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Estimation of Blood Concentrations in Skin Layers with Different Depths

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Abstract

In this research, we proposed a method to estimate the concentrations of melanin and blood in different layers of skin tissue. Furthermore, we stimulated skin with a warm bath and a carbon dioxide bath and obtained spectral data by a multispectral camera six times during 18 minutes. Based on the captured image, we estimated the blood concentrations in each blood layers by the proposed method. The result showed that the blood concentration of the deep layer is increased only with the stimulation by carbon dioxide bath, and the blood concentration in the shallow layer is increased in both stimuli cases, but the rate of increase in the carbon dioxide bath was higher and the increase time was longer. Our result is consistent with the result of the previous research.

Introduction

The condition of skin gives us various information such as health degree and age. For example, if there are many spots on face, it may give the impression that the age is high. If there are dark circles under the eyes, it may give the impression of tiredness. In the beauty field, many products have been proposed to control the condition of skin. Skin has a complex multilayered structure, and the color of the skin depends on the chromophores contained in the layer structure. It is said that spots are caused by melanin contained in the skin, and dark circles appearing under the eyes are said to be caused by melanin and blood. Melanin component is contained in the epidermis. On the other hand, blood component is contained in multiple layers [1]. It is not clarified blood of which layer affects the condition of skin. If it is possible to obtain the blood concentrations of each layer, it can be applied to the evaluation of products to control skin condition.

In this study, therefore, we used a seven-layer model of skin and proposed a method for estimating melanin and blood concentrations in skin layers with different depths. First, we used Monte Carlo simulation of light transport in multi-layered tissue (MCML) [3] to make a function to describe the relation between skin reflectance and chromophore concentrations by the method of Hirose *et al.* [2]. Next, the accuracy of the estimation was verified by estimating the numerical phantom in which the chromophores concentrations had been set in each layer. Furthermore, by estimating the chromophores concentrations of the actual skin, we verified the effectiveness of our method for practical use.

Method of Estimating Five Components in Skin

Analysis of the Relation between Absorbance and Chromophore Concentration

First, we obtained diffuse reflectance data of skin by MCML proposed by Jacques S. L. *et al.* [3].

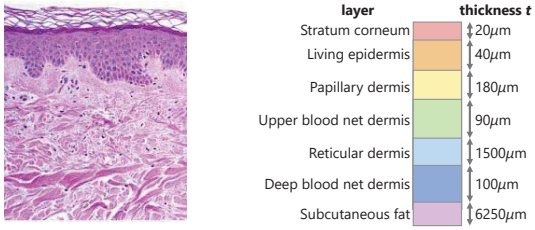

Figure 1. *Layered structure of skin: (a) Cross-sectional image, (b) seven-layered skin model[4][5]*

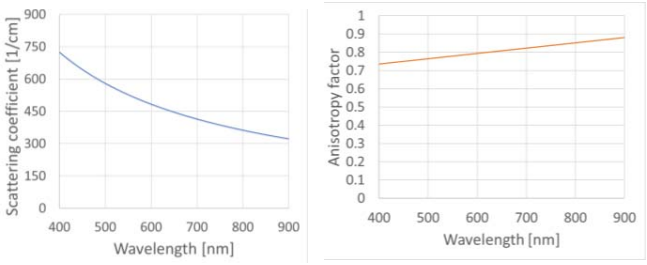

Figure 2. *Scattering parameters: (a) scattering coefficient, (b) anisotropy factor.[6]*

As shown in Fig.1, we assumed seven-layered skin model composed in epidermis and dermis [4][5]. The five optics parameters were set in each layer such as thickness t, index of refraction n, anisotropy factor g, scattering coefficient μ_s and absorption coefficient μ_a. Concretely, n was set to 1.4 and μ_s and g *was set to* values as shown in Fig.2 [6]. The absorption coefficient μ_a is calculated by the absorption coefficients of chromophores such as melanin, oxy-hemoglobin and deoxy-hemoglobin as shown in Eq.(1). Considering the computational cost, blood volume was set for only the 4th layer and the 6th layer, and the other layers was set to 0 because the 4th layer and the 6th layer have much more blood than the other layer[5].

$$\begin{aligned} \mu_{a.epi}(\lambda) &= Mel \times \mu_{a.mel}(\lambda), \\ \mu_{a.der4}(\lambda) &= Ohb_4 \times \mu_{a.ohb}(\lambda) + Hb_4 \times \mu_{a.hb}(\lambda) \\ \mu_{a.der6}(\lambda) &= Ohb_6 \times \mu_{a.ohb}(\lambda) + Hb_6 \times \mu_{a.hb}(\lambda), \end{aligned} \tag{1}$$

where λ is wavelength. The subscripts of *epi*, *der*4, and *der*6 indicate epidermis, 4th layer and 6th layer respectively. The subscript of *mel*, *ohb* and *hb* indicate melanin, oxy-hemoglobin and deoxy-hemoglobin. The absorption coefficients of chromophores are shown in Fig.3[7]. The percentage of melanin is expressed as *Mel.* The percentages of oxy-hemoglobin of 4th layer and deoxy-hemoglobin of 4th layer are expressed as Ohb_4 and Hb_4 respectively. Similarly, the percentages of oxy-hemoglobin of 6th layer and deoxy-hemoglobin of 6th layer are expressed as Ohb_6 and Hb_6 respectively. The blood volume is defined by the sum of oxy-hemoglobin and deoxy-hemoglobin, $[Ohb] + [Hb]$. We used these percentages of chromophores as the input for MCML and acquired diffuse reflectance of skin $R_{MCML}(\lambda)$. The concentrations of chromophores used in this study are shown in Fig.4. We acquired 675 reflectance data from their combinations.Next, the reflectance $R_{MCML}(\lambda)$ was converted to absorbance $Abs_{MCML}(\lambda)$. The relation between chromophores concentrations and absorbance for 400nm, 500nm, 600nm, 700nm, 800nm and 900nm are shown in Fig.5. It is impossible to visualize with 4 variables: melanin concentration, blood volume of 4th layer, blood volume of 6th layer and absorbance. Therefore, the absorbance is taken on the *Y*-axis and concentrations of chromophores are taken on the *X*-axis. We obtained the well fitted curves for 675 absorbance data, modelling an absorbance function $Z(Mel, Der_4, Der_6, \lambda)$ for each wavelength using a least squares function to calculate sum of squared residuals between absorbance data by MCML and the absorbance function. This function is shown in Eq.(2). Three types of curved surfaces were modeled: quadratic, cubic, and quartic function. The evaluation for these three types of curved surfaces is described in Table 2.

$$RSS_{func} = \sum_{i=1}^{675} [Abs_{MCML}(i,\lambda) - Z(Mel, Der_4, Der_6, \lambda)]^2 \quad (2)$$

where RSS_{func} is the squared residual between Abs_{MCML} and *Z*. $Abs_{MCML}(i,\lambda)$ is the *i*-th absorbance data by MCML and *i* indicates combination of chromophores concentrations.

Estimation of Chromophores Concentrations and Shading from hyperspectral Images

Hirose *et al*. proposed to extract five components, melanin, oxy-hemoglobin, deoxy-hemoglobin, shading and surface reflection from five band images of skin by using the cubic function $Z(\lambda)$ represented by Eq.(2). We assumed that the surface reflection is removed by the polarizing plate to improve the estimation accuracy of the components. It is noted that the relationship between the diffuse reflection $R(\lambda)$ and absorbance $A(\lambda)$ is shown as follows.

$$A(\lambda) = -\log(R(\lambda)). \quad (3)$$

In modified Lambert-Beer law, absorbance $A(\lambda)$ can be calculated from an absorbance of the absorbance function $Z(\lambda)$ and shading *k* as shown in Eq.(4). Diffuse reflection $R(\lambda)$ is calculated as shown in Eq.(5) from Eq.(3) and Eq.(4).

$$A(\lambda) = Z(\lambda) + k. \quad (4)$$

$$R(\lambda) = \exp(-(Z(\lambda) + k)). \quad (5)$$

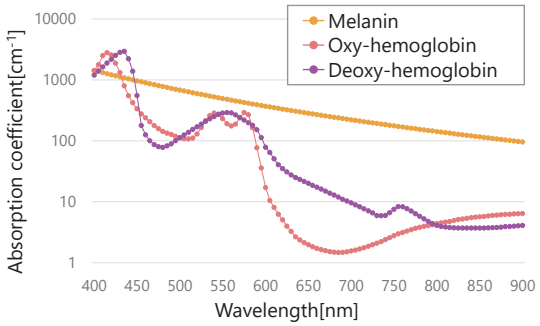

Figure 3. *Absorption coefficient of chromophores that are melanin, oxy-hemoglobin and deoxy-hemoglobin [7]*

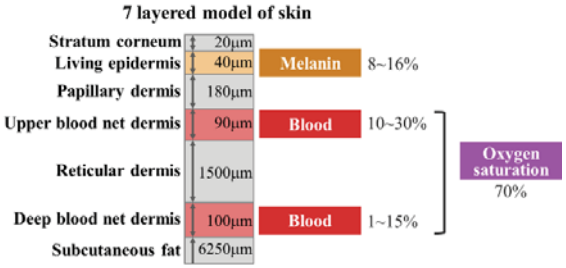

Figure 4. *Set concentrations of chromophores*

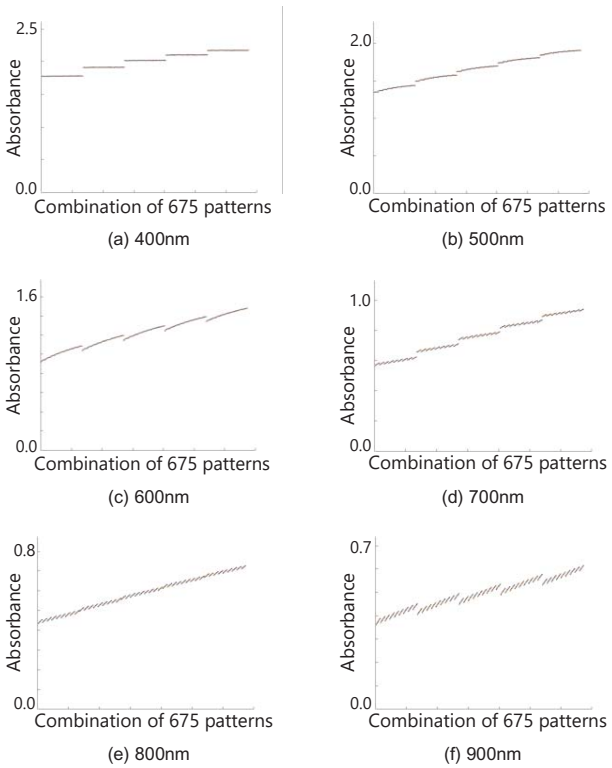

Figure 5. *Nonlinear relation between Monte Carlo simulation and chromophore concentration at five wavelengths*

In this proposed method, chromophores concentrations and shading are determined to minimize the residual sum of squares RSS_{est} as shown in Eq.6. Outline of the method is shown in Fig. 6.

$$RSS_{est} = \sum_{\lambda} [R_{MCML}(\lambda) - (\exp(-(Z(\lambda)+k)))]^2, \quad (6)$$

Optimizing the absorbance function $Z(\lambda)$

In this chapter, we performed cross validation to select an optimal absorbance function for performing the estimation by three types function defined in the previous chapter. Spectral reflectance were obtained by Monte Carlo simulation as the correct value. We set melanin concentration, 4th layer blood concentration, 6th layer blood concentration and acquired 675 reflectance data from their combinations. We added shading to the simulated reflectance. We used a reflectance corresponding to one combination as test data and modeled an absorbance function using other 674 data. The wavelength used for the estimation is 61 wavelengths in the range from 400 nm to 900 nm in 10 nm intervals. Fig.7,8,9 show maps of correct values and estimated values of chromophores concentrations. Fig.7 is the melanin map, Fig.8 is the map of 4th layer blood concentration and Fig.9 is the map of 6th layer blood concentration. Table.1 shows the average relative error of each chromophore concentration in each type of the absorbance function. When quadratic functions are used, the estimation accuracy is poor. The cubic function has better estimation accuracy than the quartic function. Therefore, cubic function is most suitable for estimating chromophores concentration.

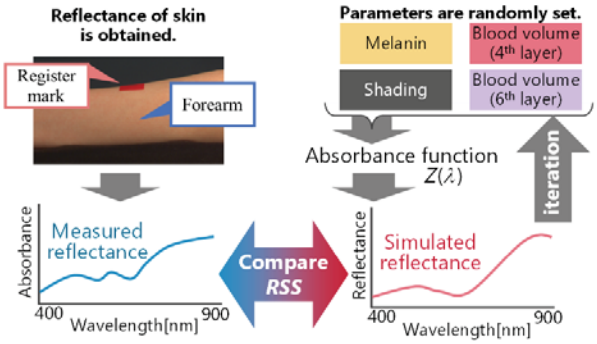

Figure 6. *Outline of the estimation method*

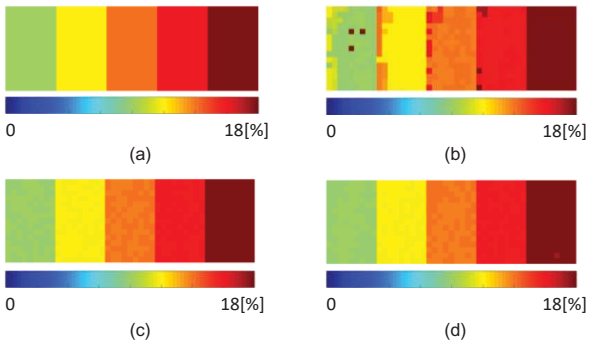

Figure 7. *Maps of melanin concentrations: (a) ground truth values, (b) estimated values by quadratic function, (c) estimated values by cubic function, (d) estimated values by quartic function.*

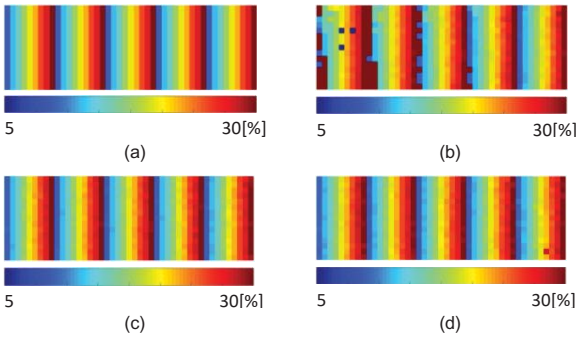

Figure 8. *Maps of blood concentrations of 4th layer: (a) ground truth values, (b) estimated values by quadratic function, (c) estimated values by cubic function, (d) estimated values by quartic function.*

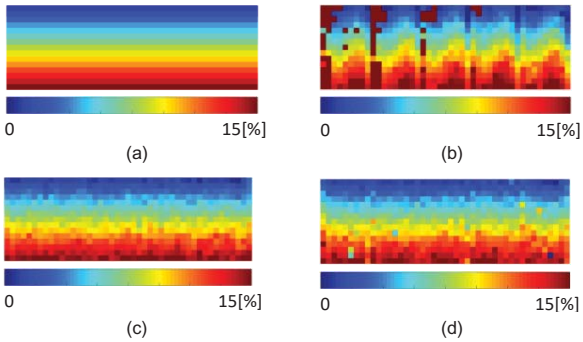

Figure 9. *Maps of blood concentrations of 6th layer: (a) ground truth value, (b) estimated values by quadratic function, (c) estimated values by cubic function, (d) estimated values by quartic function.*

Table 1. average relative error when using three types of functions

	Melanin	4th blood	6th blood	shading
quadratic	0.02906	0.19893	1.35172	0.08047
cubic	0.00124	0.00706	0.07460	0.00411
quartic	0.00208	0.01029	0.09815	0.00630

Estimation for actual skin from measured hyperspectral image by our method

Acquisition of actual skin image

A hyperspectral image of forearm was acquired to estimate the chromophores concentrations and shading by using our method. Experimental environment is shown in Fig.10. As a light source, we used SOLAX XC-500 (SERIC, Tokyo, Japan). As a spectral camera, we used ImSpector (JFE Techno Research, Tokyo, Japan). Hyperspectral image of skin was acquired 30 × 30 pixels in the 400-900nm range.

Changes in the blood concentrations of different layers of the skin by stimulating the skin

The experimental protocol is shown in Fig.11. After giving the stimuli to the skin, a hyperspectral image of forearm had been taken six times for each timing. Based on the images, our method was performed to observe the changes in the blood concentration of different layers of the skin. Two types of stimuli were used: a warm bath and a carbon dioxide bath. The temperature of the water was 40-42°C, and the temperature of the was 23°C. The captured forearm image is shown in the Fig.12(a). We stimulated the forearm as shown in the figure 12(b). Fig.13 shows a change in the average concentration of each chromophore. Fig.14 shows the blood map of 4th layer in the experiment with a hot bath stimulus. Fig.15 shows the blood map of 4th layer in the experiment with a carbon dioxide bath stimulus. Melanin changed slightly when both stimuli was given. Generally, melanin does not change in a short period of time. Therefore, it is said that the correct tendency was obtained about melanin. Blood concentration of the 4th layer was increased immediately after the both stimulations. However, in the case of the stimulation with carbon dioxide bath, the increase rate of blood concentration is higher and the increase time is longer than those of hot bath. Blood concentration of 6th layer decreases after giving a hot bath stimulus. In contrast, by giving the stimulus by carbon dioxide bath, it increased. It was confirmed that the blood concentration in the deep layer of skin increase in carbon dioxide bath but do not increase in hot bath.

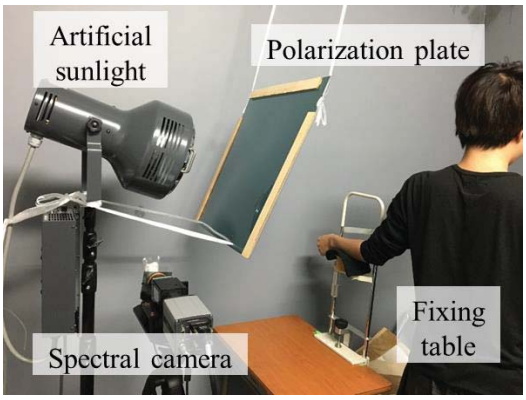

Figure 10. *Experimental environment*

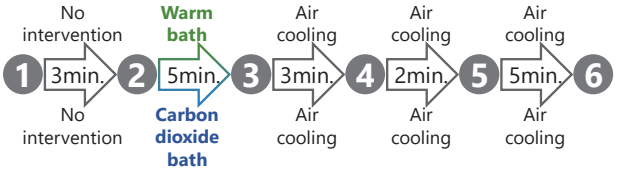

Figure 11. *The image acquisition interval*

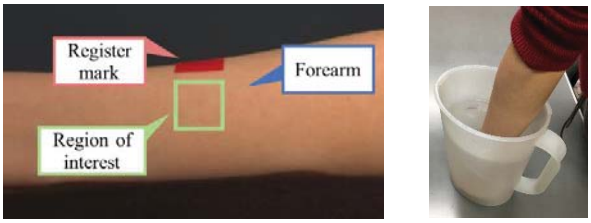

Figure 12. *(a) is RGB image of arm, (b) is stimulating addition*

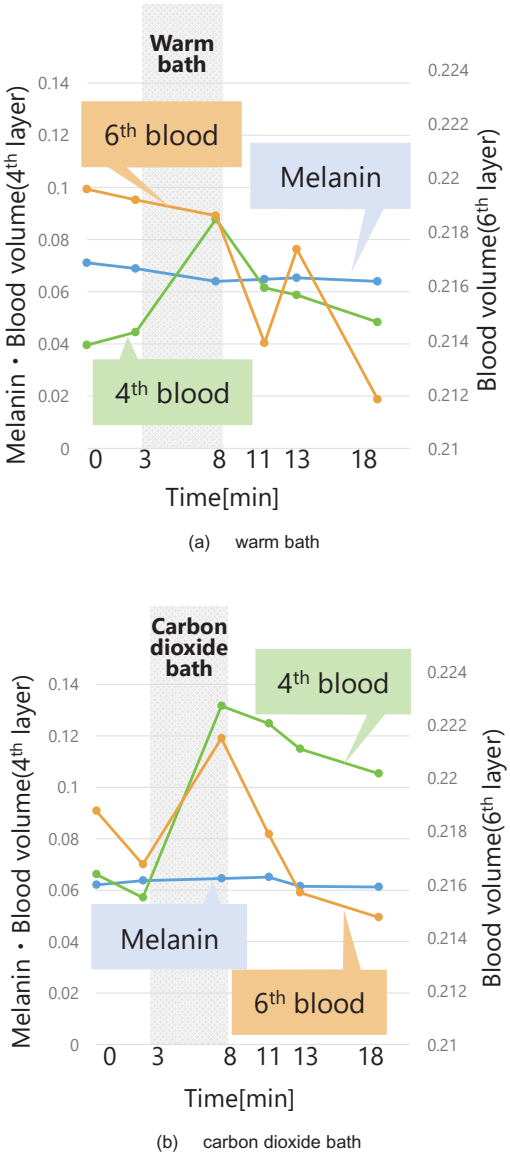

Figure 13. *Changes in the average concentration of chromophore.*

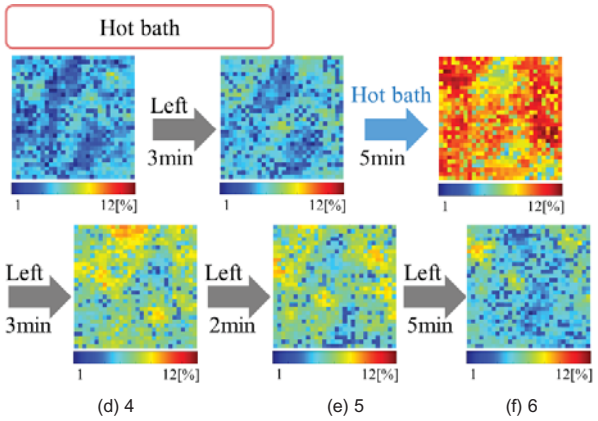

Figure 14. *Changes in the 4th layer blood concentrations map when stimulating the warm bath*

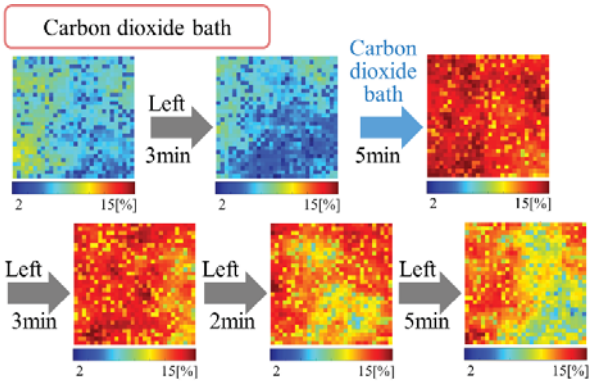

Figure 15. *Changes in the 4th layer blood concentrations map when stimulating the carbon dioxide bath*

Conclusion

In this paper, we estimated melanin and blood concentrations of different depths layers of human skin. We gave stimulations of a warm bath and a carbon dioxide bath to forearm and acquired hyperspectral data to estimate the blood concentrations of the skin by our method. The result showed that there is different change of blood concentrations in different blood layers depending on the difference of stimulation. In the carbon dioxide bath, the increase rate of the blood concentration in the shallow blood layer was higher and the increase time was longer than those of hot bath. The blood concentration of the deep blood layer increased only in the case of the carbon dioxide bath. As a future work, it is necessary to speed up the computational time toward practical use. As a future task, we need to estimate the blood concentration with the other stimulation that we did not consider this study.

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