mm. Dermis was assumed as infinitely deep media containing hemoglobin and oxyhemoglobin (blood). Back-scattered intensity of five types of lesions were modelled. Each of them has specific positions in skin and have different optical properties, which are wavelength dependent. To simulate the irregular structure of nevi, the thickness and absorption coefficient are randomly varied around their mean value. The propagation of light in complex skin tissue was simulated at five wavelengths: 450nm, 520nm, 640nm, 850nm and 940nm. The sets of optical parameters exploited in our models – range of depth, thickness, absorption μa, scattering μs and anisotropy *g* – are presented in Table 1.

Table 1. Optical properties of the modelled skin and lesions [2-5].

Tissue type	Depth, mm	Thickness, mm	μa, mm^{-1}	μs, mm^{-1}	g
Epidermis	0	0.1	0.02 – 0.5	7 – 30	0.85
Dermis	0.1	Infinity	0.01 – 0.1	6 – 15	0.85
Junctional nevus	0.05+-0.05	0.05	0.4 – 2.0	2 – 7	0.85
Intradermal nevus	0.2+-0.1	0.3	2.0 – 3.5	4 – 11	0.85
Blue nevus	0.5+-0.4	3.0	2.0 – 5.0	6 – 13	0.85
Hemangioma	0.05+-0.05	1.0	0.1 – 1.2	7 – 22	0.85
Malignant melanoma	0.2+-0.2	5.0	2.5 – 7.0	7 – 15	0.85
White reference	0	Infinity	0	7 – 30	0.85

3. Results

Figure 1 shows simulated backscattered intensity maps of skin with 5 embedded inclusions. All lesions have higher melanin concentration compared to the surrounding epidermis. Junctional nevus is shallow, limited to the epidermal-dermal junction, and has brown color. Intradermal nevus extends even deeper, mainly within the dermis. Blue nevus penetrates deep into the dermis, and it appears blue due to the Tyndall effect, while intradermal nevus is brownish. Hemangioma has reddish color due to higher hemoglobin content as it is a vascular formation. Typical junctional nevi and hemangiomas can be detected in the visible light spectrum, especially at 450 nm and 520 nm. As the malignant melanoma can be highly invasive, reaching deep into the dermis, it has the highest absorption due to high melanin content. As the near-infrared 850-940 nm radiation penetrates deeper in the structures, blue nevus and malignant melanoma may be seen more clearly. In contrast, the simulated malignant melanoma is more contrastive with the surrounding skin across the entire spectral range (450–940 nm).

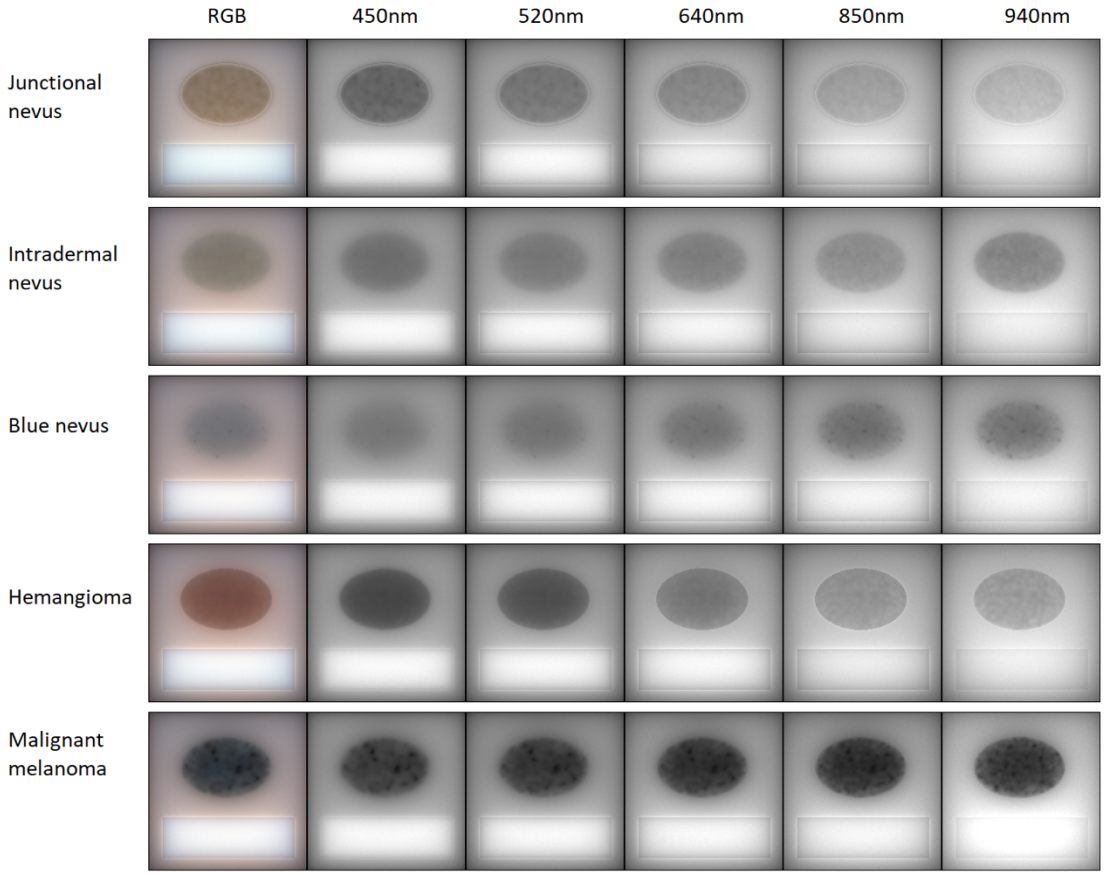

Fig. 1. Back-scattered intensity maps of five simulated nevi. RGB color images and spectral images.

4. Summary

Our first results on MC-simulations of skin spectral images comprising several types of pathologic inclusions are presented, with notable differences in contrasts depending on the lesion's type. The optical parameters (Table 1) can be further varied according to specific anatomic features of skin and embedded lesions.

Acknowledgments

This research was funded by the EU Recovery and Resilience Facility project "Internal and external consolidation of the University of Latvia" (LU-BA-PA-2024/1-0006).

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