Investigating the Effect of Total Radiated Power on Fetus Using Optical Simulation Approach Based on Exposure Safety Limit for Eye and Tissue Injury

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***Abstract*—This paper presents an analysis of the effect of the total radiated LED power on fetus in order to evaluate the exposure safety limit via optical simulation technique. The simulation results are then compared with the theoretical values calculated from the equations as defined by ICNIRP. The outcome from this study is beneficial in the future as it can be used to justify the safety issues on retinal injury and thermal heating concerning the application of low and high power LEDs specifically in the transabdominal fetal monitoring equipment which has been overlooked before.**

***Index Terms*—exposure safety limit, light emitting diode, optical simulation**

I. Introduction

The development of fetal pulse oximetry system has been spanned for almost 20 years with numerous studies circulate on the development of the fetal optical sensor probes. Similar to the pulse oximetry concept, the fetal optical sensor is comprised of two main elements namely as light source and detector. To gain the fetus signal, these sensors will be arranged in reflectance mode (adjacent to each other) on the surface of fetus skin. From the literatures, it is understood that earlier development of fetal pulse oximetry requires invasive intervention as the probes must be inserted via the birth canal before it can be placed on fetus cheek or head [1]. To avoid such invasive interference, a transabdominal fetal pulse oximetry system has been introduced [2]-[5]. Regarding the transabdominal fetal pulse oximetry, there are several studies that have been conducted to maximize the output received by the fetal detectors such as case studies involving the determination of the suitable emitter-detector spacing [6], the arrangement of optical array for fetal reflectance probes [7] as well as the best selection for wavelength pairs to be applied as the light source in the fetus pulse oximetry system [2], [8].

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TABLE I. THE ELECTRICAL SPECIFICATION OF LEDS USE IN FETAL PULSE OXIMETRY SYSTEM

Description	SMT (Bi-color)	MCPCB LED		Through-hole LED	
	735/890	735	890	735	890
Total Radiated Power (mW)	10.0/8.0	260	280	14-18	10-30

Speaking about the light source, a common emitter that can be found in pulse oximetry is the light emitting diode (LED) and the wavelength pair that is normally selected for fetal pulse oximetry is 735/890nm [9]. Now, various types of LEDs can be found in the market such as through-hole LED, surface mount type (SMT) as well as metal core PCB that comes with various radiated power and light intensity. Table I shows the available high and low power LEDs for 735 and 890nm with the highest power can reach up to 0.28W.

According to the International Commission on Non-Ionizing Radiation Protection (ICNIRP) document, although several laboratory attempts to create retinal injury using high power LEDs have so far been unsuccessful [10], this attempt does not include the effect it may have on the fetus if the transabdominal fetal pulse oximetry is applied. In general, the retinal hazard range is within 400nm to 1400nm of optical spectrum. Therefore, any wavelength resides outside of this hazard range is considered not safe to the eye as it will bring hazard to the cornea. However, since the interest wavelength for fetal pulse oximetry is within the retinal hazard range spectrum; therefore, we are interested to explore and estimate how much power the fetus eyes and skin can absorb based on various radiated power and will it exceed the safety limit as outline by ICNIRP.

For that reason, this paper will investigate the exposure safety limit in terms of retinal injury and tissue heating on the fetus's eyes and skin due to the LED power radiated through the pregnant mother's abdomen. To achieve the

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objective, an optical simulation has been conducted to explore the effect of high as well as low power LEDs. This approach offers huge advantage since it is able to simulate the human tissue characteristics based on the optical properties of tissue absorption and scattering. Moreover, it is easier to investigate the radiated power effect on fetus in the simulation environment rather than conducting experiments on a real pregnant woman. For comparison analysis, the theoretical exposure safety limit will be calculated based on the equations as outlined in the ICNIRP document.

II. Exposure Safety Limit Formula

The ICNIRP is one of the organizations that set a certain guideline on the limit of human exposure to incoherent optical sources [10]. Two types of injury related to the non-ionization radiation is first the retinal injury and secondly, the thermal injury. The exposure limits (EL) for retinal injury can be calculated based on the type of light source whether it is a point source or extended source and they can be defined as:

$$EL_{eye,\alpha<1.5} = 1.0C_A C_C [\text{mW/cm}^2] \quad (1)$$

$$EL_{eye,\alpha>1.5} = 1.8C_A C_C C_E T_2^{-0.25} [\text{mW/cm}^2] \quad (2)$$

where angular subtense, α is the angle subtended by an apparent source at the eye or point of measurement. If the light source with α further than the α_{min}=1.5miliradian, the light source is assumed as an extended light source.

Meanwhile, to calculate the EL for skin, following equation can be used:

$$EL_{skin} = 0.2C_A [\text{mW/cm}^2] \quad (3)$$

C_A, C_C, and C_E, are spectral correction factors and are defined as below, whereas T_2=100s if α is assumed to be greater than 100miliradian.

$$C_A = 10^{[0.002(\lambda-700)]} \text{ for } \lambda = 700-1050\text{nm} \quad (4)$$

$$C_C = 1 \text{ for } \lambda \leq 1050\text{nm} \quad (5)$$

$$C_E = \alpha / \alpha_{min} = 66.67 \text{ when } \alpha = 100\text{milirad} \quad (6)$$

III. Methodology

A commercial optical Monte-Carlo simulation namely as Advanced System Analysis Program (ASAP) has been used as a tool to simulate the effect of the radiated LED power. Details elaboration on how the simulations can be performed can be referred here [11], [12]. As a rule of thumb, four main steps are required to simulate the light interaction through tissue using ASAP software and the sequences are: i. Define the tissue geometry; ii. Create the light source; iii. Launch the rays of flux and the last step; iv. Perform analysis.

A geometrical tissue of pregnant woman is defined as in Fig. 1 with the first layer represent the mother tissue follow by amniotic fluid layer and finally is the fetus layer. The overall dimension (diameter x length) of the three-layer tissue is 300mm x 57mm with 24, 13 and 20mm length of mother, amniotic fluid and fetal; respectively.

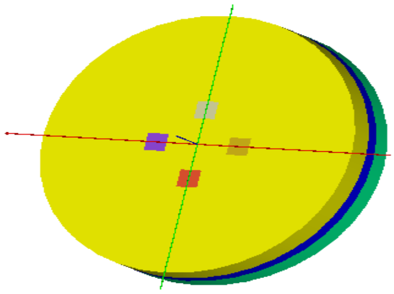


Figure 1. A cylindrical homogenoues three-layer tissue of pregnant woman

In order to make the tissue simulation becomes significant, relevant optical properties that mimic the absorption as well as scattering properties of the tissues are calculated based on [8] and are assigned to each layer according to 735 and 890nm optical properties. Also, there are four detectors with individual active area of 1 x 1 cm^2 and are positioned on the surface of mother's abdomen. For comparison, various power magnitudes will be implemented for data analyses which are 10m, 50m, 100m, and 300mW. The simulations results will be analyzed not only based on the flux absorbed by the fetus layer but also by the detectors.

IV. Results & Discussion

A. *Effects of Total Radiated Power on Absorbed Flux at Detectors*

Fig. 2 shows the total absorbed flux of all detectors estimate from the simulations. The trend observed in Fig. 2 presents adequate evidence of linear increment in the accumulated absorbed flux collected by the detectors as a function of proportional increase in the total radiated power of the LED. Note that at both wavelengths, the highest absorbed flux can be obtained when a high power LED is operated. The high power LED may increase the current that drives the LED and so does the light intensity. Therefore, an improvement in the quality of the PPG signals can be obtained. Nevertheless, the trade-off will be an increase in the power consumption.

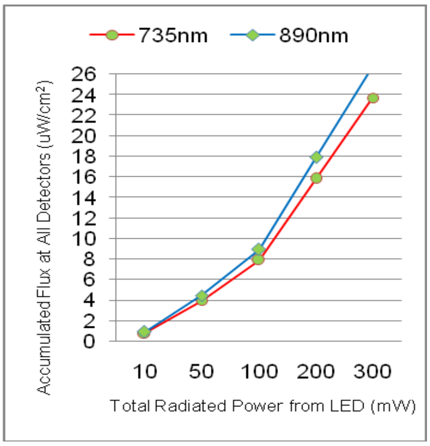
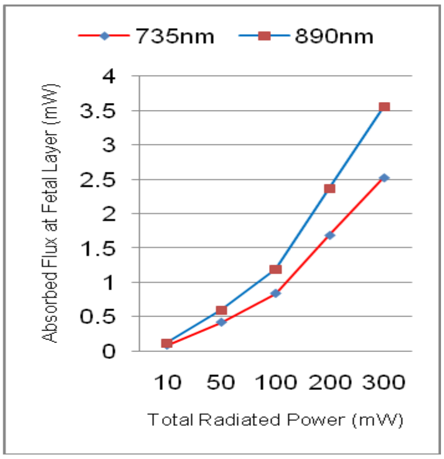


Figure 2. Total flux obtained at all detector against the total radiated power of LEDs

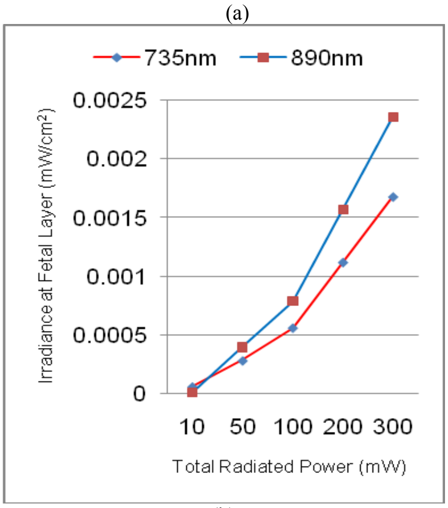
B. *Effects of Total Radiated Power on Eye and Tissue of the Fetus*

TABLE II. THE EXPOSURE SAFETY LIMIT FOR EYE AND TISSUE

Wavelength, λ	$EL_{eye,\alpha<1.5}$	$EL_{eye,\alpha>1.5}$	EL_{skin}
	mW/cm^2		
735	1.175	44.586	0.235
890	2.399	91.034	0.480



(a)



(b)

Figure 3. (a) Resulted flux that being absorbed by the fetus; and (b) Absorbed flux intensity at fetus layer

The theoretical values of exposure safety limit to avoid any retinal injury as well as tissue heating at interest wavelengths of 735nm and 890nm are presented in Table II. Generally, the LEDs are not only classified as incoherent source but it is also assumed as an extended source whereas laser is an example of point source type that having an apparent source size with angular subtense, α of less than 1.5milliradian. The data presented in Table II shows that the extended source (α>1.5 milliradian) is likely to have higher power limits than the point source (α<1.5 milliradian). This is to say that, to avoid retinal hazard to the fetus eye, the exposed power limit must not exceed 45 and 91 mW/cm^2 for 735nm and 890nm; respectively. Meanwhile, to evade the problem of tissue heating on the fetus skin, the irradiance must not exceed 0.24 and 0.48 mW/cm^2 for 735 and 890nm; respectively.

To simplify the simulation process, the fetus layer is assumed as a homogenous cylindrical shape. Although the simulation covers a stack of tissues layers, the fetus layer can be analyzed alone by issuing the 'CONSIDER' command. Then, the statistics of absorbed flux with respect to fetus layer is obtained from the 'STATS' command. Fig. 3(a) illustrates the absorbed flux accumulated at the fetal layer whereas Fig. 3(b) represents the ratio of the absorbed flux within a square cm of fetus area or estimated irradiance at fetal layer. The estimated irradiance is calculated by dividing the total absorbed flux with the area of the cylinder occupies by the fetus layer. From the data depicted in Fig. 3(b), it is evident that even at the highest radiated power (300mW), the flux absorbed by the fetus are way too small to create any potential retinal injury as well as tissue damage. Although, no harm can be found if using such high power LEDs, the effect it has on mother must be considered too in terms of tissue heating since the reflectance optical sensor of the transabdominal fetal pulse oximetry will be attached on the mother's abdomen and one way to preserve tissue heating at safety level is by employing time multiplexing when driving the LEDs current.

V. CONCLUSION

In summary, an optical simulation has been successfully employed in order to investigate the potential hazard of retinal injury as well as tissue heating on the fetus that caused by the total radiated power of the LEDs in application of transabdominal fetal pulse oximetry. The exposure safety limit (EL) formula as outlined by ICNIRP has been used to calculate the permissible light exposure specifically on the eyes and skin. The findings from comparison analyses between simulation and theoretical EL values have shown zero hazard potential towards the fetus eye and skin even when high power LED is implemented.

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