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Research Article

Modeling light propagation in a reconstructed breast model using the Monte Carlo method

Quy Tan Ha[1,2], Ngoc An Dang Nguyen[1,2,*], Trung Nghia Tran[1,2]

ABSTRACT

Breast cancer is one of the most common types of cancer that causes the highest death among women. One of the main aspects of effectively monitoring the effectiveness of breast cancer treatment is the early detection of abnormalities in breast tissue. It is one of the most critical factors that may determine how well breast cancer therapy is carried out. On the other hand, the techniques used in breast diagnostics today have several limitations, including the hazards connected with radiation exposure, the high price, and the likelihood of creating false-positive results. Therefore, optical techniques are considered feasible strategies for the early diagnosis of breast abnormalities. The optical-based technique has been studied to develop self-diagnostic aids and high-tech devices such as optical tomography. The recent development of therapeutic applications using low-power light also creates a new direction in treating benign tumors through photobiological effects. Therefore, much more research must be conducted to understand how light interacts with breast tissue for developing the diagnosis device and treatment device. In this study, light interaction with tissue was investigated by simulating light propagation at wavelengths of 650 nm, 800 nm, and 950 nm in a breast model that was generated using an MRI data collection. Specifically, the tissue's absorption of these three wavelengths was evaluated to understand better how light interacts with breast tissue. The results of the simulation show that normal breast models and sick breast models have significantly different total quantities of energy absorbed, and these results indicate this discrepancy. The distribution map acquired correlates with the image obtained using optical transillumination imaging. The simulation results can steer further research toward developing a novel breast diagnostics methodology based on optical approaches.

Key words: Monte Carlo Simulation, Breast Tissue, Light Propagation, Absorption, Transillumination

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INTRODUCTION

Breast cancer is the most common type of cancer and one of the leading causes of death in women [1]. The ability to detect breast abnormalities early is one of the key factors for effective breast cancer control and treatment [2]. Breast cancer screening is done by various methods such as clinical breast examination (CBE), X-ray mammography, magnetic resonance imaging (MRI), ultrasound (US). However, each method has its limitations.

Mammography and CBE are the most commonly used methods of breast cancer screening. While mammography carries risks of radiation exposure to patients, CBE has a high false-positive rate [3]. Limited specificity, long image acquisition time, and cost of examination are among the disadvantages of MRI. US has low sensitivity in monitoring small-volume tumors, it also requires experience of the diagnostician because of the similarity in acoustic properties of normal and diseased tissues [4,5].

In recent years, the use of red and near-infrared light (NIRS) to study women's breasts is considered one of the possible alternative or supportive methods in the diagnosis of breast cancer in particular. abnormalities in breast tissue in general [6]. One of the main cornerstones of the development of optical techniques in breast diagnosis is the high sensitivity of the wavelength range in the optical window region to the concentrations of the major constituents of the breast including hemoglobin, lipids and water [7]. That is, based on the difference in optical properties (absorption and scattering of light) between normal tissue and diseased tissue is used to characterize the tissue and detect abnormalities.

Research on the application of optical techniques in the diagnosis of breast abnormalities is becoming more and more diverse in different modes such as continuous mode (CW), time domain (TD), frequency domain and frequency domain. (FD) or both in reflected and transmitted image acquisition methods [8]. However, understanding the interaction between light and the components that make up breast

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tissue remains one of the challenges for research. In particular, the modeling of light propagation in biological tissues based on Monte Carlo simulation is considered one of the popular methods to understand the interaction of light in turbid tissues in general and in turbid tissues. biology in particular.

In this report, to better understand the behavior of light at red and near-infrared wavelengths in breast tissue, a three-dimensional breast model was built based on the breast MRI dataset and simulated its propagation. light in that breast model by a diffused light source (laser) at three wavelengths 650 nm, 800 nm and 950 nm, respectively. The results of this study are used to guide further studies in the development of diagnostic methods based on optical techniques and device fabrication.

And in the long-term direction, the results of the study have the potential to contribute to the development of a method for diagnosing breast abnormalities at an early stage, including both benign and malignant tumors. However, in this study, the focus was on stage II/III breast tissue malignancies, where the tumor tissues exhibit distinct intrinsic properties including (hemoglobin, lipid, water, ...) compared with normal tissue.

MATERIALS AND METHOD

Breast MRI Dataset

In this study, a set of breast MRI images was used with public permission for use by the University of Iowa Health Care's Magnetic Resonance Research Facility. This dataset of images includes 83 tomography images of female breast tissue that are used to reconstruct a three-dimensional model[9].

Monte Carlo Method (MC)

The process of interaction between light and the biological environment is a complex combination of events related to the absorption and scattering of light in the biological medium. One of the most common approaches to describe these processes is to use the radiative transfer equation (RTE) or its simpler form - the diffusion equation (DE)[10–12]. Essentially, the equations that describe light propagating into a biological medium are packets of photons, that is, omitting the wave properties of light such as interference or polarization because when propagating through media, such as interference or polarization are removed. Since the field has a higher scattering than absorption, the wave behavior of light traveling through the medium tends to be "averaged" after a few scatters in the medium[13].

There are many methods to solve RTE equations including numerical or analytical methods, but the Monte Carlo simulation method is considered a "gold standard" because it provides an accurate and fast solution method when available. the ability to speed up calculations by customizing the error[14].

The MC method involves randomly sampling the transport of photons in a biological medium according to a random probability of a free path. Photon particles can be changed direction due to physical factors inside the medium such as collision with microparticles inside the tissue (characterized by scattering coefficient - μ_s) or absorbed by chemical components in the environment (characterized by absorption coefficient - μa). In addition, the scattering angles of photons inside the medium are also regulated by the anisotropic scattering coefficient (g) or refractive index (n) of each layer of medium when photons can propagate in multiple layers of tissue[15].

Breast Model Reconstruction

In this report, the breast model was built using the program Mimic Innovation Suite (Materialise HQ, Leuven, Belgium). Figure 1 shows the main steps of the breast reconstruction process.

In it, two tools are used to segment the layers of breast MRI images including Thresholding and Region Growing. While the Thresholding technique isolates attenuated voxels within the Hounsfield Unit (HU), Region Growing is automatically selected by the software for voxels within the specified HU that are physically connected to the original point is selected. In this study, the breast model were divided into three main layers including skin, adipose tissue and breast tissue. The specific steps in the process of reconstructing the model by MRI images are presented in detail in the report of Andreas A. Giannopoulos et al in 2015[16].

Optical Simulation

The light propagation in the breast model was simulated using MOSE 2.3 software developed by S. Ren et al in 2013[17] at 650 nm, 800 nm, and 950 nm. The scenarios simulated in this report include a normal breast model and a tumor survival breast model.

In both simulation models, the refractive index of the layers in the model was assumed in average of 1.40. Each tissue layer in the model is considered to be optically homogeneous, the optical properties of the tissue layers are shown in Table 1. In which, the tumor is simulated as a malignant tumor in cancer in stage II/III (near the end stage). The selection of wavelengths 650 nm, 800 nm and 950 nm in the simulation

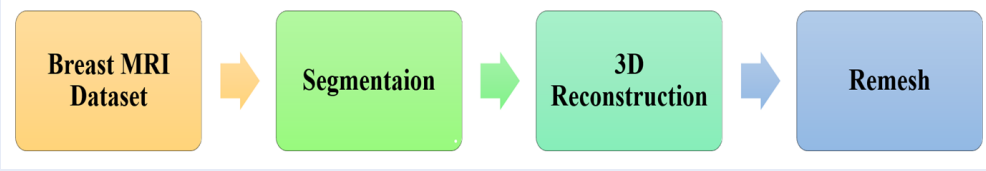

Figure 1: The main steps of the breast model reconstruction process.

scenario is because they are specific to specific substances in malignant breast tumors. In which, 650 nm is specific for oxy - hemoglobin, 800 nm is for deoxy - hemoglobin and 950 nm is for lipid and water[6,18].

The diffused light source (laser) is set up in simulated light propagation, it is placed close to the breast surface and set to CW mode. The azimuth angles of the light source were from 0^o to 360^o and the deflection angle was 180^o. The total incident photon number was 1 000 000 and the energy of incident light was set as 1.

Figure 2 shows the simulation models in this study.

RESULT AND DISCUSSION

Breast Reconstruction Model

In our reconstruction model, the breast model was made with 3 main layers including skin, fat and breast tissue. Figure 3 shows the breast model built using Mimic Innovation Suite software (Materialise HQ, Leuven, Belgium).

Breast models are built as a triangular mesh and they are presented as off files to match the MOSE software. Figure 4 shows the breast model reconstructed as a freeform mesh and changed to a triangular mesh.

Light distribution breast tissue

Absorption and scattering of photons in turbid media in general or in breast tissue in particular is a complex process related to the physical and chemical properties of the medium. In this study, the propagation of photons into the breast tissue was simulated using MOSE software. The scenario given is the propagation of the laser into the normal and tumor-free breast model at three wavelengths 650 nm, 800 nm and 950 nm. The absorption maps of photons in the models were reconstructed with MATLAB and shown in Figures 5 and 6.

The photon absorption maps in Figure 5 show strong absorption of normal breast tissue at the wavelengths of 650 nm, 800 nm, and 950 nm. The absorption of breast tissue is characterized by the main components that make it up including hemoglobin, lipids and water.

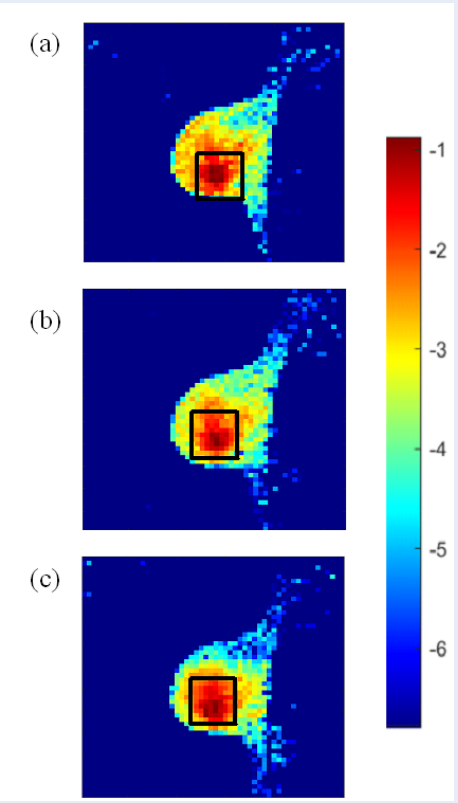

Figure 5: The absorption map of normal breast tissue at (a) 650 nm, (b) 800 nm and (c) 950 nm.

Meanwhile, in the simulation scenario of breast tissue with tumors, a heterogeneous model was built to model the treat lesions or tumors in breast tissue as an object in a homogeneous background[5]. The absorption map in Figure 6 shows that, in addition to the strong absorption in the breast tissue, photons absorbed by the tumor are embedded in the model. The cause of the strong absorption in the tumor is because the tumor cells have an abnormal metabolism compared to the surrounding normal tissues, they are nourished by many blood vessels to supply oxygen and nutrients. In addition, tumor cells differ significantly from nearby capillaries in terms of oxygen dif-

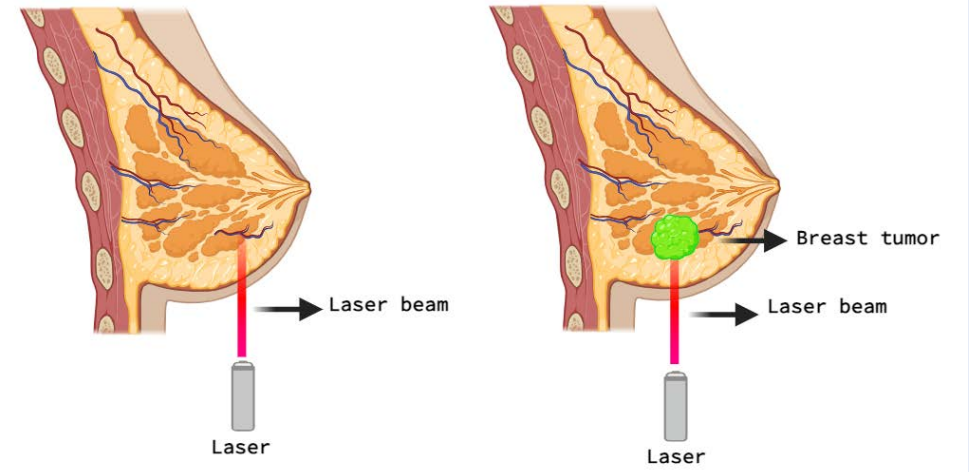

Figure 2: The simulation model with (a) normal tissue and (b) breast tumor tissue.

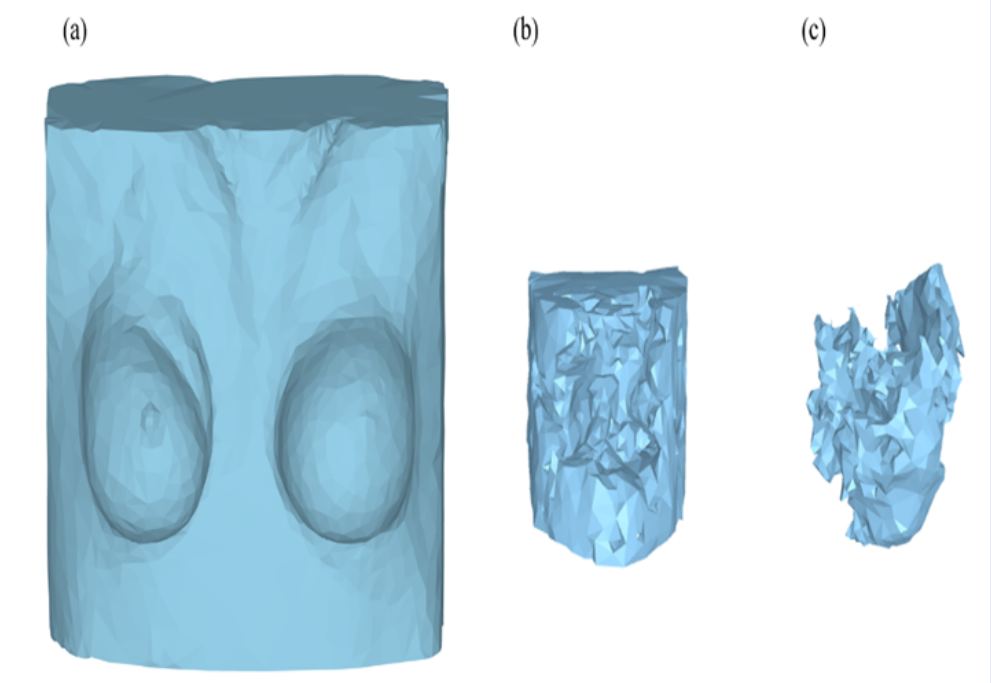

Figure 3: The 3D optical model of breast. (a) skin (b) fatty tissue and (c) glandular tissue.

Table 1: Optical properties of breast [18,19].

Wavelength (nm)	Tissue type	μa (mm^{-1})	μs (mm^{-1})	(g)
650	Skin	0.5852	18.3514	0.9000
	Adipose (Fatty) Tissue	0.0880	30.1600	0.9736
	Glandular Tissue	0.0650	42.1700	0.9630
	Tumor	0.7700	30.8900	0.9610
800	Skin	0.0430	14.0000	0.9000
	Adipose (Fatty) Tissue	0.0820	31.3800	0.9760
	Glandular Tissue	0.0550	33.2700	0.9500
	Tumor	0.6500	9.4100	0.9000
950	Skin	0.2979	16.8000	0.9000
	Adipose (Fatty) Tissue	0.0850	30.8900	0.9763
	Glandular Tissue	0.0710	24.5600	0.9620
	Tumor	0.4500	16.2900	0.9555

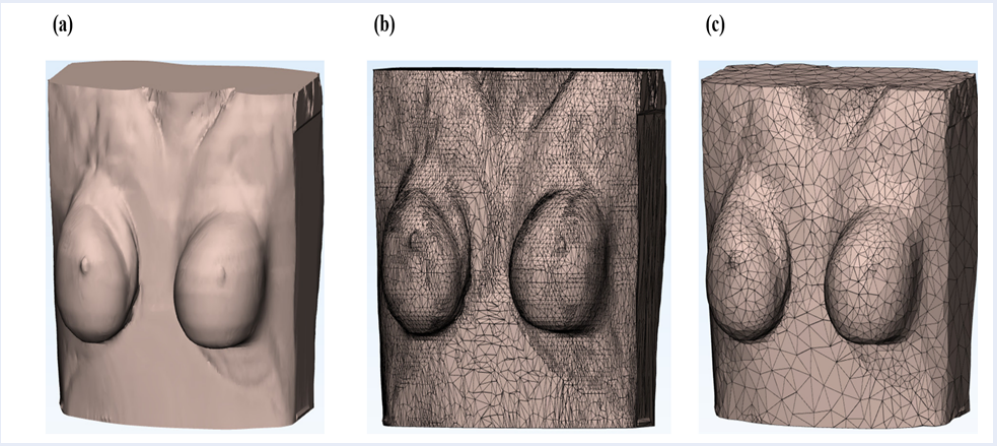

Figure 4: The breast reconstruction model with (a) block model (b) free mesh and (c) triangle mesh.

fusion limits and higher hemoglobin concentrations compared with normal tissues [5,19].

Figures 7 and 8 show absorption maps of normal and abnormal breast tissue in the contour map.

Based on the absorption contour maps shown in Figures 7 and 8, the tumor locations in the model are clearly represented by the absorption contour. Because of the difference in the optical properties of the tissues at the wavelengths of 650 nm, 800 nm and 950 nm, there is a difference in the absorption of photons in the tumor. This is clearly shown in Figure 9 when the absorption is depicted in 3D.

At each wavelength investigated, the absorption of photons in breast tissue is closely related to the absorption spectrum of the constituents of breast tissue. While at 650 nm the absorption of hemoglobin becomes relatively large, the wavelength of 800 nm is characteristic of near the absorption peak of deoxyhemoglobin and the wavelength of 950 nm is characteristic of the absorption peak of lipids and amount of water in breast tissue [8].

Figure 10 shows a graph showing the maximum absorptivity in normal and abnormal breast tissue at the three wavelengths examined.

As the results show in Figure 10, the most obvious difference in absorbance between normal and tumor tissue is at the wavelength of 650 nm. This result is similar to the experimental results of Albert E. Cerussi et

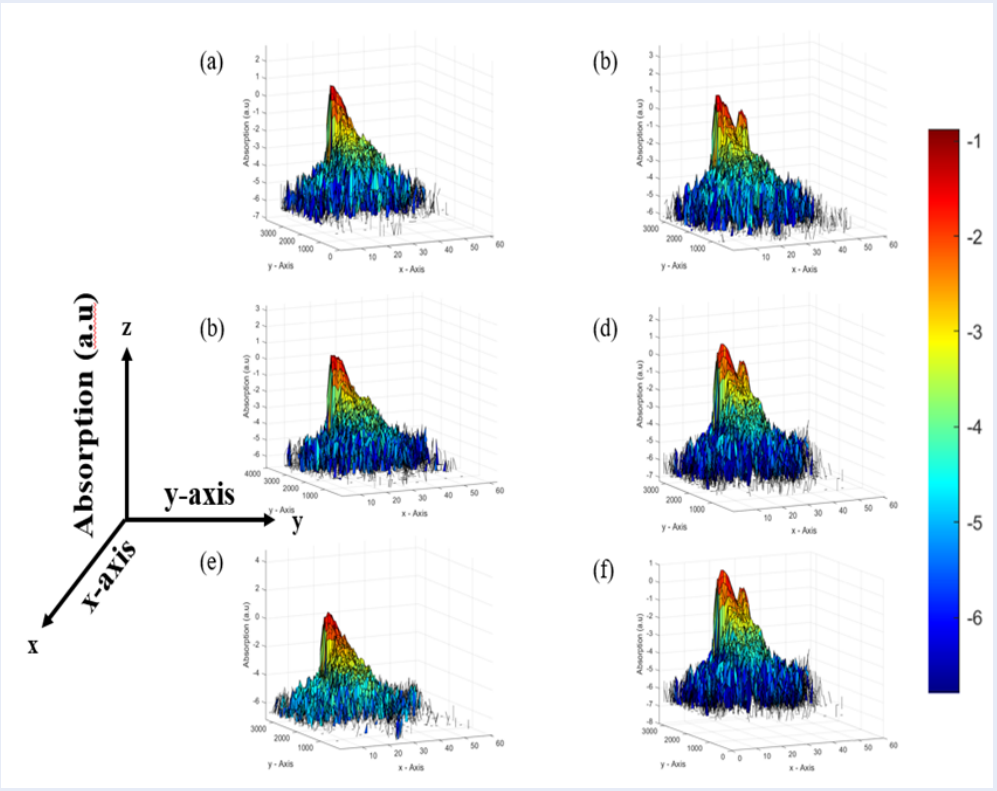

Figure 9: The 3D absorption map of normal breast tissue at (a) 650 nm (b) 800 nm (c) 950nm and abnormal tissue at (d) 650 nm, (e) 800nm (d) 950 nm.

al in 2006 [18].

The cause of the marked difference in absorbance at 650 nm versus 800 nm and 950 nm is attributed to the hemoglobin composition. Malignant tumors are often fed by more blood vessels than the surrounding normal tissue [6,18]. Consequently, there is an increase in oxygen-hemoglobin in melanoma compared with normal tissues, which in turn leads to more pronounced absorption results at 650 nm.

CONCLUSION

The development of optical techniques for the early detection of breast tissue abnormalities is one of the main keys to effective treatment control. However, the interaction of light in biological tissue in general and breast tissue in particular remains a challenge for research.

In this study, the light of 650 nm, 800 nm and 950 nm propagation were simulated in a breast model that reconstructed using a set of MRI images. The investigated wavelengths characterize the absorption peaks of the constitutive components of breast tissue including hemoglobin, lipids and water.

The simulation results show the difference in absorbed energy levels of normal and abnormal breast models. Photons are highly concentrated in the tumor due to metabolic abnormalities leading to differences in optical properties. The results show the absorption maps of the breast model at wavelengths similar to those found in optical mammography experiments [5,8].

The simulation results in this study serve as a guide for further studies in the development of optical methods for breast diagnosis and the design of device models.

LIST OF ABBREVIATIONS

MRI: Magnetic Resonance Imaging.
MC: Monte Carlo.
CBE: Clinical Breast Examination.
TD: Time Domain.
FD: Frequency Domain.
CW: Continuous Wave.

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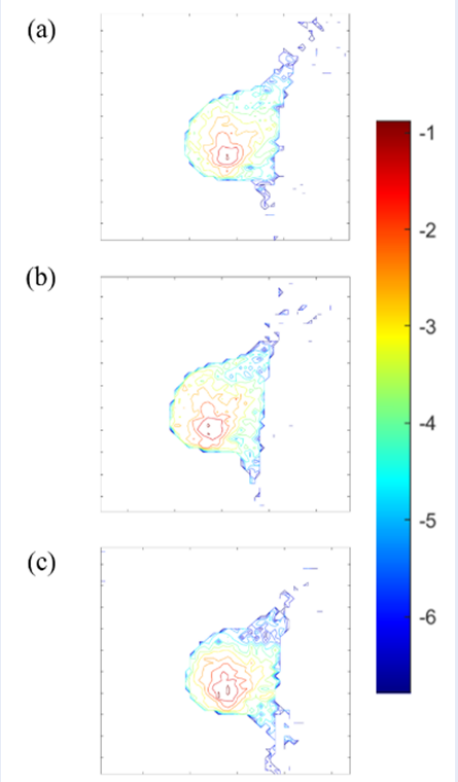

Figure 7: The absorption contour map of normal breast tissue at (a) 650 nm, (b) 800 nm and (c) 950 nm.

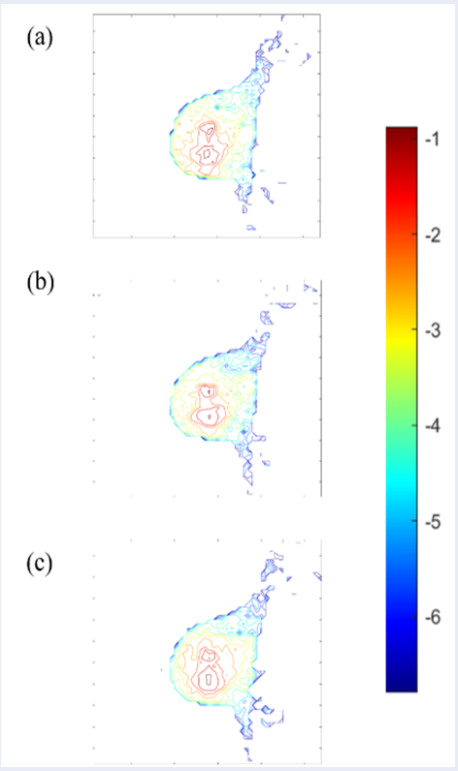

Figure 8: The absorption contour map of abnormal breast tissue at (a) 650 nm, (b) 800 nm and (c) 950 nm.

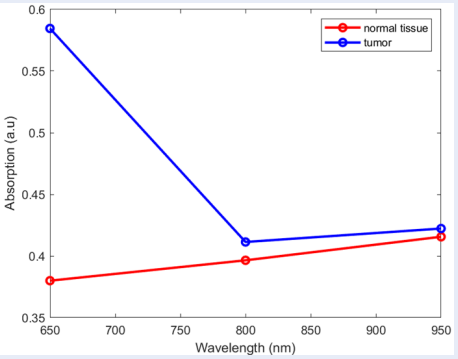

Figure 10: The maximum absorption of normal and abnormal breast tissue in simulation results.

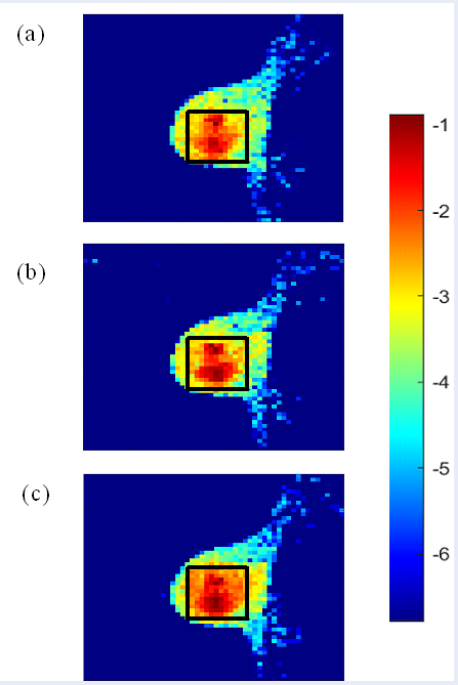

Figure 6: The absorption map of abnormal breast tissue at (a) 650 nm, (b) 800 nm and (c) 950 nm.

CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

AUTHOR CONTRIBUTIONS

All authors contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

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Bài nghiên cứu

Mô hình hóa sự lan truyền ánh sáng trong mô hình vú tái tạo bằng phương pháp Monte Carlo

Hà Quý Tân[1,2], Đặng Nguyễn Ngọc An[1,2,*], Trần Trung Nghĩa[1,2]

TÓM TẮT

Ung thư vú là một trong những loại ung thư phổ biến gây tử vong cao nhất ở phụ nữ. Một trong những khía cạnh chính của việc theo dõi hiệu quả hiệu quả điều trị ung thư vú là phát hiện sớm những bất thường trong mô vú. Đây là một trong những yếu tố quan trọng nhất có thể xác định liệu pháp điều trị ung thư vú được thực hiện tốt như thế nào. Mặt khác, các kỹ thuật được sử dụng trong chẩn đoán vú ngày nay có một số hạn chế, bao gồm các nguy cơ liên quan đến phơi nhiễm phóng xạ, giá cao và khả năng tạo ra kết quả dương tính giả. Do đó, các kỹ thuật quang học được coi là chiến lược khả thi để chẩn đoán sớm các bất thường ở vú. Kỹ thuật quang học đã được nghiên cứu để phát triển các thiết bị hỗ trợ tự chẩn đoán và các thiết bị công nghệ cao như chụp cắt lớp quang học. Sự phát triển gần đây của các ứng dụng điều trị bằng ánh sáng công suất thấp cũng tạo ra một hướng mới trong điều trị các khối u lành tính thông qua hiệu ứng quang sinh học. Do đó, cần phải tiến hành nhiều nghiên cứu hơn nữa để hiểu cách ánh sáng tương tác với mô vú để phát triển thiết bị chẩn đoán và thiết bị điều trị. Trong nghiên cứu này, tương tác ánh sáng với mô đã được nghiên cứu bằng cách mô phỏng sự lan truyền ánh sáng ở các bước sóng 650 nm, 800 nm và 950 nm trong mô hình vú được tạo ra bằng cách thu thập dữ liệu MRI. Cụ thể, sự hấp thụ ba bước sóng này của mô được đánh giá để hiểu rõ hơn cách ánh sáng tương tác với mô vú. Kết quả mô phỏng cho thấy người mẫu ngực bình thường và người mẫu ngực ốm có tổng lượng năng lượng hấp thụ khác nhau đáng kể và những kết quả này cho thấy sự khác biệt này. Bản đồ phân bố ánh sáng thu được tương quan với hình ảnh thu được bằng cách sử dụng hình ảnh thấu quang. Các kết quả mô phỏng có thể thúc đẩy nghiên cứu sâu hơn hướng tới việc phát triển một phương pháp chẩn đoán vú mới dựa trên các phương pháp quang học.

Từ khoá: Mô phỏng Monte Carlo, Mô vú, Lan truyền ánh sáng, Hấp thụ, Truyền qua

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