Measurement of skin color : practical application and theoretical considerations

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Abstract : Quantification of erythema and/or pigmentation is important for *in vivo* assessment of skin reactions to external stimuli such as ultraviolet radiation. Measurement of lesional color is also useful for quantitative evaluation of the efficacy of therapies for skin lesions. Several types of portable optoelectronic instruments have recently become available for these purposes and have been applied to research in dermatology, physiology, pharmacology, and cosmetic science. As color is not a genuine physical quantity but a sensory perception based on color vision, any colorimetric data obtained for the skin should be interpreted carefully. Erythema and melanin indices derived from skin reflectance data should also be evaluated in relation to the optical properties of the skin to avoid misuse. In this article, various methods for quantifying skin color and related parameters are reviewed and the characteristics of each method are discussed theoretically using an optical model of the skin. J. Med. Invest. 44 : 121-126, 1998

Key Words : *colorimetry, spectrophotometry, erythema index, melanin index*

INTRODUCTION

In *in vivo* studies in dermatology, physiology, pharmacology, and cosmetic science, it is often necessary to quantify skin color or the extent of erythema and pigmentation objectively. As a result of progress in opto-electronic engineering, several kinds of portable instruments have become available and have been practically utilized for this purpose (1-4). These instruments provide us with skin color data in the form of coordinates or indices, such as L*a*b* or an erythema index, which may be unfamiliar to researchers involved in life science. These are indeed quantitative data, but what is L*a*b* ? How is the erythema index defined and read? Which is the more appropriate value for determining the degree of erythema, a* or the erythema index?

There are many textbooks about optics and color research. The optical properties of the skin have also been investigated and described (5-7). To my knowledge, however, there have been few articles on the analysis of the relationship between the color and optical structure of the skin, including the content of pigments. The purpose of this article is to review the methods for evaluating color and related parameters of skin and to discuss interpretation of experimental data.

QUANTIFICATION OF COLOR

The basis of investigation of optical properties of an object is recording the intensity of light reflected from it at many narrow-band wavelength(s) throughout the spectra of visible light (400-700 nm), namely, reflectance spectrophotometry. The term reflectance indicates the ratio of the intensity of reflected light to that of incident light. Although the wavelength-dependent pattern of the reflectance leads to the perception of color, human color vision cannot recognize this pattern as precisely as can a spectrometer. Known as the trichromatic theory (Young and Helmholtz), almost any kind of color can be matched by using three primary stimuli, i.e., three wave-bands that are well separated in the spectrum, e.g., red, green, and blue (RGB), and by mixing them in different proportions (8).The physiological basis of this theory is provided by the presence of three cone pigments in the human retina which have three different absorption spectra (9), indicating that our eyes are a sensor of light filtered by the pigments into three different wave-bands and we perceive color by their mixing in the brain. In practice, video cameras record the intensities of light in RGB bands and the original color is reproduced by emitting and mixing RGB lights on a screen according to the record. Therefore, color can be described as a three-dimensional quantity based on the trichromatic mechanism of color vision and quantifying color in this way is called colorimetry.

To standardize the quantification of color, CIE (Commission Internationale de l'Eclairage) recommended tristimulus color values X,Y, and Z, which are read using spectrometric reflectance data from an object and three primary stimuli (the Standard Observer curves) strictly defined by the commission. Roughly speaking, tristimulus values X, Y, and Z correspond to the intensities of the reflected light from an object in the RGB bands, respectively, though the

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Y value is defined as representing the brightness of the color. In practical use, these values are further transformed into the Yxy system (Y% =100 Y, x = X / (X+Y+Z), y = Y/(X+Y+Z)) or other color systems, such as L*a*b* and L*u*v* (10), which are designed to have characteristics similar to three attributes of color in psychological color perception. For instance, the L*a*b* color system is a three-dimensional coordinate system with an L*-axis (brightness) and two orthogonal axes representing chromaticity, namely, an a*-axis (red-green) and a b*-axis (yellow-blue). These coordinates are defined as follows (10) :

$$L^*=116\,(Y/Y_0)^{1/3}-16$$

$$a^*=500\,[\,(X/X_0)^{1/3}-(Y/Y_0)^{1/3}]$$

$$b^*=200\,[\,(Y/Y_0)^{1/3}-(Z/Z_0)^{1/3}]$$

where X_0, Y_0, and Z_0 are the tristimulus values of the illuminant used. In the fields of art and industry, quantification of color using these attributes is often used. Munsell notation may be representative of this system, in which a color is quantified or expressed as the Hue, Value (brightness), and Chroma (chromaticity or saturation) based on the color chart originally created by Munsell. This system may be familiar to many people as a number of graphic editors for computers use this system to express the color of picture elements. In computer software, however, the color system is a quasi-Munsell system called the HSI (hue, saturation, intensity) system in which a color is mathematically determined using a polar coordinate system mimicking Munsell's notation (11, 12). The relationship between the L*a*b* color system and the quasi-Munsell system is shown schematically in Fig.1.

OPTICAL THEORIES OF LIVING SKIN

Under normal conditions, the intensity of reflection of light from the skin surface (regular reflectance) is estimated at about 5% of incident light, irrespective of wavelength (5). Skin color is therefore mainly determined by the diffuse reflection, or scattering, and absorption of incident light inside the skin. Dawson et al. (13) and Diffey et al. (14) postulated that skin can be optically simulated by a simplified model composed of four layers. These layers correspond to the stratum corneum, the melanin-containing layer of the epidermis, the superficial vascular plexus in the upper dermis, and the dermis below them. The uppermost layer transmits most incident light, the second and third layers scatter little, but absorb light according to the absorption spectra intrinsic to melanin (2 nd layer) and hemoglobin (Hb : 3 rd layer). The bottom layer scatters back a large proportion of the incident light irrespective of wavelength. The overall reflectance (R) of this model at a given wavelength is expressed as :

$$R = T_1^2\, T_2^2\, T_3^2\, R_D \qquad (1)$$

where T_n (n=1, 2, 3) is the transmittance of the 1st-3rd layer, respectively, and R_D is the diffuse reflectance of the bottom layer. By taking the logarithm to the base 10 of the inverse reflectance given by eq. (1), we obtain :

$$\log(1/R) = 2\log(1/T_1) + 2\log(1/T_2) + 2\log(1/T_3) + \log(1/R_D) \qquad (2)$$

As the logarithm of inverse transmittance is called absorbance and can be regarded as roughly proportional to the concentration of chromophores (Beer-Lambert law) in layers 2 and 3 (13, 15), eq. (2) can be written as :

$$\log(1/R) = mC_2 + hC_3 + D \qquad (3)$$

where C_2 is the concentration of melanin in layer 2, C_3 is that of Hb in layer 3, m and h are coefficients mainly determined by the thickness of the layer and the extinction coefficient of the chromophore, and $D \approx \log(1/R_D)$. Eq.(3) indicates that the logarithm of the inverse reflectance of the skin, which is often called quasi-absorbance, may be a linear combination of the content of melanin and Hb unless the concentration of these chromophores is high. In this theory, several problematic assumptions are made. For instance, back-scatter (diffuse reflection) of light from the upper three layers is disregarded and the bottom layer is regarded as a kind of white plate. This simple theory, however, can readily explain the results of spectrophotometric studies of real skin (13), and has been used as a theoretical background for methods of quantifying erythema and pigmentation which will be mentioned later. Wan et al. (16) proposed another formula for predicting the overall reflectance of a skin model. This is a more general and mathematical method, which is also applicable to multi-layered structures other than skin. In this theory, the overall reflectance and transmittance of the complete skin model are calculated using recurrent formulas as follows :

$$R_{1,2\ldots n} = R_{1,2\ldots n-1} + (T_{1,2\ldots n-1})^2\, R_n / (1 - R_{1,2\ldots n-1}\, R_n) \qquad (4)$$

$$T_{1,2\ldots n} = T_{1,2\ldots n-1} T_n / (1 - R_{1,2\ldots n-1}\, R_n) \qquad (5)$$

where $R_{1,2\ldots i}$ and $T_{1,2\ldots i}$ (i=1,2...n) are the overall reflectance and transmittance, respectively, of the i-layered skin model, and R_i and T_i (i=1,2,...n) are the diffuse reflectance and transmittance of each component layer when separated. If all R_i and T_i values are known, the overall reflectance of the model can be predicted. However, this recurrent formula is so computer-oriented that it is difficult to obtain a direct "feel" for the optical characteristics of the skin from this formula. Therefore, it seems more useful and practical to use Dawson's theory if only moderate erythema and pigmentation is to be analyzed theoretically. It is likely that Wan's method is suitable for studying skin

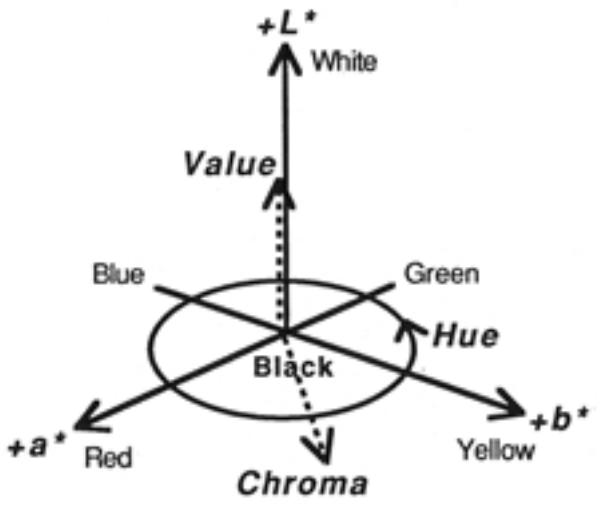

Fig.1. The L*a*b* and quasi-Munsell color systems.

color in more complicated situations of skin disease. In fact, we have developed software for skin color simulation using this model (17) and found that the colors of some complex skin lesions, such as dermal melanocytosis, were readily simulated by it. These optical theories for the skin have enabled us to analyze the results of measurement of skin reflectance and to develop a new method distinct from colorimetry for estimation of the amounts of cutaneous chromophores *in vivo*.

METHODS FOR EVALUTION OF SKIN COLOR AND RELATED PARAMETERS

The reflectance data for the skin obtained throughout the wavelength of visible light are difficult to handle practically, as they contain too much information. The data are usually converted into colorimetric values or indices for estimating chromophores in the skin. There are formulae defined by CIE to convert them into tristimulus values and the CIE-L*a*b* values may be the most commonly used for quantification of skin color (18). There are also formulae proposed and used by several authors (13, 19-21) for converting reflectance data into several indices, which show relative amounts of epidermal melanin, oxy- and deoxy-Hb in the superficial vascular plexus of the skin. These indices are read theoretically and experimentally according to Dawson's theory, by calculating the reflectance or quasi-absorbance values of the skin measured at several wavelengths, which are determined in such a way as to enable abstraction of information about the amount of the targeted chromophore. In practical use, however, a reflectance spectrometer is expensive and cumbersome because it necessitates connection to a computer. Several portable opto-electronic instruments have therefore been designed and become widely used (1-3, 14, 22-24). Of the two representative instruments commercially available (25), one type (Chromameter™, Minolta, Osaka, Japan) is a colorimetric instrument, which contains a xenon lamp as a light source, photodetectors, a microcomputer, and colored filters which closely match the CIE colorimetric Standard Observer curves (2), and another type (DermaSpectrometer™, Cortex Technology, Hadsund, Denmark) is an index-calculating, narrow-band spectrophotometric instrument composed of LEDs, which emit light in two narrow-wavebands corresponding to red and green, photodetectors, and a microcomputer (3). Color values in accordance with the CIE color systems (Chromameter) or erythema and melanin indices (DermaSpectrometer) are calculated automatically with these instruments. Erythema and melanin indices obtained from the DermaSpectrometer are different from those which are derived from full-spectrum spectrophotometric data, but similar to those of the measurement principle. In both instruments, to obtain data the probe head is placed (opening : about 50 mm^2) gently onto the skin and the shutter button pushed ; the results are immediately displayed. However, skin color shows regional and diurnal variation (26, 27) and is easily influenced by pressure on the skin and orthostatic position (28). To avoid the influences of differences in the manner of measurement, standardized guidelines for skin color measurement with these instruments has been proposed by Fullerton et al. (25).

One deficiency of these spectrophotometric or colorimetric instruments is that the color of an object smaller than the opening of the probe head cannot be measured exactly. The evaluation of the pattern or distribution of color in a test area is also impossible, as the values obtained indicate an average of the whole test area. These problems may be solved by computer-assisted image analysis of digitized color pictures of an object. However, as the color of an object depends on the illumination and the characteristics of the device used to record the image such as a CCD (charge coupled devices), the color values obtained with software for image analysis are not absolute, but should be considered as relative data which are comparable only with those obtained using the same system and under the same situations. Therefore, color information from digitized images must be carefully processed in order to express it in terms of the values of an authorized color system. By handling color images obtained with a videomicroscope under standardized conditions, we reported that the brightness of the image in RGB bands can be approximated to the values of CIE-L*a*b* and erythema and melanin indices of the DermaSpectrometer (15, 29). Furthermore, we have developed a system for computer simulation of skin color using the same videomicroscopic system and Wan's multi-layered skin model (17), where real images of the skin, the amount of chromophores in the skin model, and the color or index values of both real and modeled skin can be compared.

SKIN COLOR AND THE CONTENT OF MAJOR CHROMOPHORES

As a result of comparison of the colors of actual skin lesions with those of simulated models (15, 17, 29), it was found that our system could simulate closely the variation in the color of the skin in epidermal pigmentary disorders and acute inflammatory or blanching conditions, although the simulated color had less yellow tint, due probably to disregarding minor chromophores such as carotene in the model, than the actual skin. Using this system, we have examined the relationship between the amount of major cutaneous chromophores and the change in the L*a*b* values and the erythema and melanin indices of the skin model. Noteworthy results are as follows : (a) The L*, b*, and melanin index values correlate almost linearly with the amount of epidermal melanin. However, the L* and b* values are also considerably influenced by the amount of Hb in the superficial vascular plexus, while the influence is less on the melanin index (Fig.2). The L* and melanin index values correlates almost linearly, if the amount of Hb is held constant. (b) The a* and erythema index values correlate almost linearly with the amount of Hb in the superficial plexus. Both are comparatively independent of the amount of melanin and the two correlate linearly (Fig.3). (c) The linear relationships between color or index values and the amounts of chromophores are broken if

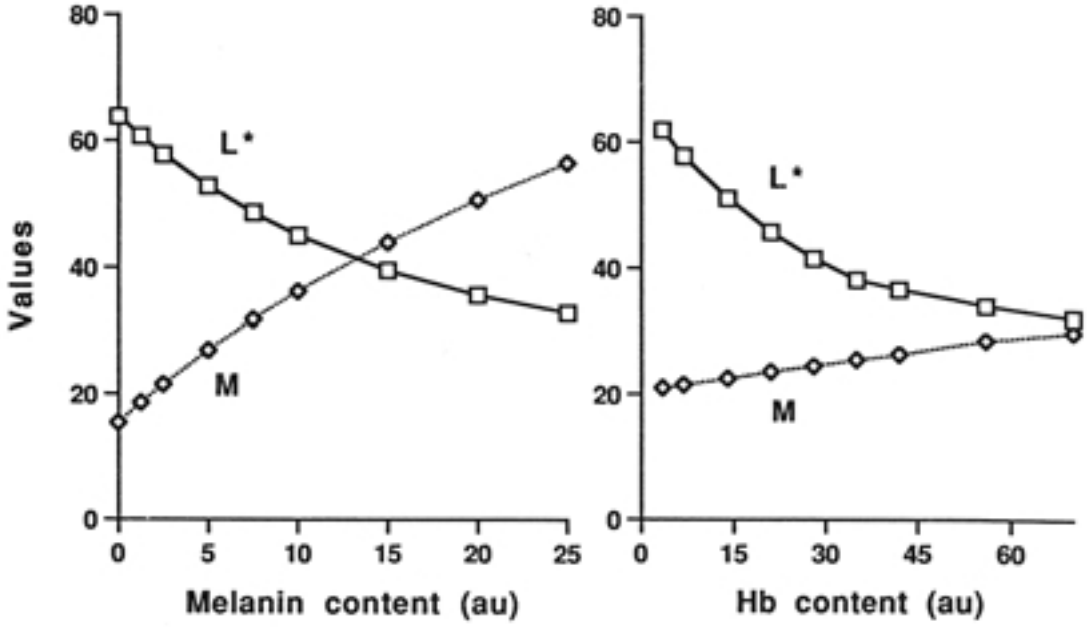

Fig.2. Changes in the L* and melanin index (M) as functions of the contents of melanin and Hb in our muti-layered skin model (17). *left* **: The amount of Hb is held constant at the level of "standard" condition (7 a.u.). right : The amount of melanin is held constant at the level of "standard" condition (2.5 a.u.).**

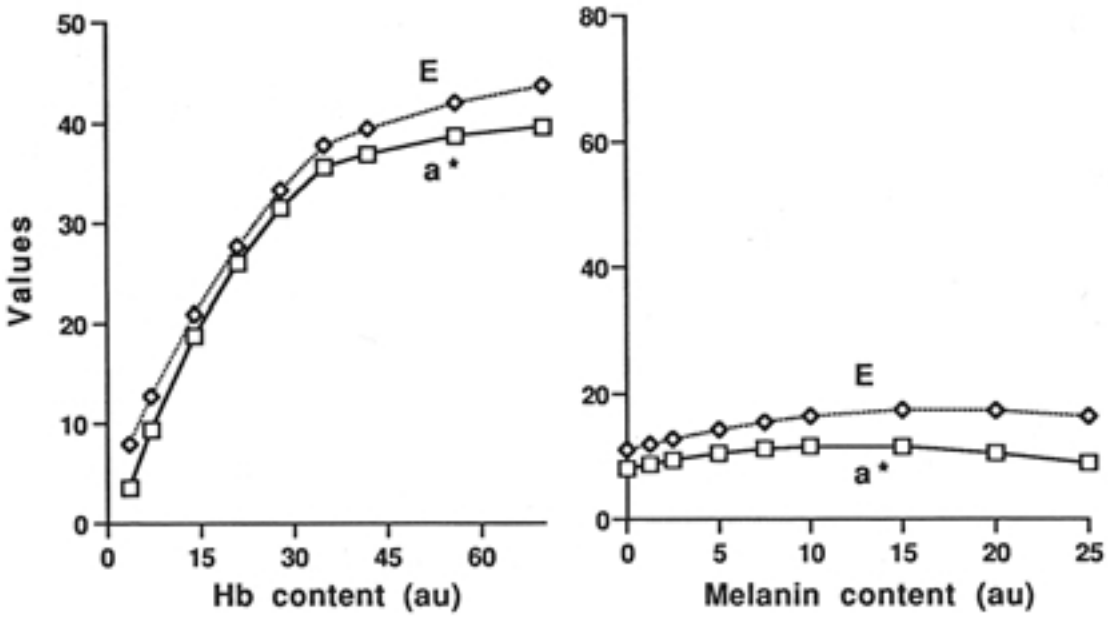

Fig.3. Changes in the a* and erythema index (E) as functions of the contents of melanin and Hb in our multi-layered skin model (17). left : The amount of melanin is held constant at 2.5 a.u.. *right* **: The amount of Hb is held constant at 7 a.u..**

the amounts are significantly large. These findings indicate that (a) L*(30), b*(31), or a combination of L* and b*(32) are reasonable parameters for evaluation of the degree of pigmentation, if the cutaneous blood volume is considered to be similar at all test sites (b) The melanin index is a good parameter for pigmentation, which is less influenced by cutaneous blood volume than colorimetric values (c) Both a* and the erythema index are good parameters for evaluating the degree of erythema or cutaneous blood volume (d) The difference values between the test and control sites are the best parameters for evaluating erythema and pigmentation (33), because the relationships between the amounts of chromophores and color values are linear but non-proportional (e) Measurement of color values or indices in such cases as hemangiomas or pigmented nevi with deep or dark color is regarded as a qualitative examination with less quantitative significance.

These simulation results also explain well the findings in clinical research that (a) L* is low on the palm in spite of the lack of melanin (b) The correlation between a* and the erythema index measured at various body sites is almost completely linear, while that between L* and melanin index is less remarkable (26). Although L* has frequently been used as a marker of pigmentation, it should be kept

in mind that L* is susceptible to changes in the cutaneous blood volume. This is especially important when L* is used for evaluation of dark spots on the face, such as chroasma and solar lentigo, where blood flow is relatively high and changes diurnally. It is desirable to simultaneously record a* in such cases and refer to it when unexpected results are obtained. Although the melanin index obtained with the DermaSpectrometer is considered to be a better marker for pigmentation than L* , this index is influenced by the increase in reduced Hb, which in practice occurs easily in static or congestive conditions (28).

CONCLUSION

Color is easy to perceive, but difficult to evaluate objectively. We have now obtained convenient measures for evaluation of skin color. However, even if one can measure skin color accurately, it is just a description rather than a true quantitative science. It is of value to analyze skin color data and identify important information from them.

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