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Simulation based investigation of source-detector configurations for non-invasive fetal pulse oximetry

Abstract: Transabdominal fetal pulse oximetry is a method to monitor the oxygen supply of the unborn child non-invasively. Due to the measurement setup, the received signal of the detector is composed of photons coding purely maternal and photons coding mixed fetal-maternal information. To analyze the wellbeing of the fetus, the fetal signal is extracted from the mixed component. In this paper we assess source-detector configurations, such that the mixed fetal-maternal components of the acquired signals are maximized. Monte-Carlo method is used to simulate light propagation and photon distribution in tissue. We use a plane layer and a spherical layer geometry to model the abdomen of a pregnant woman. From the simulations we extracted the fluence at the detector side for several source-detector distances and analyzed the ratio of the mixed fluence component to total fluence. Our simulations showed that the power of the mixed component depends on the source-detector distance as expected. Further we were able to visualize hot spot areas in the spherical layer model where the mixed fluence ratio reaches the highest level. The results are of high importance for sensor design considering signal composition and quality for non-invasive fetal pulse oximetry.

Keywords: Monte-Carlo simulation; photon propagation; fetal pulse oximetry; voxel model

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1 Introduction

Pulse oximetry is a clinical standard method for measuring oxygen saturation non-invasively since decades. Applying the basic principle to the abdomen of a pregnant woman is an approach still under research. The feasibility of the method has been shown by several animal and simulation studies [2, 5, 6]. Two or more light sources are placed on the abdomen of the pregnant woman. Emitted photons travel through maternal and fetal tissue layers, are scattered, absorbed and reflected. According to the principle of reflection pulse oximetry, a photo-detector captures photons reflected back to the surface of the abdomen [8]. The acquired signal is composed of two kinds of photons. There are photons that traveled through maternal tissue, coding purely maternal components and there are photons that reached fetal tissue layers, coding mixed fetal-maternal information. Signal composition in this context is mainly influenced by the interaction of source-detector distance and geometry of the tissue layers [3, 4].

Transabdominal fetal pulse oximetry requires the extraction of the fetal signal, maternal components are regarded as disturbancies. To facilitate signal separation the power of purely maternal components can be minimized by applying a proper source-detector configuration [3, 4].

This paper describes an investigation of the influence of source-detector distances to the signal composition more in detail. Monte-Carlo method is used to simulate light propagation inside maternal and fetal tissue layers. The basic investigations described in [3] are based on a three-layered plane model. We extended the approach to also analyze a more complex and more realistic spherical model. The simulation results give an indication of a suitable sensor configurations for implementation in non-invasive fetal pulse oximetry.

2 Methods

2.1 Monte-Carlo method

Monte-Carlo method enables to compute the path of single photons through tissues up to photon interactions with the tissue. Further, photon fluence in various depths and tissue layers is computed. The algorithm described by Wang and Jacques in [7] is widely used to analyze photon distributions in tissue. The program uses planes with infinite width to model different tissue layers.

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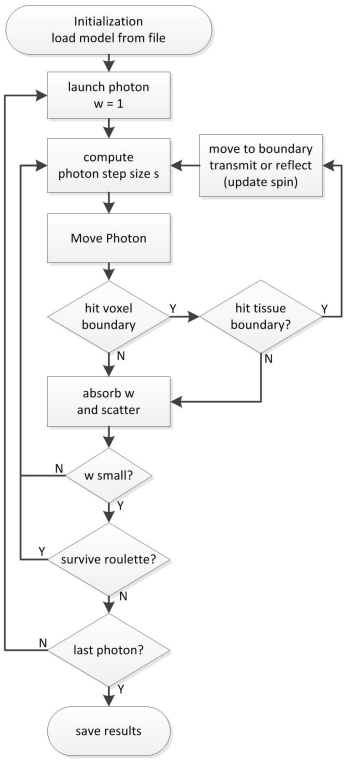

Figure 1: Flowchart of the algorithm used to simulate photon propagation in a voxel based tissue model. The algorithm is motivated by [7] and [1].

In this work the algorithm is extended to allow utilization of more complex and realistic (voxel-based) model geometries, inspired by Boas et al. [1]. However, photon migration in general is done as described in [7], considering a finite number of voxel elements. The flowchart of our algorithm is shown in Fig. 1. First, the software initializes and loads the model data from a file to the main memory to, speed up read and write processes. A photon is launched with normalized weight w of 1 and a tissue specific step size s. In case there is no tissue boundary on the path, w is reduced and saved to the current voxel. The values saved to the voxels are interpreted as absorption and used to compute the fluence as described in [7]. Scattering is done by updating the spin of the photon after the step. If there are voxel boundaries along the way of the photon and a tissue boundary is reached, the photon stops at the boundary. Based on Fresnel's law the photon is reflected at the boundary or transmitted into the next tissue. After the interaction, the photon finishes the step with a new direction and an updated step size. At the end of every step w is checked. Roulette is performed if w is smaller than 0.0001. If the photon survives the roulette, one more step is computed, else the photon is terminated and a new one is launched. The algorithm terminates, if the preset number of photons migrated through the tissue model. Photons that reached fetal tissue layers are marked to allow extraction of the fluence caused by purely maternal and mixed fetal-maternal photons at the surface of the model. Mixed components of the detected signal correspond to the fluence generated by marked photons, unmarked photons carry purely maternal components. Total signal power is the sum of these two components. We successfully validated the algorithm by performing the standard simulations described in [7].

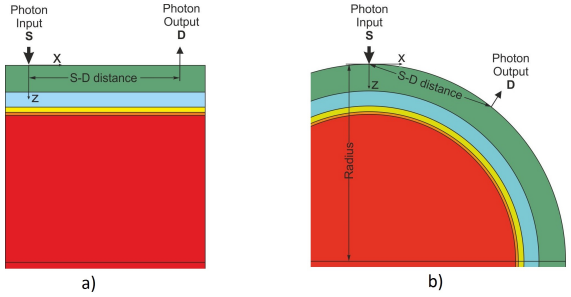

Figure 2: Visualization of the plane (a) and the spherical (b) models. Both models consist of five tissue layers (top to down): maternal tissue, amniotic fluid, fetal tissue, fetal skull and fetal brain.

2.2 Tissue model and simulation setup

The model geometry is based on three dimensional cubic voxels with an edge length of 0.02 cm. We considered two basic shapes to model the abdomen: plane layers and spherical layers. The plane model with different tissue layers is shown in Fig. 2 a). Most of the former works use planes for simulating photon distributions and analyzing feasibility of fetal pulse oximetry and expected signal composition [3, 5]. Using spheres instead of planes allows modeling of surface curvature that certainly influences photon propagation and leads to more reliable and realistic simulations. The spherical model with tissue layers is shown in Fig. 2 b). The radius of the outer sphere represents the abdomen of a pregnant woman and is set to 15 cm. We considered five tissue layers for both models with geometrical and optical properties listed in Tab. 1 below. The values were taken from [5] and represent averages for the tissue volumes. All optical parameters are valid for wavelengths in the near infrared range between 800 to 900 nm.

A point source S and a point like detector D are used to simulate the impulse response of the system as proposed by Wang and Jacques [7]. However, Monte-Carlo is a method for stochastic. To reach convincing results for photon distributions, $5{\cdot}10^8$ photons were launched. The absorption values saved in voxels at the surface are inte-

Table 1: Geometrical and optical properties of the five tissue layers are listed. The scattering coefficient (μ_s), absorption coefficient (μ_a), anisotropy (g) and refractive index (n) describe the optical characteristics of the tissues and d is the thickness of the layer.

Tissue layer	d in cm	μ_s in cm^{-1}	μ_a in cm^{-1}	g	n
Maternal tissue	1.6	5.0	0.08	0.800	1.300
Amniotic fluid	0.9	0.1	0.02	0.850	1.300
Fetal tissue	0.34	14.0	0.18	0.800	1.300
Fetal skull	0.16	10.0	0.70	0.935	1.564
Fetal brain	8.8	9.6	0.20	0.978	1.400

grated over the circumference of the sphere at the position of the detector and normalized by the number of launched photons.

3 Results

The fluence distribution at the surface of the models is shown in Fig. 3. Plots a) and b) show the spatial distribution of the total fluence for the plane and spherical layer model, respectively. Depicted are sections from the top view of the models with values represented in a logarithmic scale for visualization purposes. The point source S is represented by a white spot, indicating a very high fluence at this point. The graphics show that the fluence decreases with larger distance to the point source S. However, the fluence distributions are more or less the same for both models.

Fig. 3 c) shows the fluence as a function of the S-D distance in the range between 2 cm an 16 cm. The fluence of the reflected light captured by the detector drops exponentially with increasing S-D distance in both models. The acquired signal is slightly stronger in the sphere model. Assuming the source emitted light with a fluence of 1 J/cm^2, the optical fluence at the detector is at around 1 µJ/cm^2 at 11 cm for the plane and 14 cm for the spherical layer model.

The fluence of the photons that reached the fetal layer in relation to the total fluence for various source-detector distances is shown in Fig. 4. The corresponding spatial distribution is visualized in a) and b). Fig. 4 c) shows the fluence ratio as a function of S-D distance in the range between 2 and 16 cm. Both have a very weak mixed component next to the source, represented by the dark area in Fig. 4 a) and b). Purely maternal components dominate in this area and the ratio of the mixed component goes down to below 10 %. However, there are characteristic difference visible between the two models. As expected and already shown in [3], the fluence of the mixed component increases with the S-D distance and converges to a maximum of around 65 % in the plane model. This implies that for an S-D distance larger than 14 cm the mixed component causes 65 % of the total fluence. The distributions are slightly different in the spherical model. The bright area in Fig. 4 b) indicates that there is a hot spot area, in which the ratio of the mixed component reaches a maximum. From c) can be seen that the relative fluence of the mixed component reaches a maximum of 50 % at around 8.5 cm and drops down to 30 % with larger S-D distances.

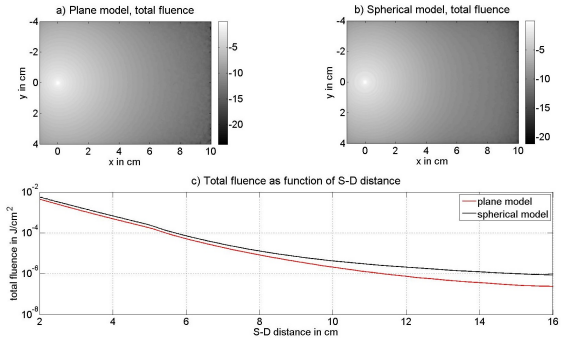

Figure 3: Spatial fluence distribution for the total signal in logarithmic scale is shown in a) for the plane model and in b) for the spherical model. Visualized are sections from the top view of the models. In c), the total fluence is shown as a function of the S-D distance. Fluence drops exponentially with increasing S-D distance in both models.

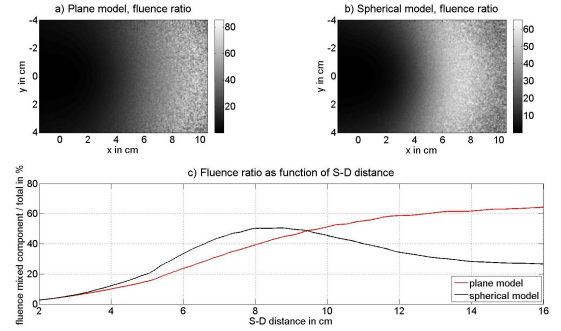

Figure 4: Spatial distribution of the fluence ration between mixed component and total signal is shown in a) and b) for the plane and spherical layer models, respectively. The fluence ratio as a function of S-D distance is plotted in c). The amount of the mixed component steadily increases with the S-D distance and converges to 65 % in the plane model. For the spherical model, the curve reaches a maximum of 50 % at the hot spot area.

4 Discussion

The extraction of the fetal pulse curve from the mixed signal requires a sufficient fluence of the fetal component at the detector side. Due to the anatomy, there always will be a maternal component in the captured signal, since photons necessarily travel through maternal tissue to reach the fetus. However, it seems to be possible to minimize the influence of purely maternal information coding photons by choosing a proper S-D distance.

The simulation results from the plane layered model indicate that a large S-D distance enhances the composition of the fluence. Assuming an ideal detector with infinite sensitivity and without noise, S-D distance should be set to 14 cm. Assuming a source fluence of 1 J/cm^2, for example, total fluence is 0.2 µJ/cm^2 and mixed component fluence is 0.14 µJ/cm^2. Choosing a smaller S-D distance leads to a larger fluence at all, but reduces the relative amount of the mixed component, thus the fetal signal. The simulations with the spherical model show a hot spot area. The fluence of purely maternal components tends down to a minimum, implicating the highest possible power of the fetal signal is achieved by placing the sensor in this area. At a S-D separation of 8.5 cm, the fluence of the mixed component is at 5 µJ/cm^2 in the configuration described above.

Real detectors have a limited sensitivity and a certain noise level. Smaller S-D distances should be preferred to receive a sufficient signal at all. Our simulation results regarding signal composition imply, that the spherical shape of the abdomen facilitates signal separation especially at S-D distances below 9.5 cm. Future investigations should consider more realistic, at least spherical, geometries to get more practically relevant information.

5 Conclusion

We conclude that the distance between source and detector significantly effects the signal composition. We did simulations with a plane and a spherical layer model to show their characteristic differences and the impact of the model choice and design. The results of the plane layer model imply that a larger S-D distance also leads to a more convenient signal composition at the detector side. Noise level and sensitivity of the detector may be the only limitation in this scenario. The more realistic spherical model showed that there is a hot spot area where the power of the mixed component reaches a maximum. The knowledge of the hot spot is of high importance for sensor design. The simulations help to find an optimum, where the ratio of the mixed fluence component and the fetal signal reaches its maximum, while the signal quality at all is still sufficient. More realistic models are needed to finally use the results for implementation purposes.

Author's Statement

Conflict of interest: Authors state no conflict of interest. Material and Methods: Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use has been complied with all the relevant national regulations, institutional policies and in accordance the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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