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Estimation of diffuse reflectance spectrum from RGB values by the synthesis of new colors for tissue measurements

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ABSTRACT

A modified Wiener estimation method is presented for the accurate estimation of diffuse reflectance spectra from RGB values. In this method, the original RGB values are combined with a set of synthetic optical filters to generate another new three color values by using the system matrix. A modified Wiener matrix can then be created with the RGB values and the new color values, which will yield more accurate estimation because of the new color information incorporated. This method is tested on *in-vivo* color measurements from 200 skin sites in 10 volunteers. The results show that the proposed method improves the accuracy of the estimated diffuse reflectance spectra significantly compared with the traditional Wiener estimation method. Because of the fast computation in Wiener estimation, this method could be potentially developed for a cost effective alternative to a spectral imager.

Keywords: Wiener estimation, diffuse reflectance spectroscopy, color imaging, spectral imaging

INTRODUCTION

Diffuse reflectance spectroscopy has been a widely used non-invasive technique in biomedical optics in recent years[1-4]. Diffuse reflectance spectra can provide information about the absorption and scattering properties of tissues[5]. These optical properties are correlated with several important biophysical and biochemical parameters, e.g. hemoglobin concentration, oxygenation and average nuclei size, in tissues for the early diagnosis of skin diseases. However, the common disadvantage of traditional diffuse reflectance spectroscopy is its employment of fiber-optic probes, in which only point measurements can be performed. Therefore, the data acquisition in traditional diffuse reflectance spectroscopy is slow when diffuse reflectance spectra at multiple locations are required. Multi-spectral imaging has been developed to acquire diffuse reflectance images at multiple wavelengths[6]. However, image acquisition can be still slow when the required spectral resolution is high. Although there have been efforts in the development of snap shot spectroscopic imaging techniques[7], the advantage of these techniques in quick image acquisition are usually compromised by the slow postprocessing especially when the data dimension is large. Therefore, it is important to develop a rapid spectral imaging technique, which could offer real time acquisition of diffuse reflectance spectra for tissue measurements in multiple locations without sacrificing the accuracy.

The reconstruction of diffuse reflectance spectra from color values taken by a color camera is a potential solution to this problem. A large tissue area could be captured by a color camera at a high frame rate, which typically contains the color values in Red, Green and Blue bands at each pixel. In addition, each color band covers a relatively wide range of wavelengths thus the signal is usually strong thus suitable for fast imaging. Several methods, e.g. pseudo-inverse[8], finite-dimensional modeling[9], Wiener estimation[10] etc, have been explored to recover diffuse reflectance spectra from color information in multiple bands. Among them, Wiener estimation is one of most frequently used methods because of fast data processing[11]. However, one serious problem of using Wiener estimation in the estimation of diffuse reflectance spectra is that multi-channel information is always needed for sufficient accuracy[10]. Wiener estimation with only RGB bands is considered not adequate because of the underdetermined nature of the problem, in which three values corresponding to RGB colors are mapped to diffuse reflectance intensities at a few hundred wavelengths in a spectrum. Therefore, an accurate estimation method requiring only RGB values is desired for both convenience and low cost.

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In this paper, we propose a modified Wiener estimation method to address this problem by synthesizing new colors, which will provide additional information required for accurate Wiener estimation. According to the results, this method shows significant improvement compared with traditional Wiener estimation in the estimation of diffuse reflectance spectra from color measurements acquired *in vivo* from human skin. In addition, the fast speed of this method may enable the estimation of diffuse reflectance spectra at multiple tissue locations from color images in real time, which provides a cost effective alternative to spectral imaging with the additional advantage of high spectral resolution.

MATERIALS AND METHODS

This method consists of three stages: the calibration stage, the test stage and the selection stage. The first two stages are for the estimation of the diffuse reflectance spectra. And the selection stage is a post-processing step to improve the accuracy of the estimation.

In the calibration stage as shown in Fig. 1, we first calculate the system matrix using the calibration data which contains both measured RGB color values and the corresponding measured diffuse reflectance spectra. The estimation of the system matrix should be accurate because it is an over-fitting problem which diffuse reflectance spectrum contains much more data points than RGB values. Diffuse reflectance spectra can be estimated from measured RGB color values by applying the system matrix using the traditional Wiener estimation method. Then, by applying a synthetic absorption filter, which contains three absorption bands different from RGB filters, to the system matrix, a modified system matrix is created, which is used to generate three new color values from both the measured and estimated diffuse reflectance spectra. Because the high accuracy of the system matrix as mentioned above, the new color values estimated from the measured diffuse reflectance spectrum should be accurate thus could be seen as the reference new color values. The new color values generated from the estimated diffuse reflectance spectra, which are not accurate enough, are called estimated new color values to facilitate the discussion next. The relation between the estimated new colors and the reference new colors can be found by the following two strategies: (A) to model each reference new color value as a second order polynomial function of estimated new color values; (B) to record the differences in each color band between two sets to be used later. Moreover, the reference new color values combined with the original RGB values are used as 6 channels to create a modified Wiener matrix for the estimation of diffuse reflectance spectra, which should be more accurate than using the RGB values alone because of the increase in the number of available color bands. Therefore, in the calibration stage, the modified Wiener matrix and the relation for color correction are obtained for the estimation in the following test stage.

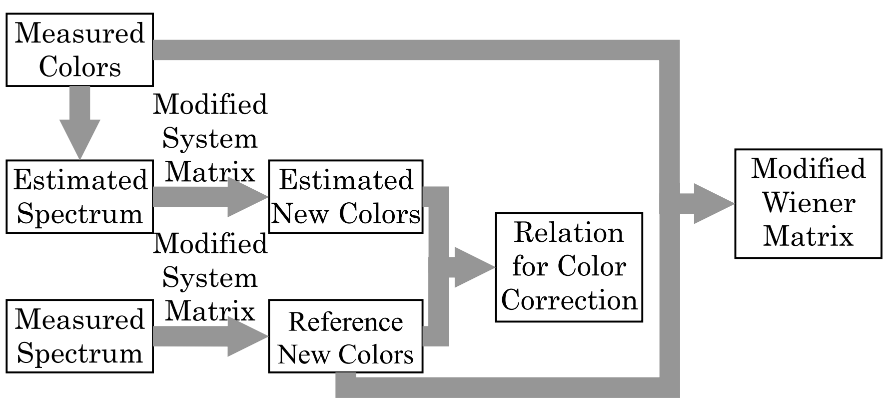

Fig. 1 Schematic of the calibration stage

In the test stage, the initial estimated diffuse reflectance spectrum will be computed by applying the initial Wiener matrix to measured RGB values first, which is usually not accurate enough because the initial Wiener matrix is based on RGB values alone. Estimated new color values will be generated from the initial estimated diffuse reflectance spectrum by applying the modified system matrix obtained in the calibration stage. Then the estimated new color values are corrected by the relation between the estimated new colors and the reference new colors found in the calibration stage. Then the Modified new color values jointly with the measured RGB values can be used to estimate more accurate diffuse reflectance spectra by applying the corresponding modified Wiener matrix obtained in the calibration stage. Therefore, two sets of estimated diffuse reflectance spectra are obtained by using two different strategies when doing the color correction. These two sets of estimated diffuse reflectance spectra will be selected in the selection stage in order to get a better accuracy for the estimation of the diffuse reflectance spectra. The scheme of the test stage is shown in Fig. 2.

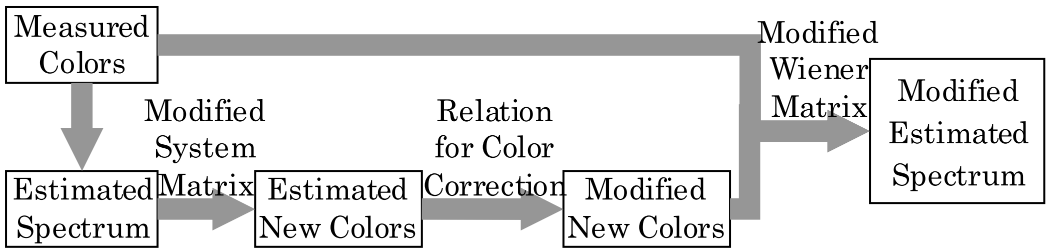

Fig. 2 Schematic of the test stage

For the second order relation, the modified new colors are generated by substituting the estimated new colors into the second order polynomial function. And for the difference relation, the difference values used to modify the estimated new colors are calculated by using the equation as follows:

$$D = \sum_{i=1}^{n} w_i d_i \tag{1}$$

where D denotes the difference values used to modify the estimated new colors, w_i and d_i denote the i-th weight and difference values for each point in the calibration data set, respectively. The weight w_i is calculated by the equation as follows:

$$w_i = \frac{l_i^{-1}}{\sum_{i=1}^{n} l_i^{-1}} \tag{2}$$

where l_i denotes the distance in the RGB color space between the measured color in the test data and the i-th color in the calibration data. From Eq. (1) and (2), the summation of w_i is 1, and the contribution of d_i to D is proportional to the similarity between the measured color in the test data set and the i-th color in the calibration data set.

Because two methods used to correct estimated new color values generate different results, selecting more accurate new color values between the two methods will subsequently yield a better estimation of diffuse reflectance spectra. In this selection stage, the estimated spectra based on the two methods are multiplied by the original system matrix to find the estimated RGB color values. Then, the estimated spectrum that yields color values closer to the measured values will be selected as the final result.

This method was evaluated in the data measured *in vivo* from ten volunteers. All the data were measured by the system shown in Fig. 3 which consists of a light source (HL-2000-FHSA, Ocean Optics, US), a spectrometer (USB4000, Ocean Optics, US), a fiber-optic probe (custom probe VIS/NIR, Ocean Optics, US) and a color CCD camera (DS-Fi1, Nikon, Japan) in which the Bayer color filter array is used for RGB image acquisition. The probe was composed of one source fiber with a core diameter of 600 μm surrounded by ten detector fibers with a core diameter of 100 μm. The measured diffuse reflectance spectrum was normalized to remove the wavelength dependence of system response by dividing the spectrum measured on the skin by the spectrum measured on a reflectance standard (SRS-99-010, Labsphere, US). Then the data points in the spectrum were binned so that the spectral resolution was 5 nm from 400 nm to 700 nm. By using this system, both RGB color values and diffuse reflectance spectrum were measured from the same position on the skin to prevent the mismatch in measurements sites between two sets of measurements.

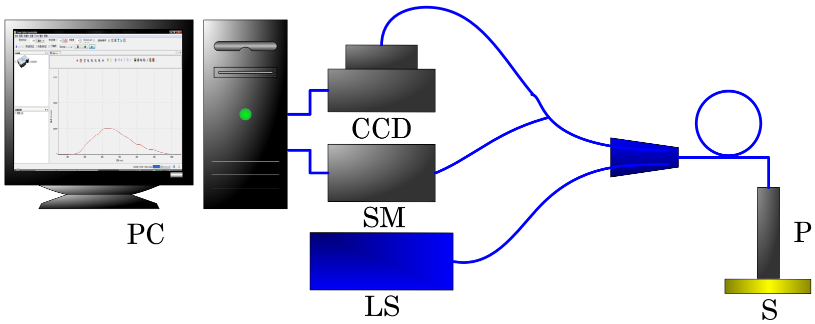

Fig. 3 Diagram of the system for taking color images and diffuse reflectance spectra. The following acronyms are used. SM: spectrometer; LS: light source; P: probe; S: sample.

RESULTS AND DISCUSSIONS

A total of 200 skin sites from 10 volunteers, which includes 6 Chinese, 3 Indians, and 1 Caucasian, were measured in this experiment. The reason of using not color chart but human skin as the calibration data is that special selection of calibration data set has obvious impact on the accuracy of the diffuse reflectance spectra estimation[12]. A leave-one-out method was used to evaluate the proposed method. Only one data point was picked as the test sample each time and other 199 data points were used as the calibration data set. The procedure was repeated until all the 200 data points have served as the test sample once. The proposed method were coded and run in Matlab (R2008a, MathWorks, US).

In order to show the improvement of the proposed method, Wiener estimation was applied to the same data set for comparison. The mean RMSEs (Root Mean Square Error) calculated between estimated diffuse reflectance spectra and measured diffuse reflectance spectra for different estimation methods are shown in Table 1. The representative diffuse reflectance spectra are shown in Fig. 4.

Table 1 shows that the modified Wiener estimation method reduces the RMSE by 7.2% or 4.5%, respectively, compared to the traditional Wiener estimation, when Strategies A or B is used to correct new RGB values. Moreover, a much larger reduction in the RMSE, i.e. 15.3%, is seen when the selection step is added. This infers that more accurate new color values yielded by the selection step are critical to the accurate estimation of diffuse reflectance spectra. It took 19.3 milliseconds to estimate the diffuse reflectance spectra from 400 nm to 700 nm with a resolution of 5 nm at 50 skin sites in a PC with Intel Core 2 CPU 2.4GHz, 2G RAM and Windows Vista operating system. This short estimation time implies the potential of performing real time estimation of diffuse reflectance spectra based on color images acquired from a large tissue area.

Table 1 Comparison of mean RMSE between the traditional Wiener estimation and modified Wiener estimation[a]

	Traditional WE	**Modified WE with Strategy A**	**Modified WE with Strategy B**	**Modified WE with the selection step**
RMSE	1.11×10^{-2}	1.03×10^{-2}	1.06×10^{-2}	9.40×10^{-3}

[a]WE is the acronym of Wiener Estimation

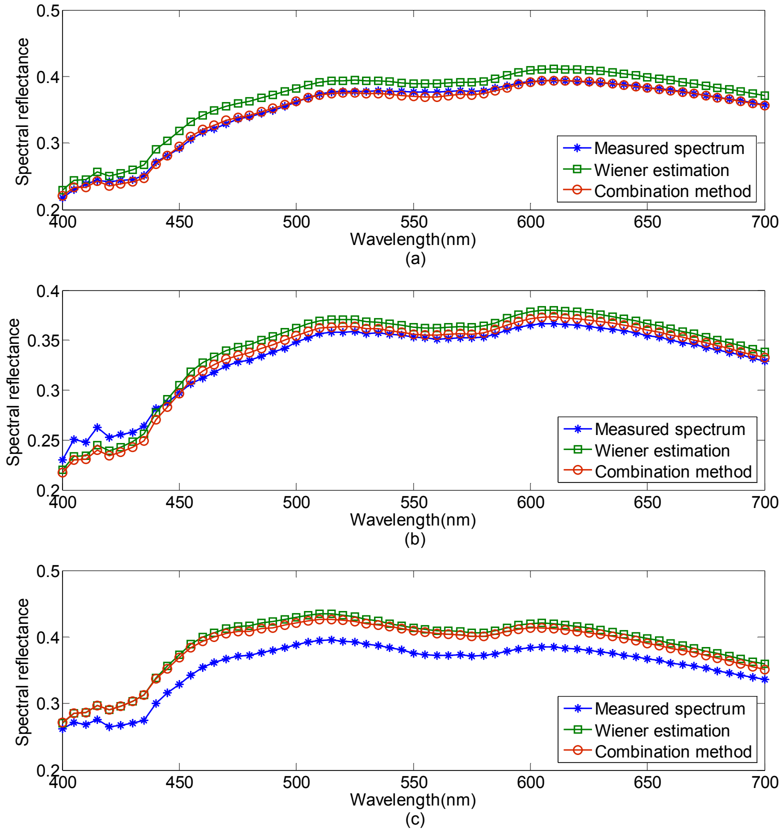

Fig. 4. Comparison of measured diffuse reflectance spectrum, Wiener estimation result and combination method result: (a) best estimation, (b) normal estimation, (c) worst estimation.

CONCLUSION

In conclusion, we developed a modified Wiener estimation method by the synthesis of new colors from the system matrix based on a calibration data set. The proposed method significantly improved the accuracy of estimated diffuse reflectance spectra for RGB color values acquired from human skin. Because of the ability to capture a large area at one time using a color camera and fast Wiener estimation, the proposed method may be developed for real-time acquisition of diffuse reflectance spectra from human skin, which provides a cost effective alternative to spectral imaging with the additional advantage of high spectral resolution.

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