Numerical and Experimental Analysis of High Frequency Acoustic Microscopy and Infrared Reflectance System for Early Detection of Melanoma

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The target of this work is the presentation of the optimal design of the scheme combining high frequency acoustic microscopy and infrared reflectance system for the early detection of melanoma. Specifically, the identification of morphological changes related to carcinogenesis is required. In this work, we simulate the propagation of the ultrasonic waves of the order of 100 MHz as well as of electromagnetic waves of the order of 100THz in melanoma structures targeting to the estimation and optimization of the basic characteristics of the under development systems. The simulation results of the acoustic microscopy subsystem aim to provide information such as the geometry of the transducer, the center frequency of operation, the focal length where the power transmittance is optimum and the spot size in focal length. As far as the infrared is concerned, the optimal frequency range and the spot illumination size of the external probe is provided. This information is next used to assemble a properly designed system which is applied to melanoma phantoms as well as real skin lesions. Finally, the measurement data are visualized to reveal the information of the experimented structures, proving noteworthy accuracy.

Ultrasonic of high frequency wave propagation simulation in melanoma simulating structure using Finite Difference Time Domain (FDTD) technique

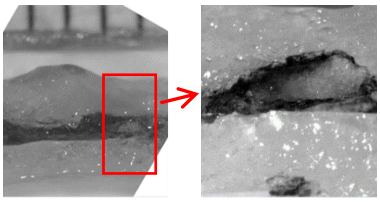
The simulations are performed in two dimensions (2D), which are mainly developed for planar objects (stratified media). When an acoustic wave excites a skin phantom, its particles are being displaced. The equation that is used for the calculation of the particles displacement **u**= [*ux*, *uy*]^T in each point of the skin phantom for each time instance *t* is the approximation of the elastic wave equation:

$$\rho \frac{\partial^2 \tilde{u}}{\partial^2 t} = \left[\lambda + \mu + \varphi \frac{\partial}{\partial t} + \frac{\eta}{3}\frac{\partial}{\partial t}\right]\nabla\left(\nabla\cdot\tilde{u}\right) + \left[\mu + \eta\frac{\partial}{\partial t}\right]\nabla^2\tilde{u},$$

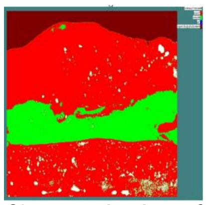
where $\vec{u} = \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix}$ are the shift of particles in three dimensions [m],

ρ= density of material [kg/m3]
λ, μ= first and second regularly Lamé [N/m^2]
η= shear viscosity [N*s/m2]
φ= bulk viscosity [N*s/m2],

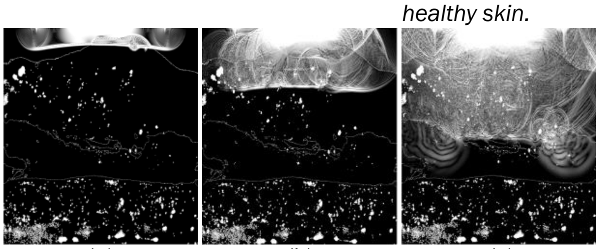
Phantom creation and simulation of wave propagation in it



Cross section of melanoma phantom (optical microscope).



Characterization of the melanoma areas and the healthy skin.

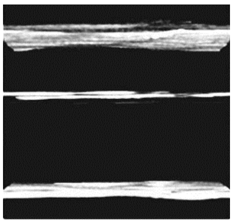


(a) (b) (c)

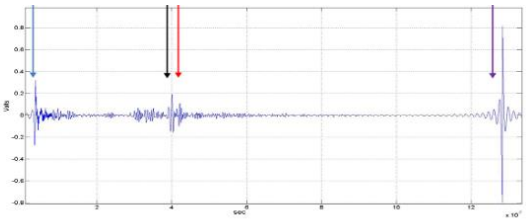
Excerpt instances of the simulation of the acoustic wave propagation through a phantom of melanoma, in (a) the acoustic wave reaches to the upper layer, in (b) the wave propagates through the interface between the 1st (simulated skin) and 2nd layer (melanine) and in (c) the wave propagates through the interface between the 2nd (melanine) and the 3rd layer (simulated skin).

Real scan using 175MHz transducer of the phantom

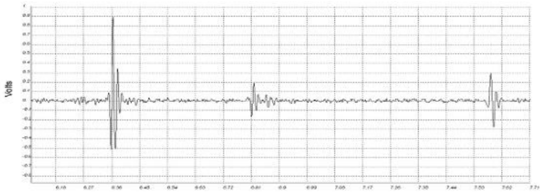
The transducer of 175MHz while scanning the phantom.



Measured C-Scan of the phantom revealing the layer simulating melanoma.



Simulated a-scans



Corresponding measured a-scans

Simulation of EM waves propagation in melanoma simulated structure using Finite Integration Technique (FIT)

Theory

FIT discretize Maxwell's equations in integral form – equations enabling easier physical interpretation of electromagnetic theory.

$$\oint_{\partial S} \mathbf{E}\cdot d\mathbf{l} = -\iint_S \frac{\partial \mathbf{B}}{\partial t}\cdot d\mathbf{S}$$

$$\oint_{\partial S} \mathbf{H}\cdot d\mathbf{l} = \iint_S \left(\frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}\right)\cdot d\mathbf{S}$$

$$\oiint_{\partial V} \mathbf{D}\cdot d\mathbf{S} = \iiint_V \rho \cdot dV$$

$$\oiint_{\partial V} \mathbf{B}\cdot d\mathbf{S} = 0$$

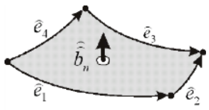
$$\hat{e}_k = \int_{L_k} \mathbf{E}\cdot d\mathbf{l}$$

$$\hat{\hat{b}}_m = \iint_{A_m} \mathbf{B}\cdot d\mathbf{S}$$

Faraday:

$$+\hat{e}_1 + \hat{e}_2 - \hat{e}_3 - \hat{e}_4 = -\frac{d}{dt}\hat{\hat{b}}_n$$

$$\sum_{j:L_k\in G} C_{ij}\hat{e}_j = -\frac{d}{dt}\hat{\hat{b}}_i \quad \forall i : A_i \in G$$

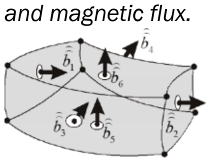


Interface A_m a cell of the grid, and the distribution voltages and magnetic flux.

Gauss:

$$-\hat{\hat{b}}_1 + \hat{\hat{b}}_2 - \hat{\hat{b}}_3 + \hat{\hat{b}}_4 - \hat{\hat{b}}_5 + \hat{\hat{b}}_6 = 0$$

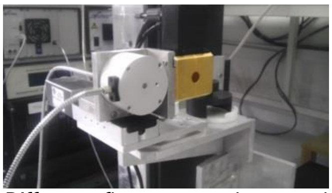
$$\sum_{j:A_j\in G} S_{ij}\hat{\hat{b}}_j = 0 \quad \forall i : V_i \in G$$



Magnetic flows distribution on the surfaces of a cell of the lattice G.

Measurement of the ε_r of skin and melanine

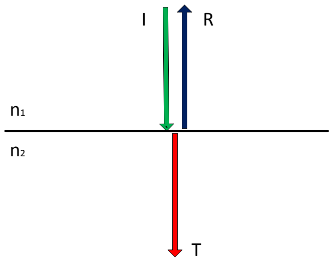
Tablet-pellet of melanin.



Diffuse reflectance probes used for the measurement of the ε_r of melanine and skin phantom using infrared reflectance spectroscopy.

$$R_m(l) = 1 - T_m(l) = \frac{n_1 - n_2}{n_1 + n_2}$$

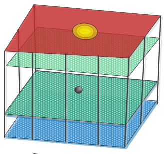
$$R_m(l) = \frac{\sqrt{\frac{e_1}{e_o}} - \sqrt{\frac{e_2}{e_o}}}{\sqrt{\frac{e_1}{e_o}} + \sqrt{\frac{e_2}{e_o}}} \;\text{Ÿ}\; R_m(l) = \frac{\sqrt{e_1} - \sqrt{e_2}}{\sqrt{e_1} + \sqrt{e_2}}$$



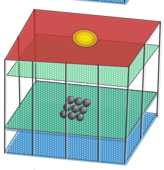
$R_m(\lambda)$, the measured reflection spectra and $T_m(\lambda)$, the transmittance spectra from the melanine and the skin and n_1 and n_2 the refraction index of the free space and the melanine or the skin respectively.

Model of skin with melanoma tumour of various sizes illuminated in the infrared area of the spectrum using various illumination spot sizes

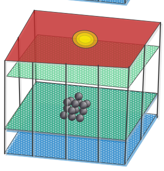
The model includes the epidermis, dermis layer and the hypodermis layer. The measured εr for the skin and the melanine was inserted in the model. Then in the corresponding area of the basal cells starting from small structures and increasing them simulation the creation of melanoma propagation towards the epidermis and hypodermis were inserted in the model. The illumination sizes varies from 1.5 mm to 0.25mm diameter.



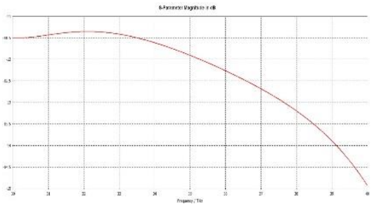
The structure of the model with one "grain" of melanine.



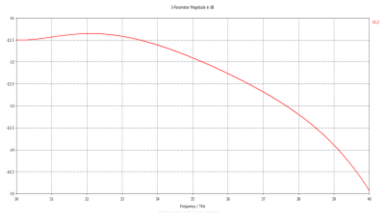
The structure of the model with nine "grains" of melanine.



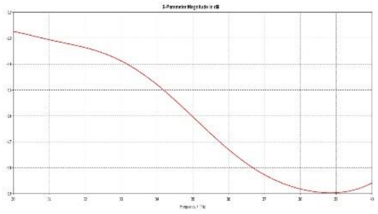
The structure of the model with 24 "grains" of melanine.



The received spectra- 1 grain (different compared to the measured melanine one).



The received spectra- 9 grain (still different compared to the measured melanine one).



The received spectra- 24 grains (starting changing like the measured pattern of the melanine one).

Results

High frequency acoustic wave simulation executed using FDTD method. The results from the simulations and the prototype developed system show very good agreement among them. The frequencies used according to the simulations are covering the area between 50-175MHz and the spot size area is of the order of 0.1μm. The radiation of the infrared area of the spectrum penetrates the skin in depths that are sufficient for the detection of melanine and melanoma cases in the band from 7000cm^{-1} up to 400cm^{-1}. The illumination sizes finally developed are of the order of 0.5mm permitting the high resolution spectroscopic mapping imaging.