Modelling light propagation for fetal monitoring *in utero*

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ABSTRACT

About one in three births in the United States is through Cesarean section. Current monitoring techniques are insufficient to determine hypoxia and acidosis in the fetus during labor. An FDA approved transvaginal fetal pulse oximeter has been used in clinical trials to show that the device can help decrease the rate of Cesarean section. However, this technique has not been adapted into normal hospital procedure. Past pre-clinical and clinical studies have shown the feasibility of transabdominal fetal pulse oximetry. To understand the fundamentals of transabominal fetal pulse oximetry, we examined a layer model with both Monte Carlo and NIRFAST simulations. The NIRFAST model was used to model concentric spheres to understand the effect on geometry. The simulations were used in order to determine how much optical power can be detected from the fetus with a light source at 850 nm. The signal decreased as the fetal depth increased and as source-detector distance increased. The results can be used to aid in the design of a transabdominal fetal pulse oximeter.

Keywords: Monte Carlo, NIRFAST, light propagating, pulse oximetry, fetal monitoring

1. INTRODUCTION

The rate of Cesarean section in the western word has increased and now takes place in about 1 in 3 births. Delivery by cesarean section represented around 32% of all births in 2017 for the United States [1]. The current methods include electronic fetal heart monitoring, which is ineffective at determining hypoxia and distress for the fetus. The electrical fetal heart monitors have a high false positive rate of detecting fetal distress, which leads to the overuse of Cesarean sections as a mode of delivery. By monitoring the fetus with a transvaginal pulse oximeter placed directly on the fetus' cheek during labor, the rate of Cesarean section was shown to decrease [2].

There have be several pre-clinical [3, 4] and clinical studies [5-7] on transabdominal fetal pulse oximetry that suggest that the technique is feasible. One group used an eight layer Monte Carlo (MC) model to determine the best wavelengths when designing a system, in which they determine that 735 nm and 850 nm would provide sufficient signal [8]. Here, we use similar methods to determine fetal signal using both MC and NIRFAST. For the NIRFAST modelling concentric spheres were established to mimic the dimensions of a pregnant woman and provide a more accurate geometry. The simulations have provided information on the amount of power to be expected to return from the fetal layer.

2. METHODS

2.1 Monte Carlo and NIRFAST simulations

Here we compare MC simulations with NIRFAST simulations, which use the diffusion approximation as the method of modelling light propagation. The MC simulations were run from the GPU optimized CUDAMCML code [9], based off of the original MCML algorithm [10]. The MC simulations used 1 billion photons for each simulation. NIRFAST is a MATLAB-based package that uses finite elements methods in order to model the light propagation in 2D or 3D in tissue [11]. A truncated sphere with a radius of 11 cm was used for the NIRFAST simulation.

2.2 Simulation Parameters

An eight layer model for MC and a seven layer model for NIRFAST were used. The amniotic fluid layer was neglected in the NIRFAST model since it did not meet the diffusion approximation requirement of the scattering coefficient (0.1 cm^{-1}) being significantly higher than the absorption coefficient (0.042 cm^{-1}). The amniotic fluid layer was 1 mm and was relatively small compared the centimeters of tissue that were being simulated and therefore was considered negligible.

The optical properties that were used for the study can be found in Ref. [8] and Table 1. The anisotropic factor (g) was 0.9. The maternal subdermal layer was changed in order to observe different fetal depths. A fetal depth of 20 mm, 25 mm, and 30 mm are reported here.

2.3 Fetal Signal

The model was run twice for each method. First, the simulations were run with the optical properties described in Table 1. Then another simulation was run with all the fetal layers with very high absorption. Therefore, any light that travelled to the fetal layer would be completely absorbed and would not reenter the mother layers. The intensity at the surface of the tissue (assuming 1 cm^2 detector) was calculated and the mother simulation was subtracted from the overall simulation to obtain the fetal signal, similar to Ref. [5].

Table 1 Optical properties and parameters for computer simulations [12].

	Maternal Dermal	Maternal Subdermal	Maternal Uterus	Amniotic Fluid	Fetal Scalp	Fetal Arterial	Fetal Skull	Fetal Brain
μ_a (cm^{-1})	0.125	0.088	0.100	0.042	0.157	0.155	0.215	0.132
μ'_s (cm^{-1})	17.7	11.1	8.15	0.10	6.23	30.0	9.1	9.8
n	1.4	1.4	1.4	1.334	1.3	1.3	1.3	1.3
Z (cm)	0.15	0.9-3.9	0.85	0.1	0.2	0.1	0.15	Semi-∞

3. RESULTS

Figure 1 shows just the fetal component of the signal that would be detected at different source detector separations. As expected, the power decreases as the source-detector distance increases. Also, as the fetal depth increases, there is a decrease in the fetal signal. There was a clear difference between the NIRFAST and MC simulations in which the NIRFAST simulations showed that there was generally more power from the fetal layer compared to the MC simulation at the same fetal depth.

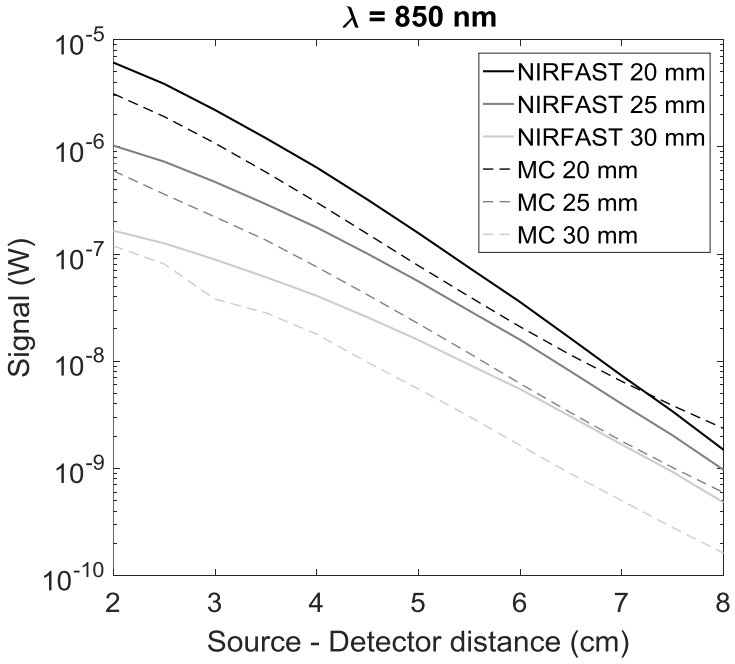

Figure 1 The fetal contribution to the overall signal as a function of source-detector distance for a 850 nm light source. The simulated signal is compared at different fetal depths (20 mm, 25 mm, and 30 mm) and using both Monte Carlo (MC) and NIRFAST simulations.

4. DISCUSSION AND CONCLUSION

The preliminary results show that a very small signal from the fetus would be expected and this signal diminishes further if the fetus is further below the surface. The difference between the two different models could be contributed to the difference in the geometry (slabs versus spheres).

Even though MC simulations are the gold standard of light propagation models, the output is still limited by the number of photons injected into the medium. In other words, very few photons travel centimeters into the tissue which causes the simulation to be inaccurate at large source-detector distances. However, since NIRFAST is mesh based and solves for an analytical equation, the simulation should be accurate at these larger distance. Additionally, NIRFAST has the flexibility to form different geometries and therefore, we compared the flat semi-infinite MC simulations with concentric spheres to establish the difference in the signals. The MC simulations had similar, although not exact results to reference [8], but this could be contributed to the difference in obtaining fetal signal and the number of photons used.

The simulations can be used to determine optimal conditions for obtaining fetal signal through the abdomen of a pregnant mother. Using these simulations, we can determine optimal source-detector distance and the expected signal from different fetal depths. There needs to be a balance between how much power is acquired and how much of the signal comes from the fetus. As the source-detector distance increases there is more of a chance of capturing the light that travels deep into the tissue. We plan to compare the results with experimental data and expand on the NIRFAST model.

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