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EFFECT OF MULTI-DESIGN SKIN MODEL AND CHARACTERISTIC ON MONTE CARLO SIMULATION OF LIGHT-SKIN DIFFUSE REFLECTANCE SPECTRA

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Abstract

This study was carried out to analyze the impact of four skin models and three skin characteristics on Monte Carlo simulation of light-skin diffuse reflectance spectra. The simulation was performed using graphic processing unit (GPU)-based Monte Carlo code (CUDAMCML). The computation platform was a laptop with 2.3 GHz processor (Intel Core i5-2410M) and supported by NVIDIA's Compute Unified Device Architecture (CUDA) graphic card (GeForce GT 520M). This analysis showed the importance of taking into account the depth distribution of melanin in designing a multi-layered skin model. Addition of complexity to the model caused only less than two minutes increment of computation time. Increase of melanin concentration reduced the values of diffuse reflectance over the spectrum while the profile of 'W' curve became less-defined. Increase of blood concentration also decreased the values of diffuse reflectance (particularly at wavelengths < 600 nm) but the profile of 'W' curve became more-defined. Increase of epidermal and dermal thicknesses influenced the diffuse reflectance spectra but not for subcutaneous fat thickness.

Keywords: Diffuse reflectance, skin model, Monte Carlo, GPU, CUDAMCML

Abstrak

Kajian ini dijalankan untuk menganalisis kesan empat model kulit dan tiga ciri kulit ke atas simulasi Monte Carlo spektrum pantulan resapan cahaya-kulit. Simulasi dilakukan menggunakan kod Monte Carlo berasaskan grafik (CUDAMCML). Platform komputasi ialah sebuah komputer riba dengan pemproses 2.3 GHz (Intel Core i5-2410M) dan disokong oleh kad grafik seni bina peranti perkomputeran bersepadu (CUDA) (GeForce GT 520M). Analisis ini menunjukkan kepentingan mengambil kira taburan kedalaman melanin dalam mereka bentuk suatu model kulit pelbagai lapis. Penambahan kekompleksan kepada model menyebabkan peningkatan masa komputasi hanya kurang daripada dua minit. Peningkatan kepekatan melanin mengurangkan nilai pantulan resapan sepanjang spektrum sementara profil lengkuk 'W' menjadi kurang jelas. Peningkatan kepekatan darah juga mengurangkan nilai pantulan resapan (khususnya pada panjang gelombang < 600 nm) tetapi profil lengkuk 'W' menjadi lebih jelas. Peningkatan ketebalan epidermis dan dermis mempengaruhi spektrum pantulan resapan tetapi tidak bagi ketebalan lemak subkutaneus.

Kata kunci: Pantulan resapan, model kulit, Monte Carlo, GPU, CUDAMCML

1.0 INTRODUCTION

The biophysical interaction of light within human skin tissue is basically occurs through absorption and scattering processes. In principle, when light emission enter the skin tissue, it propagates along the way while being absorbed by chromophores particularly melanin and blood, and scattered by cells, fibres, and tissues. The light that re-emitted onto the skin surface is recognised as diffuse reflectance, as shown in Figure 1 [1]. Along visible wavelength range,

typically from 380−780 nm, diffuse reflectance forms a unique spectral profile which is characterised by a 'W' curve at green-light region. The various spectral profile of diffuse reflectance reflects the variation of skin condition, physiology, and structure. By using Monte Carlo (MC) simulation with appropriate skin model, together with measured data of diffuse reflectance spectra, the optical properties of the skin can be predicted via inverse method [2−4].

1.1 Multi-Layered Skin Model

In the MC simulation of light-skin diffuse reflectance spectra, a simplest one-layered to as many as nine-layered skin models have been used as reported in previous studies [2, 5−12]. A basic three-layered skin model which consists of epidermis, dermis, and subcutaneous fat layers is usually used since it is simple and easy to compute. This model assumes a homogenous distribution of chromophores over the epidermis and dermis and does not consider the variation of concentration in a specific depth of sub-layer. Biological skin tissue, in natural, has a complex inhomogeneous layered structure. It has been reported that the basic three-layered skin model produces significantly lower simulated spectrum in long-wavelengths range compared to the measured spectrum. The proposed nine-layered skin model then generates simulated spectrum that matches better with the measured spectrum [11].

The design of multi-layered skin model should take into account the depth distribution of chromophores in sub-layers of epidermis and dermis based on histological data. For depth distribution of melanin in epidermal sub-layers, Tadakoro *et al*. reported that, prior to UV exposure, the lower layer of epidermis (stratum basal) contains 54–68% of the melanin, the middle layer (stratum spinosum) contains 25–30%, and the upper layer (stratum granulosum) contains 7–16% of the pigment [13]. While there is no standard found for depth distribution of blood in dermal sub-layers, which led to various approaches have been used in simulation. Note that, using multi-layered skin model is important for accurate simulation, however, over adding complexity to the skin model may negatively affect its computational performance and inverse solution [6, 14].

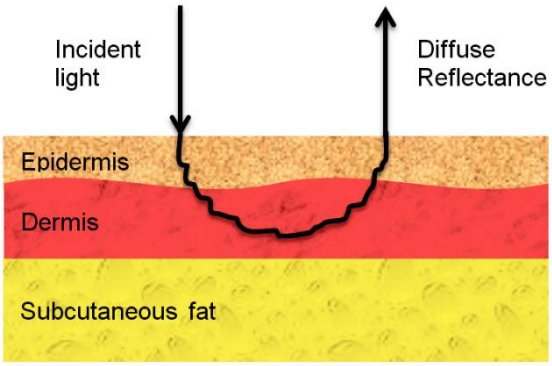

Figure 1 Illustration of the diffuse reflectance process. The line describes the simplified path of light propagation in skin tissue

1.2 Skin Characteristic

The characteristics of skin model are also important to take into consideration. The major skin characteristics include the concentration of melanin and blood as well as thickness of skin layers. Typically, melanin concentration of 1.3−6.3% was used for light-skinned adult, 11−16% for moderately pigmented adults and 18−43% for darkly pigmented adults [11, 15]. Again, the values of 0.2−7% are always used to represent blood concentration in skin model [16]. Meanwhile, different body site has different skin structure particularly the thickness of each layer. Based on literatures, the thickness of 8−20 μm was reported for stratum corneum, 27−163 μm for epidermis, 600−4000 μm for dermis, and 0.5−3 cm for subcutaneous fat [10, 11, 16, 17−19].

It is known that, using different multi-layered skin models and various skin characteristics in MC simulation will result a unique spectrum of light-skin diffuse reflectance spectra. However, to understand the influence of certain design of multi-layered skin model and characteristic on the profile of diffuse reflectance spectra needs to an analysis. Due to natural complexity of biological human skin, it is difficult to do this analysis experimentally. But, with MC simulation, it is possible for at least to provide a basic understanding on the behavior of diffuse reflectance spectra in response to multi-design skin model and characteristic.

Therefore, in this study, we used MC simulation to compare the effect of four multi-layered skin models (by taking into account the depth distribution of melanin and blood in specific sub-layers) on diffuse reflectance spectra and computation time. This analysis was also carried out to better understand how light interact with various skin characteristics particularly the melanin and blood concentrations, as well as the thickness of epidermis, dermis, and subcutaneous fat layers.

2.0 MATERIALS AND METHODS

2.1 Design of Multi-Layered Skin Model

Four multi-layered skin models were designed namely 3-layered, 6-layered (epidermis), 6-layered (dermis), and 9-layered. The characteristics for each model were as follow.

2.1.1 Basic Three-Layered

This model consists of epidermis, dermis, and subcutaneous fat layers. It would be the basis for designing of other skin models, in which, the splitting of epidermis and dermis into sub-layers would retain their thickness and concentration of melanin and blood. Thickness of each layer was; epidermis (0.01 cm), dermis (0.19 cm) and subcutaneous fat (0.6 cm). Melanin concentration in epidermis (10%), blood concentration in dermis (2%), and blood concentration in subcutaneous fat (5%) were distributed homogeneously. Oxygen saturation of haemoglobin in blood was considered 80%. The considerations of biophysical and structural characteristics for each skin layer were based on multiple references [10−11, 16, 17−19, 21].

2.1.2 Six-Layered (Epidermis)

This model consists of four epidermal sub-layers (stratum corneum, stratum granulosum, stratum spinosum, and stratum basal), dermis, and subcutaneous fat layers. Epidermal thickness was 0.01 cm which was fragmented into stratum corneum (0.001 cm), stratum granulosum (0.0003 cm), stratum spinosum (0.008 cm), and stratum basal (0.0007 cm). This fraction was an approximation based on Kohen *et al*. [18]. Melanin concentration in epidermis was 10% in which it was divided into stratum corneum (0%; dead cells), stratum granulosum (1%), stratum spinosum (3%), and stratum basal (6%). This fraction was an approximation based on Tadakoro *et al*. [13]. Other skin characteristics including blood concentration in dermis and subcutaneous fat as well as oxygen saturation of haemoglobin were similar with the basic 3-layered skin model.

2.1.3 Six-Layered (Dermis)

This model consists of epidermis, four dermal sub-layers (papillary dermis, upper blood plexus, reticular dermis, and deep blood plexus), and subcutaneous fat layers. Dermal thickness was 0.19 cm which was split into papillary dermis (0.01 cm), upper blood plexus (0.008 cm), reticular dermis (0.15 cm), and deep blood plexus (0.022 cm). This fraction was based on Sinichkin *et al*. [19]. Blood concentration in epidermis was 2% in which it was divided into papillary dermis (0.25%), upper blood plexus (0.5%), reticular dermis (0.25%), and deep blood plexus (1%). This fraction was based on Meglinski and Matcher [22]. Other skin characteristics were similar with 3-layered skin model.

2.1.4 Nine-Layered

This model consists of four epidermal sub-layers (stratum corneum, stratum granulosum, stratum spinosum, and stratum basal), four dermal sub-layers (papillary dermis, upper blood plexus, reticular dermis, and deep blood plexus), and subcutaneous fat layers. Epidermal thickness was 0.01 cm which was fragmented into stratum corneum (0.001 cm), stratum granulosum (0.0003 cm), stratum spinosum (0.008 cm), and stratum basal (0.0007 cm) [18]. Melanin concentration in epidermis was 10% in which it was divided into stratum corneum (0%; dead cells), stratum granulosum (1%), stratum spinosum (3%), and stratum basal (6%) [13]. Dermal thickness was 0.19 cm which was split into papillary dermis (0.01 cm), upper blood plexus (0.008 cm), reticular dermis (0.15 cm), and deep blood plexus (0.022 cm) [19]. Blood concentration in dermis was 2% in which it was divided into papillary dermis (0.25%), upper blood plexus (0.5%), reticular dermis (0.25%), and deep blood plexus (1%) [22]. The characteristics for subcutaneous fat were similar with other skin models. The characteristics for all four multi-layered skin models were shown in Table 1.

Table 1 Four designs of multi-layered skin models which taking into account the depth distribution of melanin and blood in epidermis and dermis respectively

Layer/		3-layered				6-layered (Epidermis)				6-layered (Dermis)				9-layered			
Sublayer		ST	C_m	C_b	SaO_2	ST	C_m	C_b	SaO_2	ST	C_m	C_b	SaO_2	ST	C_m	C_b	SaO_2
E	SC	0.01	10	0	0	0.001	0	0	0	0.01	10	0	0	0.001	0	0	0
	SG					0.0003	1	0	0					0.0003	1	0	0
	SS					0.008	3	0	0					0.008	3	0	0
	SB					0.0007	6	0	0					0.0007	6	0	0
D	PD	0.19	0	2	80	0.19	0	2	80	0.01	0	0.25	80	0.01	0	0.25	80
	UBP									0.008	0	0.5	80	0.008	0	0.5	80
	RD									0.15	0	0.25	80	0.15	0	0.25	80
	DBP									0.022	0	1.0	80	0.022	0	1.0	80
S	S	0.6	0	5	80	0.6	0	5	80	0.6	0	5	80	0.6	0	5	80

Note: E = epidermis, D = dermis, S = subcutaneous fat, SC = stratum corneum, SG = stratum granulosum, SS = stratum spinosum, SB = stratum basal, PD = papillary dermis, UBP = upper blood plexus, RD = reticular dermis, and DBP = deep blood plexus ST = skin thickness (cm), C_m = melanin concentration (%), C_b = blood concentration (%), SaO_2 = oxygen saturation in blood (%)

2.2 Variation of Skin Characteristic

For this part of study, six-layered skin model with distributed melanin at specific epidermal sub-layers was used for MC simulation of diffuse reflectance spectra. The choosing of six-layered (epidermis) skin model was based on the results obtained in earlier part (2.1). The variation of melanin and blood concentrations as well as epidermis, dermis, and subcutaneous fat thicknesses are as follow.

2.2.1 Melanin and Blood Concentrations

Melanin concentration was varied from 10−30% with 5% interval, while blood concentration was fixed to 2%. The blood concentration was then varied to 0.2%, 1%, and 2%, while melanin concentration was fixed to 10%. The fraction of melanin concentration at specific epidermal sub-layers was stratum corneum (0%; dead cell), stratum granulosum (10%), stratum spinosum (30%), and stratum basal (60%) from the total of melanin concentration.

2.2.2 Epidermis, Dermis, and Subcutaneous Fat Thicknesses

Six-layered (epidermis) skin model with 10% of total melanin concentration in epidermis, 2% of blood concentration in dermis, and 5% of blood concentration in subcutaneous fat was used for MC simulation of diffuse reflectance spectra. Oxygen saturation of haemoglobin in blood was set to 80%. The epidermal thickness was varied to 0.006 cm, 0.007 cm, 0.008 cm, 0.009 cm, and 0.01 cm, while the thickness of dermis and subcutaneous fat was fixed to 0.19 cm and 0.6 cm respectively. The fraction of thickness for epidermal sub-layers was stratum corneum (10%), stratum granulosum (3%), stratum spinosum (80%), and stratum basal (7%) from the total epidermal thickness. The dermal thickness was then varied to 0.1 cm, 0.2 cm, 0.3 cm, and 0.4 cm, while the thickness of epidermis and subcutaneous fat was fixed to 0.01 cm and 0.6 cm respectively. Lastly, the subcutaneous fat thickness was varied to 0.5 cm, 1.0 cm, 1.5 cm, and 2.0 cm, while the thickness of epidermis and dermis was fixed to 0.01 cm and 0.19 cm respectively.

2.3 Calculation of Skin Optical Properties

The optical properties of human skin tissue; refractive index (n_r), absorption coefficient (μ_a), scattering coefficient (μ_s), and scattering anisotropy (g) were calculated for wavelengths 380−780 nm with interval of 10 nm. The approaches and equations to calculate skin optical properties for respective skin layers were described in our previous study [20].

2.4 Monte Carlo Simulation

The platform used to execute MC simulation was a laptop (ACER ASPIRE 4750G) with 2.3 GHz processor (Intel Core i5-2410M, 4 GB installed memory) and supported by NVIDIA's CUDA graphic card (GeForce GT 520M, 1 GB local graphics memory). GPU-based MC source codes (CUDAMCML) were freely downloaded from Alerstam *et al*. [23]. The geometrical conditions for MC simulation were; grid size (dz = 0.01 cm, dr = 0.01 cm) and number of grid elements (no. dz = 80, no. dr = 100). In this simulation, 1 × 107 numbers of photons were launched perpendicularly (da = 1) for each point of wavelength.

Twenty five datasets (input file) were prepared; four datasets for skin model with different designs, five datasets for skin model with different melanin concentration, three datasets for skin model with different blood concentration, and thirteen datasets for skin model with different layers thickness. Each dataset contains of 41 data-for-run which are corresponding to the 41 points of wavelengths (380−780 nm with interval of 10 nm). Totally, 1025 data-for-run were executed. Figure 2 shows an example of data-for-run for 630 nm using nine-layered skin model.

```
#### SPECIFY DATA FOR RUN 26
#InParm                      # Input parameters. cm is used.
output_model4_630.mco  A     # output file name, ASCII.
10000000                     # No. of photons
0.01    0.01                 # dz, dr [cm]
80      100     1            # No. of dz, dr, da.

9                            # Number of layers
#n             mua           mus            g       d       # One line for each layer
1                                                           # n for medium above
1.379468497    0.605985977   125.8578807    0.8027  0.001   # layer 1
1.379468497    3.681295828   125.8578807    0.8027  0.0003  # layer 2
1.379468497    9.831915531   125.8578807    0.8027  0.008   # layer 3
1.379468497    19.05784509   125.8578807    0.8027  0.0007  # layer 4
1.382738497    0.624793112   76.80105267    0.8027  0.01    # layer 5
1.382738497    0.643600248   76.80105267    0.8027  0.008   # layer 6
1.382738497    0.624793112   76.80105267    0.8027  0.15    # layer 7
1.382738497    0.681214519   76.80105267    0.8027  0.022   # layer 8
1.44           0.982128687   52.47419854    0.75    0.6     # layer 9
1                                                           # n for medium below
```

Figure 2 An example of data-for-run for 630 nm using nine-layered skin model

3.0 RESULTS AND DISCUSSION

3.1 Effect of Multi-Design Skin Model on Diffuse Reflectance Spectra

Figure 3 shows the profiles of diffuse reflectance spectra simulated using four designs of skin models. By switching the basic three-layered skin model to the six-layered (epidermis), the value of diffuse reflectance increased up to 400% over the spectrum with a more-defined 'W' curve was obtained. Instead, by changing the basic three-layered skin model to the six-layered (dermis), diffuse reflectance values increased up to 76% only. The 'W' curve of the spectrum, however, became less-defined (more flat). The alteration of basic three-layered skin model to nine-layered showed the highest increment of diffuse reflectance values, that was up to 505% over the spectrum. However, the 'W' curve of the spectrum did not show any significant changes.

3.2 Effect of Complexity of Skin Model on Computation Time

It can be observed that adding complexity to the skin models by taking into account the depth distribution of melanin and blood in specific sub-layers influenced the computation time, particularly at lower wavelengths (<600 nm) as shown in Figure 4. Using six-layered (epidermis) skin model, the total time taken to execute 41 points of wavelengths was 11% longer than the time taken to execute basic three-layered skin model. Meanwhile, using six-layered (dermis) skin model, the total run time was 9% longer than the basic three-layered skin model. The longest total simulation time was for nine-layered skin model, that is 472.76 s, and it was 23% longer than the basic three-layered skin model.

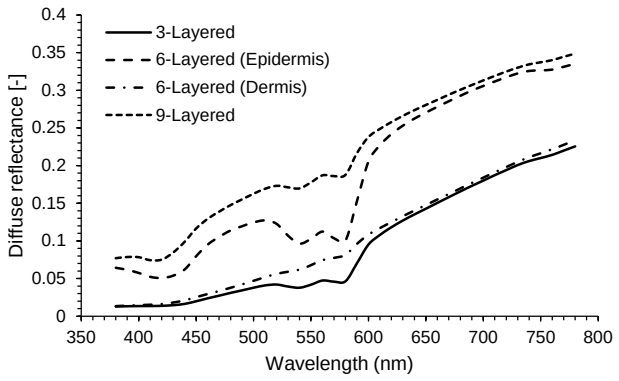

Figure 3 Diffuse reflectance spectra simulated using four designs of skin models

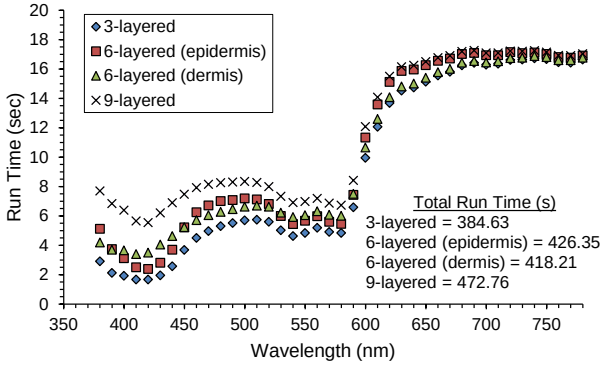

Figure 4 Distribution of run time for 41 points of wavelengths of each multi-layered skin model

3.3 Effect of Melanin and Blood Concentration on Diffuse Reflectance Spectra

Figures 5(a) and (b) show the effect of melanin and blood concentration on the profile of diffuse reflectance spectra. The increasing of melanin concentration from 10–30% reduced the values of diffuse reflectance over the spectrum while the profile of 'W' curve became less-defined [Figure 5(a)]. The increasing of blood concentration however showed different effect on the profile of diffuse reflectance spectra. When blood concentration increased from 0.2–2%, the values of diffuse reflectance also decreased particularly for wavelengths below 600 nm while the profile of 'W' curve became more-defined [Figure 5(b)].

3.4 Effect of Skin-Layer Thickness on Diffuse Reflectance Spectra

Figures 6(a) – (c) show the effect of epidermis, dermis, and subcutaneous fat thicknesses on the profile of diffuse reflectance spectra respectively. The increasing of epidermal thickness from 60–100 µm altered the profile of diffuse reflectance spectra particularly at range 450–510 nm and wavelengths above 600 nm [Figure 6(a)]. On the other hand, the increasing of dermal thickness from 1–4 mm affects the profile of diffuse reflectance spectra only at wavelengths above 600 nm [Fig. 6(b)]. The increasing of subcutaneous fat thickness from 5–20 mm however did not give any significant changes on the profile of diffuse reflectance spectra [Figure 6(c)].

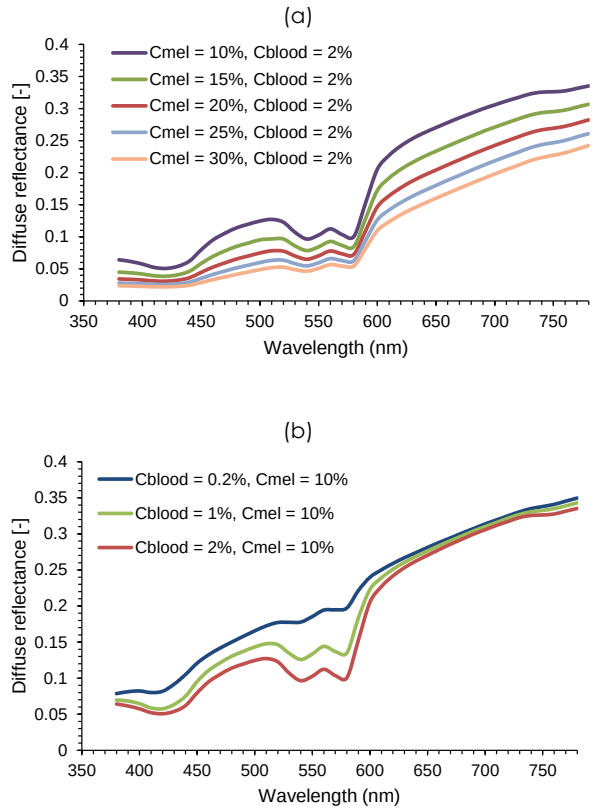

Figure 5 The effect of (a) melanin concentration, and (b) blood concentration on the profile of diffuse reflectance spectra

3.5 The Importance of Melanin Depth Distribution

The design of an appropriate multi-layered skin model is necessary towards an accurate MC modelling of diffuse reflectance spectra [14]. To achieve that, the element of depth distribution of chromophores particularly melanin in epidermis should be incorporated based on histological data.

This study revealed that the distribution of blood only, in specific depth of dermis only changes the spectral slightly. While the distribution of both, melanin and blood, and melanin only, in specific depth of epidermis and dermis significantly affect the profile of diffuse reflectance spectra. The profile of 'W' curve is found sensitive particularly to the way of melanin is distributed at specific depth of epidermis, but not to both melanin and blood. The consideration of melanin depth distribution in skin model may be important especially in albino study in which the distribution of melanin granules is not normal.

The nine-layered skin model designed in this study generated higher diffuse reflectance values compared to the basic three-layered. This result is basically in accordance with the previous study [11]. It also demonstrated that the higher values of diffuse reflectance could also be achieved by using six-layered (epidermis) skin model. The fraction of melanin concentration distributed in epidermal sub-layers was based on the histological data from Tadokoro *et al*. [13]. Since six-layered (epidermis) skin model is less complex than nine-layered, the MC simulation using six-layered (epidermis) model is obviously simpler and easier. Furthermore, with GPU-based computation and GPU-based MCML (CUDAMCML), the computation time is no longer an issue [20]. Based on the results, the addition of complexity to the skin model (by switching three-layered to nine-layered) causes only less than 2 minutes increment of computation time.

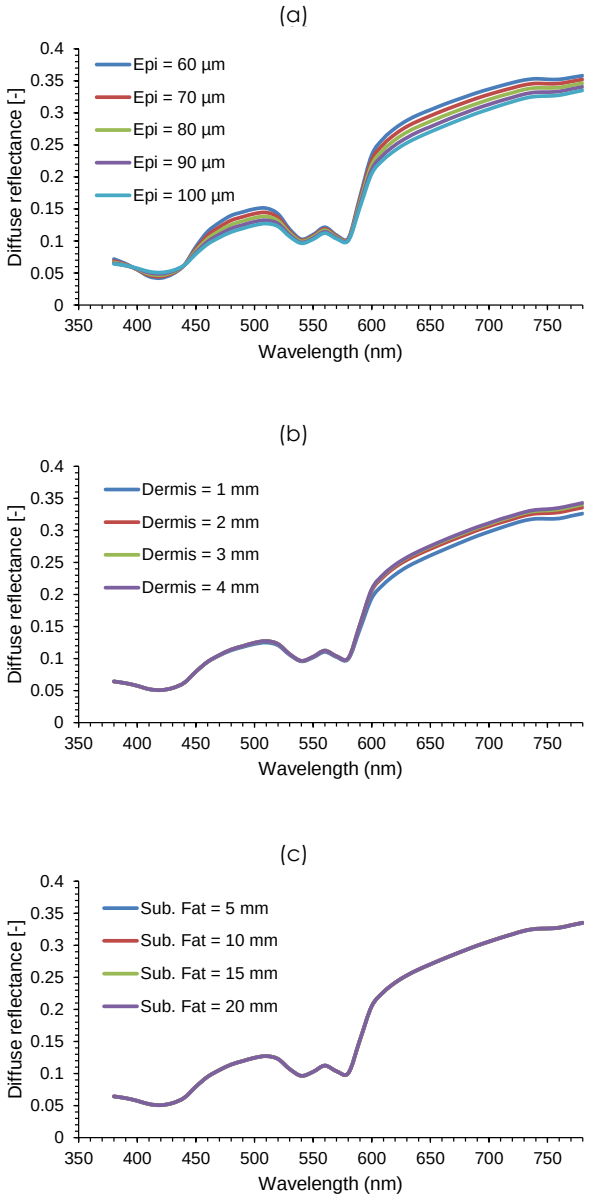

Figure 6 The effect of (a) epidermis, (b) dermis, and (c) subcutaneous fat thicknesses on the profile of diffuse reflectance spectra

3.6 Sensitivity and Behavior of Diffuse Reflectance Spectra

The variation of skin characteristics, particularly melanin, blood, and skin thickness resulted a unique profile of diffuse reflectance spectra as presented in this study. Based on the results obtained, several remarks can be acquired as follow:

i. Diffuse reflectance spectra at all visible wavelengths (380−780 nm) are found sensitive to melanin concentration, particularly at red-light region (620−740 nm). Thus, red light/laser could be an effective tool for determination of melanin.
ii. Diffuse reflectance spectra at visible wavelengths lower than 620 nm are found sensitive to blood concentration, particularly at green-light region (520−570 nm). Thus, green light/laser could be used particularly for blood diagnosis.
iii. 'W' curve is found sensitive to increase of melanin and blood concentrations. However, their respective impact on the profile of 'W' curve is opposite. By using suitable techniques, 'W' curve may be useful for predicting melanin and blood concentrations.
iv. The variation of epidermal and dermal thicknesses could affect the profile of diffuse reflectance spectra. Therefore, the selection of thickness for these two skin layers should be emphasized in the designing of skin model for MC simulation. The thickness should be realistic depends on the skin condition or body site and should be referred to the available histological data.
v. The variation of sub-cutaneous fat thickness did not give any observable impact to the profile of diffuse reflectance spectra. Therefore, any appropriate thickness could be used for this skin layer. Otherwise, the sub-cutaneous fat may be categorized as 'medium below' in MC simulation.

The knowledge on the sensitivity and behavior of diffuse reflectance spectra in response to variation of skin models and characteristics may be helpful in many skin studies such as comparing albino and normal skin [24], analyzing red blood cell [25], as well as predicting the physiological and morphological changes of cancerous skin [26, 27].

4.0 CONCLUSION

This study provides a basic understanding on how to manipulate the multi-layered skin model in order to obtain a matching simulated and measured spectrum. The depth distribution of melanin in epidermal sub-layers is important therefore should be incorporated into the multi-layered skin model. This study also provides knowledge on the effect of melanin and blood concentrations as well as skin-layer thicknesses on the profile of diffuse reflectance spectra. These understandings could assist in designing an appropriate skin model and help in choosing an effective light region for determination of specific skin properties.

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