Development of New Electronic Endoscopes Using the Spectral Images of an Internal Organ

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Abstract
We have developed a new electronic endoscopes to record and reproduce the arbitrary spectral images of the mucous membrane such as the gullet, colon and stomach. The reflectance spectra of those membranes can be estimated by the Wiener estimation method based on the principal component analysis of measured reflectance spectra of membrane by the endoscope spectrophotometer. In this paper, we show that the endoscopes are greatly significant to diagnose the various kinds of diseases in comparison with the conventional electronic endoscopes used R, G and B color information.

Introduction
We have developed the endoscope spectrophotometer (1) to measure the spectral reflectance of gastric mucous membrane in 1988. Many measured spectra of the gastric and rectal mucous membrane have been analyzed by principal component analysis and we showed that the reflectance spectra can adequately be described by only three principal components. Based on the above experimental result, it was shown that the reflectance spectra of gastric and rectal mucous membrane can be estimated from the R, G, and B signals of the conventional electronic endoscopes. This result was applied to computer simulation of the color reproduction of electronic endoscopes under different illuminants and designing of spectral transmittance of a color filter of electronic endoscopes. On the basis of these fundamental researches, we have developed a new electronic endoscopes to record the arbitrary spectral images of the mucous membrane such as the gullet, colon and stomach.

A color image taken by electronic endoscopes gives important information for diagnosis of various kinds of rectal and stomach diseases. Color reproduction of electronic endoscopes, however, is not enough to diagnose the early stage of the diagnosis. Therefore, to improve color reproduction of electronic endoscopes has been required. In our previous papers (2, 3, 4), computer simulation was introduced to estimate and improve the color reproduction of the stomach mucous membrane based on the principal component analysis.

Figure 1 shows the measured reflectance spectra of rectal membrane after the noise reduction processing and calibration used a standard white plate. It is clear that these spectra are strongly absorbed from 520 nm to 600 nm by the spectral characteristics of hemoglobin. These reflection spectra were analyzed by principal component analysis.

Figure 2 shows three principal components and the cumulative contribution ratio of three principal components, namely this result describes that 99.7% of the reflection spectra of rectal membrane can be expressed by only three principal components. The results showed that the reflectance spectra of rectal mucous membrane can be expressed as a linear combination of three eigenvectors obtained by principal component analysis. Wiener estimation method can be also applied to estimate the reflection spectra of those membranes.

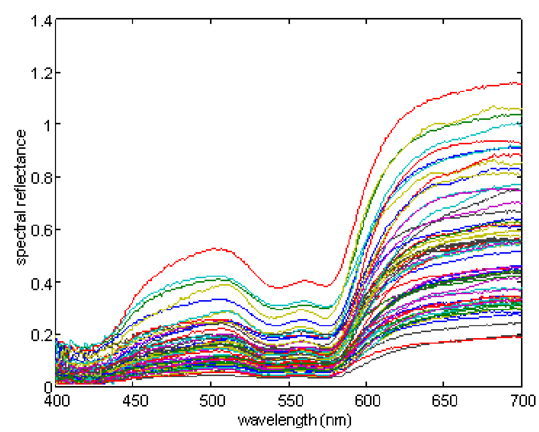


Figure 1. Examples of measured reflectance spectra of the rectal membrane

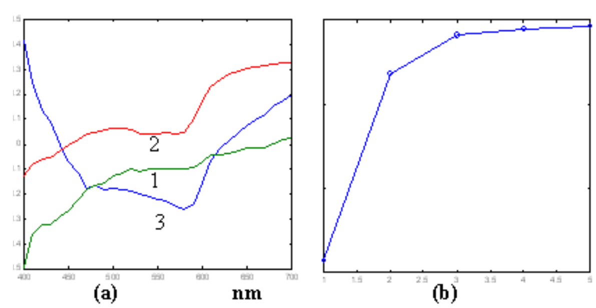


Figure 2. Three eigen vectors (a) and cumulative contributions (b) of spectral reflectance of the rectal membrane

Color Reproduction Simulator for Electronic Endoscopes
The color reproduction characteristics of electronic endoscopes are dependent on many factors such as spectral radiant distribution of

illuminant $E(\lambda)$, spectral sensitivity of CCD $S(\lambda)$, spectral transmittance of filters $f_i(\lambda)$ (i = r, g, b), and spectral transmittance of imaging lenses $L(\lambda)$. Then the output signal $v_i(x,y)$ ($i = r, g, b$) can be calculated as

$$v_i(x,y) = \int E(\lambda)S(\lambda)f_i(\lambda)L(\lambda)O(\lambda,x,y)d\lambda \quad i = r,g,b \tag{1}$$

where, $O(\lambda,x,y)$ is a spectral reflectance of the mucous membrane and (x,y) is coordinate of the object. From principal component analysis and the Wiener estimation method, reflection spectra of the object $O(\lambda,x,y)$ can be estimated from three eigen vectors and principal components of spectral reflectance of a rectal or Wiener matrix.

Then we can calculate the output image with different illuminants, CCD sensitivities and spectral transmittance of color filters.

In Wiener estimation, at first, we measure *R, G*, and *B* digital values, in Eq. (1), where *R, G, B* correspond to v_i of the Macbeth Color Checker using electronic endoscopes. Secondly, we measure the precise reflectance spectra of each color patch with a spectrophotometer. Using these two data sets, we can calculate a system matrix to estimate spectral reflectance of the object by the Wiener estimation method. Figure 3 shows the spectral image of a tongue at 400 nm, 500 nm, 600 nm and 700 nm calculated from the RGB image taken by electronic endoscopes.

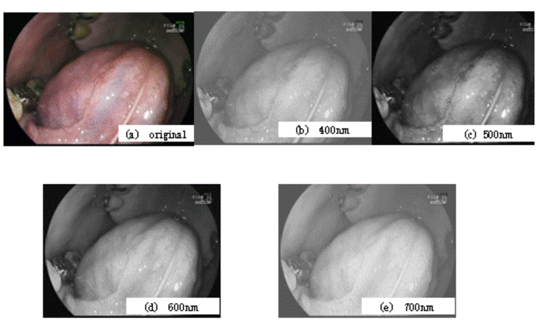


Figure 3. Example of spectral images

Developed Electronic Endoscopes and Diagnosis Using a Spectral Image

Figure 4 shows the flow diagram of developed spectral endoscopes. The RGB signals from the CCD converted to the digital data and used for processing including color transformation, noise reduction and gamma correction are performed. The spectral image is estimated by 3 x 3 matrices from corrected RGB signals. The dataset of coefficients of these matrices are calculated by the Wiener estimation method. For example, in the case of λ_1 = 500 nm, λ_2 = 620 nm, and λ_3 = 500 nm these spectral images can be calculated as follow:

$$\begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{bmatrix} = \begin{bmatrix} -0.00119 & 0.002346 & 0.0016 \\ 0.004022 & 0.000068 & -0.00097 \\ 0.005152 & -0.00192 & 0.000088 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}, \tag{2}$$

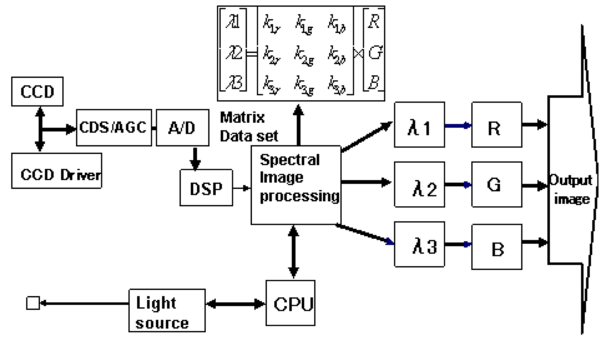
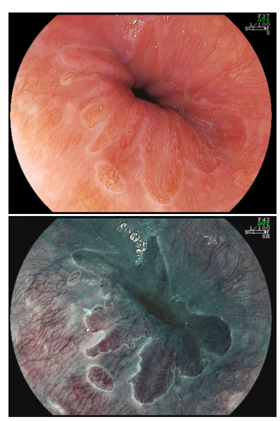


Figure 4. Flow diagram of spectral endoscopes

Then the color image is calculated by the arbitral spectral combinations. Figures 5 shows the examples of cancer of the esophagus taken by developed electronic endoscopes. In the figure, (a) is original RGB image and (b) shows the synthesized color image using spectral images at wavelength 500 nm, 450 nm and 410 nm as the red, green, blue channel. It is clearly recorded the boundary of the diseases and the detail of the blood vessel on the comparison with the original image taken by R, G and B.

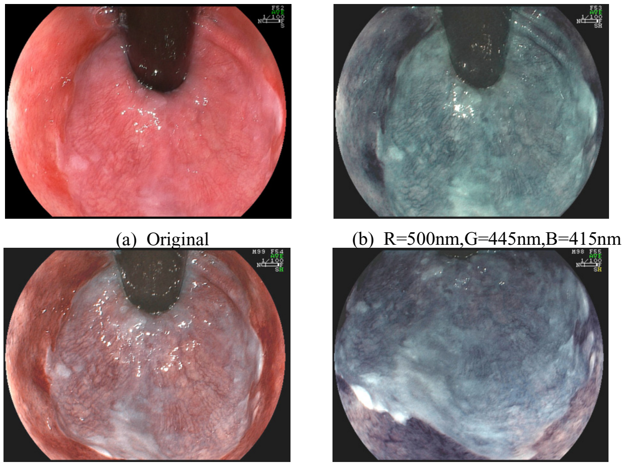
On the other hand, Figure 6 shows that the stomach membrane reproduced by three kinds of spectral image combinations. In the figure (a) is an original RGB image, (b) shows the synthesized image by R: 500 nm, G: 445 nm, B: 415 nm, (c) is the image by R: 550 nm, G:500 nm, B:470 nm and (d) shows the image by R:500 nm, G:470 nm, B:420 nm, respectively. We can clearly recognize the differences between each image. The optimum selection of spectral image depends on the kinds of diseases of the membrane.



(a) Original

(b)R:500nm
G:450nm
B:410nm

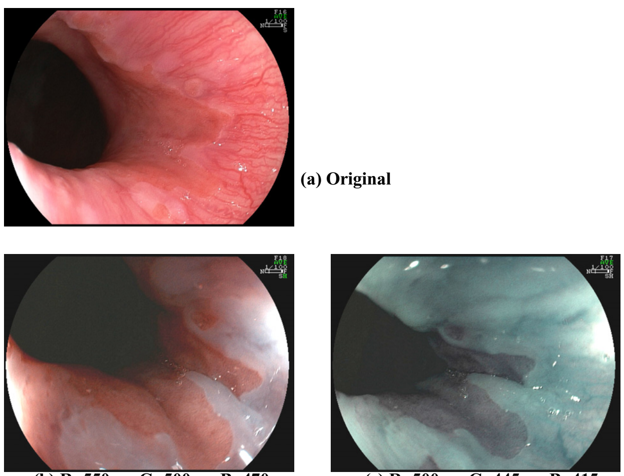
Figure 5. (a) RGB image, (b) Synthesized image by spectral images at 500 nm, 450 nm and 410 nm



(a) Original (b) R=500nm,G=445nm,B=415nm

(c) R=550nm,G=500nm,B=470nm (d) R=500nm,G=470nm,B=420nm

Figure 6. Color images with different combination of spectral images. (a) Original, (b)R:500 nm, G:445 nm, B:415 nm, (c)R:550 nm, G:500 nm, B:415 nm and (d)R:500 nm, G:470 nm, B:420 nm



(a) Original

(b) R=550nm,G=500nm,B=470nm **(c) R=500nm,G=445nm,B=415nm**

Figure 7. Color images by different spectral image combinations (a) Original, (b)R: 550 nm, G: 500 nm,B: 470 nm, (c)R: 500 nm, G: 445 nm,B: 415 nm

Therefore, many pictures with various kinds of diseases should be taken and analyzed. We are now taking many clinical images by using developed electronic endoscopes at the Chiba University hospital. Our final purpose is to find the optimum combination of spectral images for the diagnosis of the early stage of diseases of the stomach, gullet, colon and rectum. Figure 7 shows the examples of these images. Figure 7(a) is an original RGB image, Fig. 7(b) is an image obtained by the combination of R:550 nm, G:500 nm, B:470 nm, and Fig. 7(c) shows the combination of R:500 nm, G:445, B:415 nm. Figure 8 shows the photograph of the developed spectral endoscopes.

Conclusion

The first paper on the measurement of reflectance spectra of gastric mucous membrane was published in 1988 (1), on the basis of the analysis of those measured reflectance spectra, new electronic endoscopes using spectral information has been developed and clinically used to diagnose for various kinds of diseases. We are very pleased with a continued research in this field because we recognized that the importance of the basic research on the color science and technology.

Figure 8. Developed spectral endoscopes

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Author Biographies

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