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Time resolved inclusion investigation for continuous wave light

H. O. Kazanci[1]

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Abstract Time resolved inclusion investigation method has been tested based on the Monte Carlo Modeling of Light (MCML) Transport. Seven layers head structure has been built. Tissue layers are hair 100 μm, epidermis 100 μm, dermis 1 mm, skull 5 mm, cerebrospinal fluid 5 mm, gray matter 5 mm, and up to 3 cm overly thick white matter. MCML photon fluencies have been used to generate time resolved input angle forward model sensitivity weight matrix. Forward model weight matrix has been built according to the back reflected diffuse optical tomography (DOT) device model geometry. The new, triangulated input angle photon penetration model which is correlated to time resolved mode for continuous wave light has been used first. 1 source and 299 detectors were placed on the 3 cm by 3 cm grid model. Number of z Nz, and number of x Nx grid coordinates are 299 by 299. This work was done to prepare for Programmable Delay Chip (PDC) circuit included analog current input digital voltage output analog to digital converter (ADC) chip. By the help of PDC circuit, continuous wave (CW) photons which cross from different depth layers will be collected in different integrating time intervals by the capability of PDC circuit. In the simulation model, blood inclusion was buried into skull in approximately 1.8 mm depth. As long as employing the measurement capability of PDC circuit, different depth level voxels would be scanned. In this work, with the presumable existence of PDC data, an image reconstruction algorithm has been developed. The inverse problem solution has been done by pseudoinverse matrix solution method. Forward model sensitivity weight matrix functions have been calculated and used in image reconstruction algorithm.

Keywords Time resolved input angle forward model sensitivity weight matrix · Programmable Delay Chip (PDC) circuit

✉ H. O. Kazanci
ozgurkazanci@akdeniz.edu.tr; ozgurkazanci@gmail.com

[1] Department of Biomedical Engineering, Faculty of Engineering, Akdeniz University, 07058 Antalya, Turkey

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1 Introduction

In this work, new time resolved inclusion investigation method for continuous wave (CW) laser diffuse optic tomography (DOT) model has been tested. A two dimensional (2D) depth imaging plane has been used for its simplicity. 3 cm by 3 cm imaging media was built. It has been assumed that back-reflected photons were collected by photodiode photodetectors and connected to analog current input digital voltage output integrators driven by Programmable Delay Chip (PDC) circuit. This will include application specific integrated circuit (ASIC) very large scale integration (VLSI) Analog to Digital Converter (ADC) design chip. PDC circuit will trigger to acquire time resolved depth dependent (CW) photons in different time intervals which means different penetration depth layers. In this work, new search philosophy, not directly diffuse optic tomography (DOT) approach but indirectly method which is investigating inclusion location is being introduced. Hence the photons' scattering mechanism inside the heterogeneous tissue, direct tomography model is failing. So, new approaches and philosophies are need to be studied. Time resolved photon propagation analysis constitute two basic forms. One is pulsed laser propagation, and the other one is time resolved propagation of continuous wave (CW) light. According to time resolved mode of CW light propagation, in the different time intervals, back-reflected light is measured. In the different time intervals, such as 10 picoseconds and folds, CW light photons sweep different layer voxels. Roughly, we can apply input angle mask to CW forward model photon transport functions. This is ampirical approximation to time resolved CW photon transportation. In this work, it was presumed that timed resolved CW data is ready to use. In the real world application, time resolved CWDOT data will be acquired by specific PDC based ADC circuit.

2 Materials and methods

2.1 Time resolved forward model for continuous wave (CW) light

The inclusion was buried in skull, and then it was reconstructed. Forward model weight matrix has been divided into sub-weight matrixes according to time dependent input angle masks. While building the forward model, certain level weight matrix coefficients have been used between source and detector coordinate positions. As long as the PDC circuit acquires the depth dependent photons, imaging tissue geometry can be divided into different depth level slabs. Presumably until the certain level of depth it has been assumed

Table 1 Optic properties of imaging tissue

Tissue	Hair (100 μm)	Epidermis (100 μm)	Dermis (1 mm)	Skull (5 mm)	CSF (5 mm)	Gray matter (5 mm)	White matter (…–3 cm)
μ_a (cm^{-1})	20.619	4.136	0.022	0.009	0.020	0.059	0.059
μ_s (cm^{-1})	104.875	247.525	138.25	185.644	0.010	104.875	104.875

that no experimental measurement differences observed which generates no perturbation data. At certain depth level, perturbation data is observed.

Monte Carlo Modeling Light (MCML) transport model has been used. Multi-layer Monte Carlo (MC) simulation was run. The head model has 7 different layers according to Table 1. First layer is hair, absorption coefficient $\mu_a = 20.619\ cm^{-1}$, scattering coefficient $\mu_s = 104.875\ cm^{-1}$, anisotropy coefficient $g = 0.9$, hair slab thickness is 100 μm. Second layer is epidermis, absorption coefficient $\mu_a = 4.136\ cm^{-1}$, scattering coefficient $\mu_s = 247.525\ cm^{-1}$, anisotropy coefficient $g = 0.9$, epidermis slab thickness is 100 μm. Third layer is dermis, absorption coefficient $\mu_a = 0.022\ cm^{-1}$, scattering coefficient $\mu_s = 138.250\ cm^{-1}$, anisotropy coefficient $g = 0.9$, dermis slab thickness is 1 mm. Fourth layer is skull, absorption coefficient $\mu_a = 0.009\ cm^{-1}$, scattering coefficient $\mu_s = 185.644\ cm^{-1}$, anisotropy coefficient $g = 0.9$, skull slab thickness is 5 mm. Fifth layer is Cerebrospinal fluid (CSF), absorption coefficient $\mu_a = 0.020\ cm^{-1}$, scattering coefficient $\mu_s = 0.010\ cm^{-1}$, anisotropy coefficient $g = 0.98$, CSF slab thickness is 5 mm. Sixth layer is Gray Matter, absorption coefficient $\mu_a = 0.059\ cm^{-1}$, scattering coefficient $\mu_s = 104.875\ cm^{-1}$, anisotropy coefficient $g = 0.9$, Gray Matter slab thickness is 5 mm. Seventh layer is White Matter, absorption coefficient $\mu_a = 0.059\ cm^{-1}$, scattering coefficient $\mu_s = 104.875\ cm^{-1}$, anisotropy coefficient $g = 0.9$, White Matter slab thickness is 2.5 cm.

In Fig. 1 MCML realization of photon fluencies, deposited energies, Rr diffuse reflectance, Az one dimensional deposited energy, and Fz one dimensional fluence rates can be seen. MCML data have been generated in ANSI C program then transferred to MatLAB™ programming environment. Different depth layer forward model weight matrix functions have been built by the methods described in the previous works (Kazanci and Jacques 2015; Kazanci 2015a, b, c, 2016a, b, c; Kazanci and Canpolat 2014, 2015a, b; Kazanci et al. 2015; Kazanci and Oduncuoglu 2015). In Fig. 2, generated forward model weight matrix functions can be seen. In the real world applications, when the back reflected

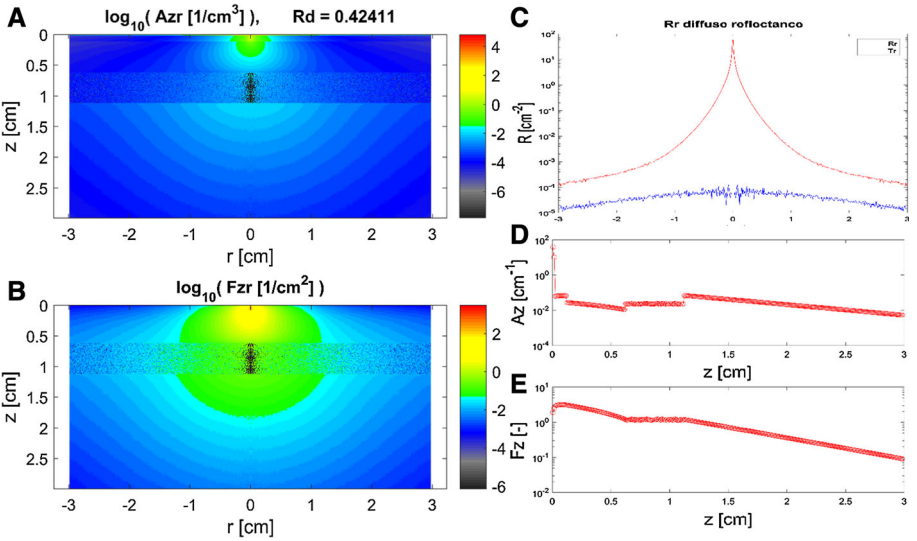


Fig. 1 Deposited energy Azr (**a**), fluence rates Fzr (**b**), diffuse reflectance Rr (**c**), one-dimensional deposited energy Az (**d**), One-dimensional fluence rate deposition Fz (**e**)

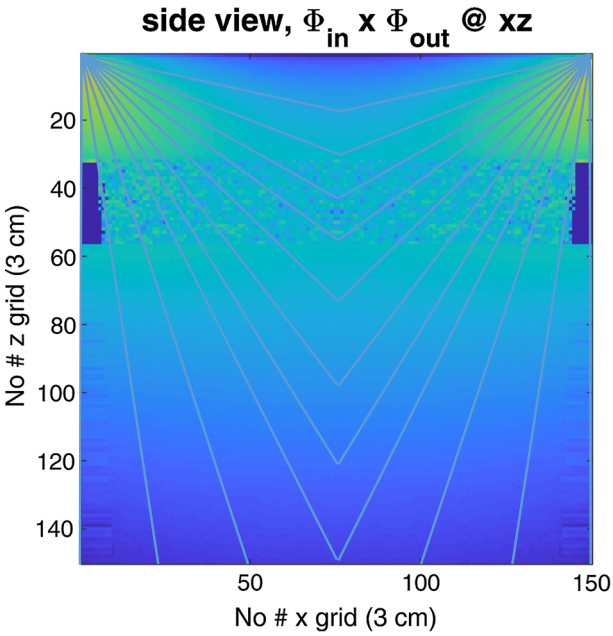


Fig. 2 Forward model weight matrix

diffuse reflectance photons are measured by the photodiode, the PDC circuit will break apart the differences over different depth layer weight functions. Here for demonstration purposes, weight matrix functions have been shown.

Photon fluencies have been transferred into MatLAB™ environment. Between source and detector positions forward model weight functions have been generated. One of the forward model weight functions for source and 150th detector has been shown in Fig. 2. In this work, time resolved photon current lines have been tested first. According to this model, photon trajectories have been grouped in different input angle groups. Solid angle lines were drawn in Fig. 2. According to this method, each CW photon groups will be acquired in different time resolved mode.

3 Results

The inclusion was buried into depth which is shown in Fig. 3 as yellow in dark blue background. In 1.8 mm depth, 100 μm thick inclusion object was buried in skull tissue. Perturbation data were created by multiplying 45° input angle line forward model weight matrix coefficients with inclusion according to triangulated model as shown in Fig. 2. Finally the inclusion image was reconstructed by simple inverse problem solution algorithm as seen in Fig. 4. Pseudoinverse mathematical inverse problem solution method was used to see the result.

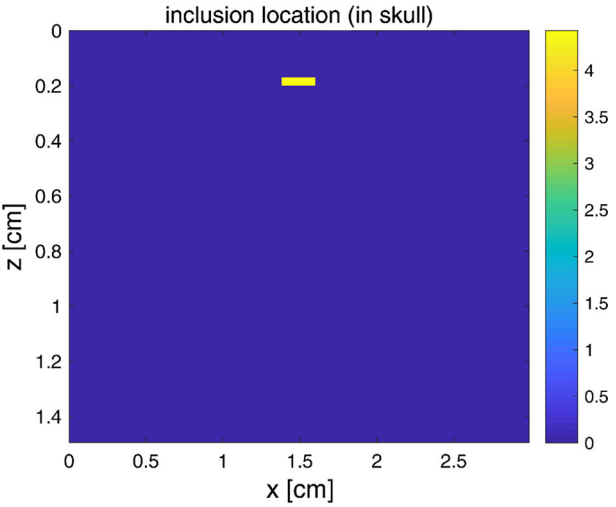


Fig. 3 Inclusion location in skull (1.8 mm depth)

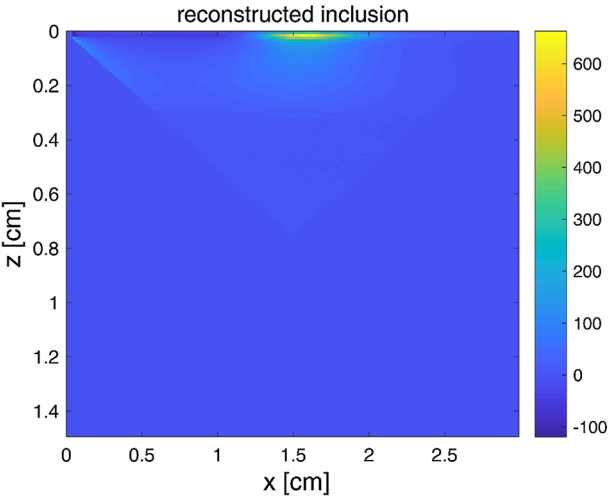


Fig. 4 The reconstructed inclusion (250 μm depth)

4 Discussion

Reconstructed images which have been created by inverse problem solution algorithms of laser tomography systems have difficulty because of less information about depth and less ability to reconstruct deep voxels. Especially for multi-layer diffuse optical tomography (DOT) systems, such as in this work head tomography model has nothing to show from the view of reconstructed image perspective if the whole tissue slab is used to build forward model and compute all weight matrix functions. In this work instead of using whole tissue slab forward model weight matrix coefficients, only time resolved depth dependent

forward model weight matrixes have been used. The main goal of this study was to partition CW forward model weight matrix in time resolved mode and use those subunits to investigate buried inclusions in biomedical materials. As it can be seen from Fig. 4, buried inclusion in skull was reconstructed superficially.

It was presumed that time resolved photon measurements will be done successfully. Specific time resolved mode forward model photon fluencies have been used for CWDOT system according to new triangulated input angle method. When the inclusion is in input angle projectory of source and detector positions which photons touch the inclusion, it is being reconstructed successfully no matter where it is. If the input angle does not see the buried inclusion then it is not being reconstructed. The only disadvantage, reconstructed image is superficial, but in this work the main goal was investigation of inclusion instead of tomography. So, it was succeeded. Triangulated angles are correlated to time resolved data acquisition of CW diffuse light.

5 Conclusions

Time resolved depth dependent image reconstruction schema for CWDOT systems has been shown. The new triangulated input angle photon penetration correlated to time resolved mode of CW diffuse light has been tested first. The reconstructed image shown that PDC circuit would be used for DOT imaging modalities, no matter the type of examined tissue. Time resolved, depth dependent approach will succeed according to time resolved integrator switching circuit topology. As technological development is in process, in this work only a presumable approach has been studied as a precursor for better future works. In the future, new time resolved CW light devices would be manufactured.

Compliance with ethical standards

Conflict of interest The author declares that he has no competing interests. Financial competing interests: In the past 5 years the author has not received reimbursements, fees, funding, or salary from any organization that may in any way gain or lose financially from the publication of this manuscript, either now or in the future. The author works as Assistant Prof. Dr. at a university that is not financing this manuscript (including the article-processing charge). The author has not held any stocks or shares in an organization that may in any way gain or lose financially from the publication of this manuscript, either now or in the future. The author does not hold or he is not currently applying for any patents relating to the content of the manuscript. The author has not received reimbursements, fees, funding, or salary from an organization that holds or has applied for patents relating to the content of the manuscript. He does not have any other financial competing interests. Non-Financial competing interests: There are no non-financial competing interests (political, personal, religious, ideological, academic, intellectual, commercial or any other) to declare in relation to this manuscript.

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