Comparison of Different Wavelengths for Estimating SpO2 Using Beer-Lambert Law and Photon Diffusion in PPG

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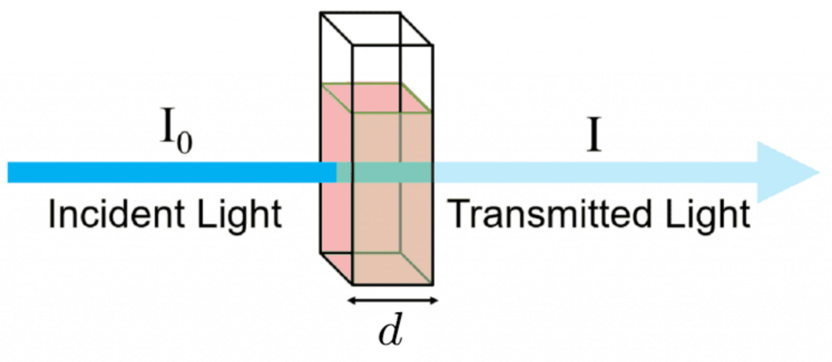
ABSTRACT

Photoplethysmography (PPG) is a non-invasive method of detecting blood volume changes in peripheral organ of human body. PPG is widely used to estimate blood oxygenation (SpO2) and thus this system requires at least two light sources to measure SpO2. In this research, these light sources' wavelengths in range of 300nm to 1000nm are compared and analyzed for which wavelength pair has the highest ratio. Both traditional Beer-Lambert law and Photon Diffusion theories are taken into consideration to assess the absorption and scattering effects of blood and tissues. And it is seen that, for the pair of violet-red wavelength ranges (378nm- 417nm and 679nm-730nm), the ratio gets the highest value with or without scattering effects and will eventually produce more accurate estimation of blood oxygenation.

KEY POINTS

- There are two types of PPG systems – Transmission and Reflection.
- For many applications of PPG (pulse oximetry, glucose measurement, heart rate monitoring, blood pressure etc.), multiple light sources are required.
- These light sources are selected by the researchers based mostly on personal preference.
- Beer-Lambert law is widely used to measure SpO2 for transmission as well as reflection type PPGs.
- Beer-Lambert law is not accurate. Specially for reflection type PPG. Which only describes absorption effects.
- Photon Diffusion theory describes the scattering effects in turbid media.

BEER LAMBERT LAW



$$A = -ln\left(\frac{I}{I_0}\right) \approx \sum_{i=1}^{N} \epsilon_i(\lambda) \times c_i \times d$$

- Stating blood as a homogeneous mixture of oxy and deoxyhemoglobin

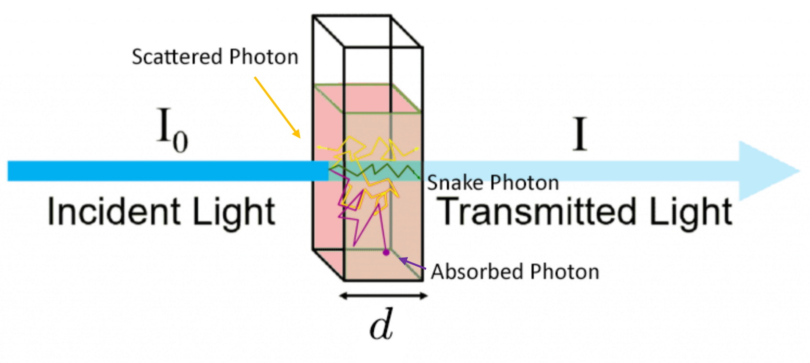
$$A = (\epsilon_{deoxy}(\lambda) \times c_{deoxy} + \epsilon_{oxy}(\lambda) \times c_{oxy}) \times d$$

- Now the ratio can be obtained as

$$R = \frac{\delta A_{\lambda 1}}{\delta A_{\lambda 1}} = \frac{\left[\ln\frac{I(d1)}{I(d2)}\right]_{\lambda 1}}{\left[\ln\frac{I(d1)}{I(d2)}\right]_{\lambda 2}} = \frac{(1 - SpO_2) \times \epsilon_{deoxy}(\lambda_1) + SpO_2 \times \epsilon_{oxy}(\lambda_1)}{(1 - SpO_2) \times \epsilon_{deoxy}(\lambda_2) + SpO_2 \times \epsilon_{oxy}(\lambda_2)}$$

$$where, \quad SpO_2 = \frac{c_{oxy}}{c_{oxy} + c_{deoxy}}$$

PHOTON DIFFUSION THEORY



- Photon diffusion (PD) theory is used to describe the properties of light in turbid biological media
- The ratio can be derived for PD theory as follows

$$R = \frac{\left(\frac{\Delta I}{I}\right)_{\lambda 1}}{\left(\frac{\Delta I}{I}\right)_{\lambda 2}} = \frac{\Sigma_s'(\lambda_1)\,K(\lambda_1)}{\Sigma_s'(\lambda_2)\,K(\lambda_2)} \times \frac{\Sigma_a^{artery}(\lambda_1)}{\Sigma_a^{artery}(\lambda_2)}$$

$$K(\lambda) = \frac{d\sqrt{3\Sigma_a(\lambda)\Sigma_s'(\lambda)} - 1}{3\Sigma_a(\lambda)\Sigma_s'(\lambda)d} \quad ; Transmission\ case$$

$$K(\lambda) = \frac{-r^2}{1 + r\sqrt{3\Sigma_a(\lambda)\Sigma_s'(\lambda)}} \quad ; Reflection\ case$$

Where,

$$\Sigma_a(\lambda) = V_a\Sigma_a^a(\lambda) + V_v\Sigma_a^v(\lambda) + V_w\Sigma_a^w(\lambda) + (1 - V_a + V_v + V_w)\Sigma_{baseline}(\lambda)$$

$$\Sigma_s'(\lambda) = (V_a + V_v)\Sigma_s'^{b} + \left(1 - (V_a + V_v)\right)\Sigma_s'^{tissue}$$

- Vein oxygen saturation is taken as 10% less than artery oxygen saturation.

For Transmission and Reflection PPG, Beer-Lambert law and Photon diffusion were tested for a range of 300nm-1000nm.

Violet (378nm-417nm) and Red/NIR (679nm-730nm) were found having the best ratio in theory.

Among commercially available light sources Red-Green (660nm and 525nm) had maximum ratio.

Transmission and Reflection systems have no noticeable difference according to Photon Diffusion theory.

RESULTS

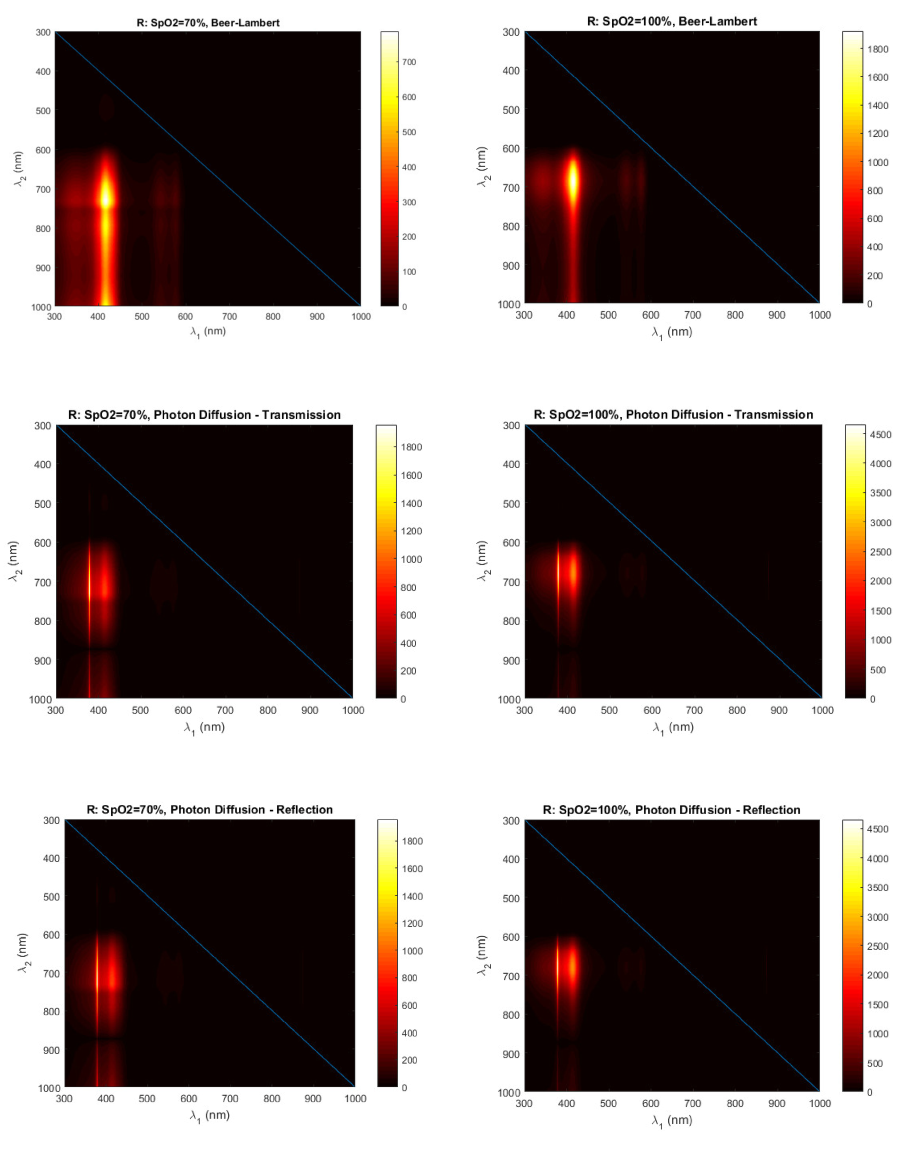
- Baseline dermis absorption coefficient is taken as $7.84e7 \times \lambda^{-3.225}$.
- Theoretically the following wavelengths can be obtained for maximum ratios –

SpO2	Beer-Lambert Law	Photon Diffusion	
		Transmission	Reflection
70%	417nm-730nm	378nm-729nm	378nm-729nm
100%	415nm-686nm	378nm-679nm	378nm-679nm

- For commercially available light sources for PPG the following pair comparison can be obtained -

Colors (Wavelength) Wavelength in nm	Ratio					
	Beer-Lambert Law		Photon Diffusion			
	SpO2 70%	SpO2 100%	SpO2 70%		SpO2 100%	
			Trn	Refl	Trn	Refl
Red-IR (660-950)	1.16	3.77	2.41	2.40	10.56	10.55
Red-Green (660-525)	26.96	96.48	23.41	23.41	83.78	83.78
Red-Orange (660-611)	3.11	4.48	2.79	2.79	4.03	4.03
Green-IR (525-950)	31.39	25.60	9.73	9.74	7.94	7.94
Green-Orange (525-611)	8.68	21.52	8.39	8.39	20.80	20.80
Orange-IR (611-950)	3.62	1.19	1.16	1.16	2.62	2.62

- For full spectrum of pairs the following results were found –



CONCLUSION

For different systems of PPG measurements (transmission and reflection), most dominant two theories were tested for a range of wavelengths (300nm-1000nm). We found that, the Violet (378nm-417nm) and Red/near IR (679nm-730nm) pair had the highest ratio, hence we will have highest resolution and accuracy for estimating SpO2. Among commercially available light sources, the Red-Green (660nm-525nm) pair had the highest ratio. And it is also seen that, the transmission and reflection systems do not differ noticeably in any case for photon diffusion.

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