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Computer Simulation for Improvement of Color Reproduction in Electronic Endoscopes

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Abstract

Image quality of the electronic endoscopes is poor compared with that from conventional optical endoscopes that use color film. Our goal is to improve the image quality, particularly color reproduction of electronic endoscopes. To achieve our goal, we have developed the endoscopic spectrophotometer to measure the spectral reflectance of gastric mucous membrane. Three hundred and ten spectra have been analyzed by principal component analysis. The results indicate that the reflectance spectra can be adequately described using only three principal components. Based on the above experimental result, it is shown that the spectral reflectance of gastric mucous membranes can be calculated from the R, G, B signals of the conventional electronic endoscopes. Therefore, spectral reflectance of all pixels in gastric mucous membrane taken by electronic endoscopes can be estimated within less than the average color difference $\Delta E^*_{uv} = 2.66$ in the L*u*v* color space. Computer simulations of the color reproduction of electronic endoscopes were performed, and the resulting spectral characteristics under various illuminants are described and analyzed.

1. Introduction

In recent years, electronic endoscopes with CCD area sensor have been developed and widely used instead of the conventional optical endoscopes that use color film. Electronic endoscopes can be easily applied to telemedicine, image filing, image processing and Picture Archiving and Communication Systems(PACS).

Color information is important for the early stage of diagnosis in various kinds of stomach diseases. However, color reproduction of the images taken by electronic endoscopes is poor compared with the optical endoscope images because the present electronic endoscopes use the NTSC system.

To improve the color reproduction of electronic endoscopes, we have developed an

endoscopic spectrophotometer to measure the spectral reflectance of gastric mucous membrane.[1] We have measured about 1000 spectral reflectance using this spectrophotometer and reported the capability of automatic diagnosis using spectral data and chromaticity.[2,3] We have also reported a color correction method in the electronic endoscope's input system, using a simple 3x3 matrix to reproduce a colorimetrically correct color based on the analysis of the spectral reflectance.[4]

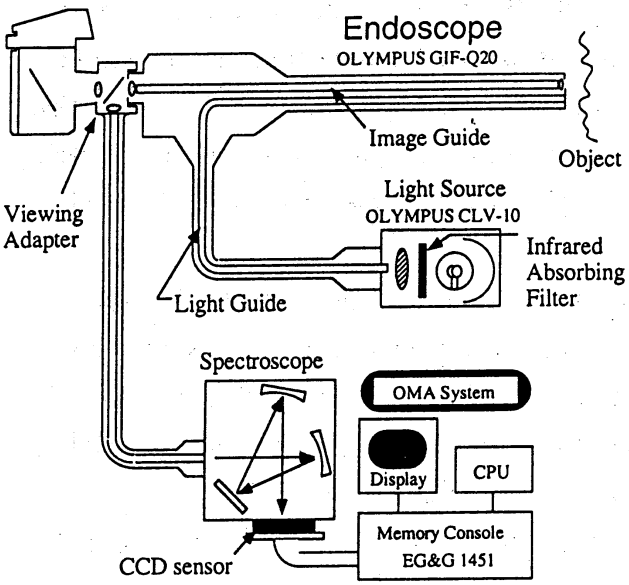
These color correction methods are based on the analysis of pixel to pixel, because the endoscopic spectrophotometer can only measure the spectral reflectance of gastric mucous membrane at specific points and cannot measure the spectra in entire viewing fields. To measure the spectral reflectance of MxN sampled points, normally, a multi-band method has been used, but the method is difficult to apply to the electronic endoscope.

In this study, we analyzed 310 spectral reflectance of gastric mucous membranes by principal component analysis, and it became clear that those measured reflectance spectra can be adequately described using only three principal components. Therefore, the spectral reflectance of all pixels in gastric mucous membranes can be estimated by R, G, B signals taken by electronic endoscopes. On the basis of the experimental results, the computer simulation of the color reproduction of electronic endoscopes was performed.

2. Principal Component Analysis of the Spectral Reflectance of Gastric Mucous Membrane

Figure 1 shows the block diagram of developed endoscopic spectrophotometer. The instrument consist of light source with xenon lamp; a conventional spectrophotometer; an optical multichannel analyzer with 1024 silicon photodiodes; and a personal computer. We measured about thousand reflectance spectra of gastric mucous membrane. Figure 2 (a) and (b) are examples of spectral reflectance of gastric mucous membrane. Three hundred and ten spectral reflectance of gastric mucous membranes excluding blurred reflectance spectra, have been analyzed by the principal component analysis. Figure 3 shows the cumulative contribution ratio of the principal components. The result shows that the contribution ratio from first to third components is about 99%; in other words, the reflectance spectra of gastric mucous membranes can be represented approximately 99% of the time using a linear combination of three principal components $\mathbf{u}_1$, $\mathbf{u}_2$ and $\mathbf{u}_3$. Figure 4 shows these three principal components or eigenvectors obtained from the covariance matrix of the reflectance spectra.

Figure 5 shows the plan of an electronic endoscopes that utilizes R, G, B sequencing, incorporating a rotating color wheel comprising of R, G, B filters used in the simulation. The value $E(\lambda)$ is the spectral radiance distribution of light source, $f_R(\lambda)$, $f_G(\lambda)$, $f_B(\lambda)$ are respectively, spectral transmittance of the R, G, B filters, $S(\lambda)$ is spectral sensitivity of CCD



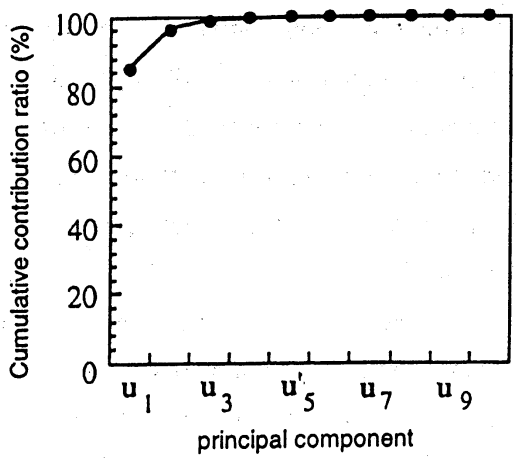


Figure 3. Cumulative contribution ratio of the principal components.

Figure 1. Diagram of the endoscopic spectrophotometer.

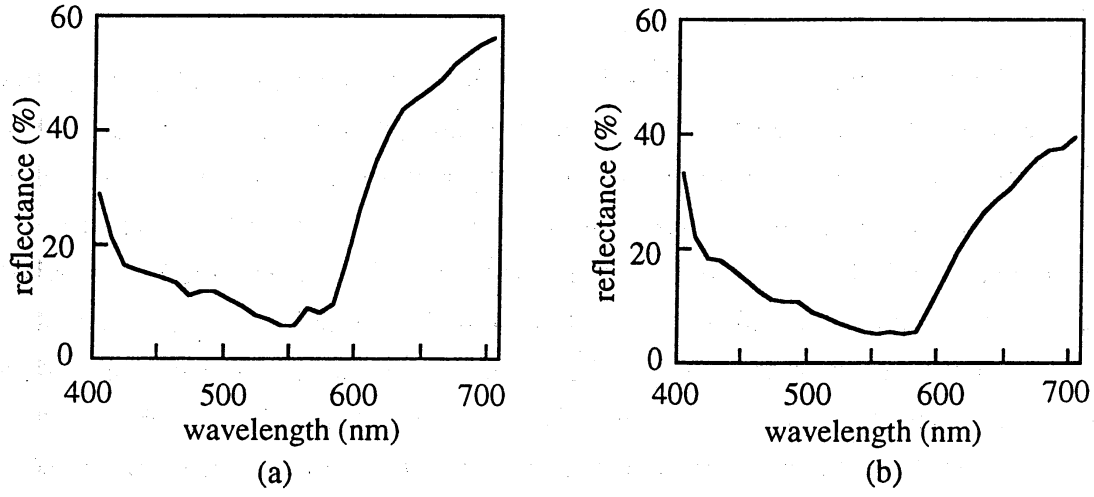


Figure 2. Examples of reflectance spectra of gastoric mucous membranes.

area sensor, $L(\lambda)$ is combined spectral transmittance of the light guide fiber and the imaging lens, and $o(\lambda)$ is the spectral reflectance of gastric mucous membranes. Then the output R, G and B values of the electronic endoscopes are calculated by Eq. (1).

$$\begin{aligned} v_R &= \int f_R(\lambda)E(\lambda)L(\lambda)S(\lambda)o(\lambda)d\lambda \\ v_G &= \int f_G(\lambda)E(\lambda)L(\lambda)S(\lambda)o(\lambda)d\lambda \\ v_B &= \int f_B(\lambda)E(\lambda)L(\lambda)S(\lambda)o(\lambda)d\lambda \end{aligned} \tag{1}$$

Although the spectral characteristics of the systems are inherently continuous, for the convenience the discrete vector notation is introduced as $E(\lambda)$:**E**, $f_R(\lambda)$, $f_G(\lambda)$, $f_B(\lambda)$:**fi**(i=R,G,B), $L(\lambda)$:**L**, $S(\lambda)$:**S**, $o(\lambda)$:**O**.

Then the R, G and B values of an object that are obtained by an endoscope are expressed as

$$\begin{aligned} v_i &= \mathbf{f}_i^t\mathbf{ELSo} \\ &= \mathbf{F}_i^t\mathbf{o} \\ &(i = R,G,B) \end{aligned} \tag{2}$$

where $\mathbf{F}_i^t(i = R,G,B)$ is an overall spectral sensitivities of the electronic endoscopes, and $[\bullet]^t$ represents transposition.

Because the orthonormal vectors with n-dimensional space were obtained by the principal component analysis, the reflectance spectra of gastric mucous membranes **o** can be calculated by

$$\mathbf{o} = \sum_{i=1}^{n} \alpha_i \mathbf{u}_i + \mathbf{m} \tag{3}$$

where α_i is an expansion coefficient and **m** is the mean vector of 310 reflectance spectra. From the result of principal component analysis, **o** can be approximated by the linear combination of the three eigenvectors $\mathbf{u}_1$, $\mathbf{u}_2$ and $\mathbf{u}_3$ with the mean vector **m**.

$$\mathbf{o} \cong \sum_{i=1}^{3} \alpha_i \mathbf{u}_i + \mathbf{m} = \begin{bmatrix} \mathbf{u}_1 & \mathbf{u}_2 & \mathbf{u}_3 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix} + \mathbf{m} \tag{4}$$

From Eqs.(2) and (4)

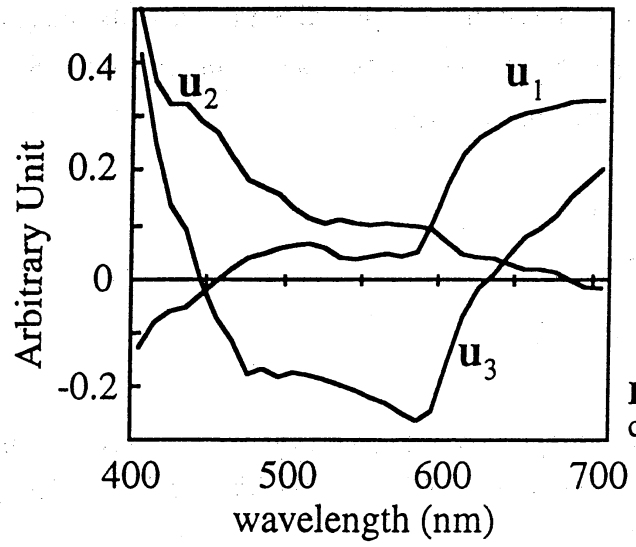


Figure 4. Eigenvectors of the principal components.

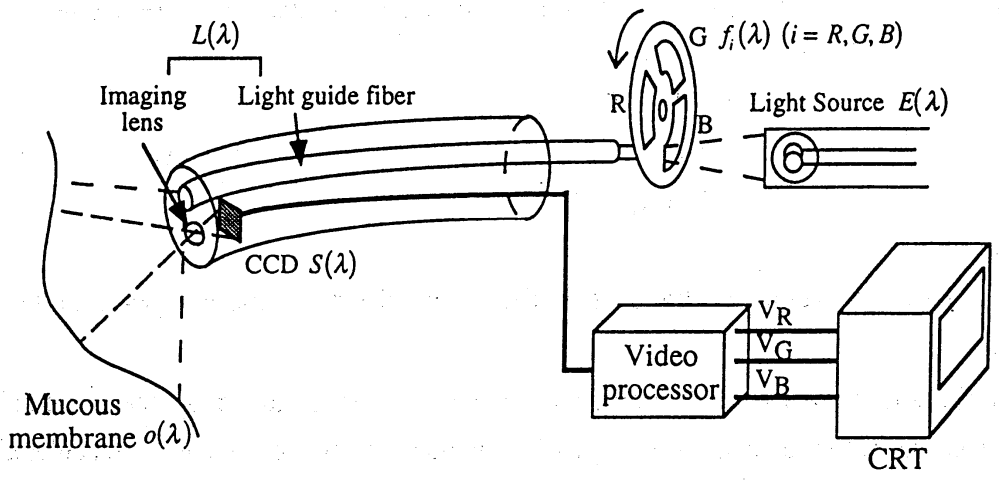


Figure 5. Simulation model of an electronic endoscope.

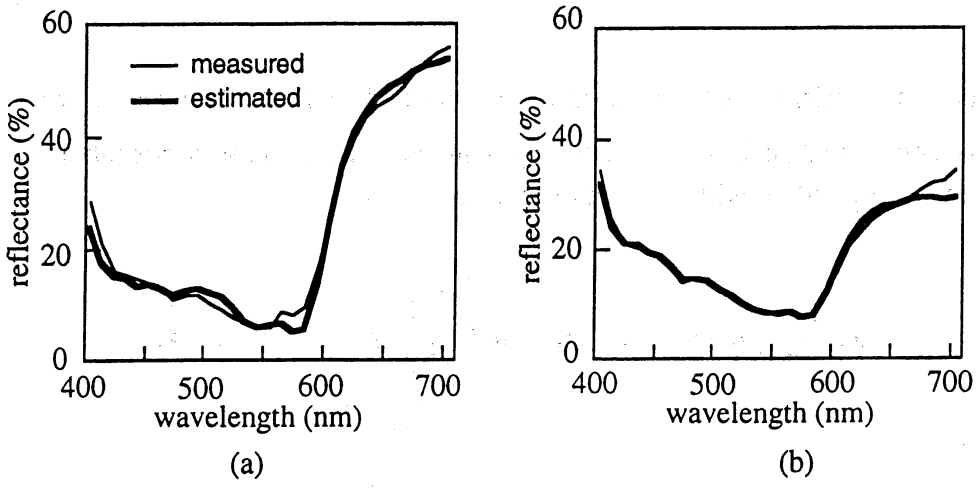


Figure 6. Examples of estimated reflectance spectra.

$$\begin{bmatrix} v_R \\ v_G \\ v_B \end{bmatrix} = \begin{bmatrix} \mathbf{F}_R^t \\ \mathbf{F}_G^t \\ \mathbf{F}_B^t \end{bmatrix} \left\{ \begin{bmatrix} \mathbf{u}_1 & \mathbf{u}_2 & \mathbf{u}_3 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix} + \mathbf{m} \right\} \tag{5}$$

Then, the constant value α_1, α_2 and α_3 is given by

$$\begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix} = \begin{bmatrix} \mathbf{F}_R^t\mathbf{u}_1 & \mathbf{F}_R^t\mathbf{u}_2 & \mathbf{F}_R^t\mathbf{u}_3 \\ \mathbf{F}_G^t\mathbf{u}_1 & \mathbf{F}_G^t\mathbf{u}_2 & \mathbf{F}_G^t\mathbf{u}_3 \\ \mathbf{F}_B^t\mathbf{u}_1 & \mathbf{F}_B^t\mathbf{u}_2 & \mathbf{F}_B^t\mathbf{u}_3 \end{bmatrix}^{-1} \left\{ \begin{bmatrix} v_R \\ v_G \\ v_B \end{bmatrix} - \begin{bmatrix} v_{Rm} \\ v_{Gm} \\ v_{Bm} \end{bmatrix} \right\}, \tag{6}$$

where,

$$\begin{bmatrix} v_{Rm} \\ v_{Gm} \\ v_{Bm} \end{bmatrix} = \begin{bmatrix} \mathbf{F}_R^t \\ \mathbf{F}_G^t \\ \mathbf{F}_B^t \end{bmatrix} \mathbf{m}.$$

Because $\mathbf{u}_i (i = 1,2,3)$ and $\mathbf{m}$ are known and $\mathbf{F}_i^t (i = R,G,B)$, $v_i (i = R,G,B)$ and $v_{im} (i = R,G,B)$ are obtained from the practical electronic endoscopes, the coefficients α_1, α_2 and α_3 can be calculated by Eq.(6).

The reflectance spectra of gastric mucous membrane can be estimated by Eq. (4); therefore it becomes possible to calculate the reflectance spectra of all pixels $O(x, y, \lambda)$ from the R, G, B output signals obtained by a general endoscope system.

We estimated 310 reflectance spectra of gastric mucous membranes by the above method. Examples of estimated reflectance spectra are shown in Fig. 6 (a) and (b). Estimated spectral reflectance are approximately equal to the measured spectral reflectance. On the other hand, color differences of *CIE* $L^*u^*v^*$ (under illuminant D65) between measured and estimated spectra are shown in Fig. 7. The average color difference ΔE_{uv}^* of three hundred and ten samples was 2.66, the minimum color difference ΔE_{uv}^* was 0.64 and maximum color difference ΔE_{uv}^* was 9.14. As shown in the next section, we simulated color reproduction of endoscope images under 12 different illuminants. The color reproduction of 310 measured and estimated reflectance spectra under those illuminants was also evaluated in *CIE* $L^*u^*v^*$ color space. The resultant average color difference ΔE_{uv}^* between measured and estimated ranged from 2.20 to 3.29. These results indicate that the proposed method has sufficient accuracy to estimate the reflectance spectra of gastric mucous membrane and that the slight estimation error does not affect the simulation of color reproduction of endoscope images.

3. Simulation of Color Reproduction in Electronic Endoscopes

The method was applied to improve color reproduction of practical eight kinds of endoscopic

images with 270x270 pixels. Namely gastric membranes with (a) cancer, (b) early stage of chronic gastritis, (c) chronic gastritis IIb, (d) advanced stage of chronic gastritis, (e) gastric ulcer, (f) normal membrane, (g) polyp and (h) xanthoma were used for computer simulation. In the simulation, first the spectral reflectance of gastric mucous membrane of all pixels was calculated from R, G, B signals, then the color reproduction of electronic endoscopes under twelve illuminants was estimated by computer simulation. The illuminants used in the simulation are CIE standard illuminant A; D65; CIE fluorescent lamps F1, F2, and F3, xenon lamp, metal halide lamp; fluorescent lamps for home use M1, M2, M3, M4, M5. The density balance for each illuminant was chosen so that the integral of the spectral radiance of each illuminant weighted by the spectral sensitivity of human visual system was constant.

The color temperature of the illuminants is shown in Table 1. Figure 8 shows the distribution of u'v' chromaticities for the images under illuminant CIE standard A and xenon lamp. The distribution shifts depending on the illuminants. To estimate the optimum illuminant, those obtained images were displayed on a CRT and evaluated by two physicians who are specialist of endoscopic diagnosis. Images by xenon lamp was selected as most preferred. Because the xenon lamp has been used as light source in conventional electronic endoscopes, we consider that the color memory of doctors may be fixed to the color reproduction by xenon lamp illumination. However, the doctors said that in the diagnosis of the membrane, particularly in the vascular pattern of polyp, image by fluorescent M2 is more significant than the image with other illuminants.

As the physical measure of the illuminant, we assumed that the illuminant with wide color gamut in reproduced images may be better for electronic endoscopes. Then, we defined the evaluation value E_V as Eq. (7).

$$E_V = \frac{\sum_{i=1}^{m-1}\sum_{j=i+1}^{m}\left\{\left(L_i^* - L_j^*\right)^2 + \left(u_i^* - u_j^*\right)^2 + \left(v_i^* - v_j^*\right)^2\right\}^{1/2}}{{}_mC_2} \qquad (7)$$

where m is the number of measured spectra. The equation means that as E_V becomes larger, the color differences between pixels becomes large.

Figure 9 shows the results of the calculated evaluation values. The evaluation values of the illuminant M3, M4, M2, A and F1 are larger than that of the xenon lamp. Simulation images with large E_V enhanced the color difference between pixels. Thus, for example, the vascular patterns of the polyp and chronic gastritis became more clear although the color reproduction is poor.

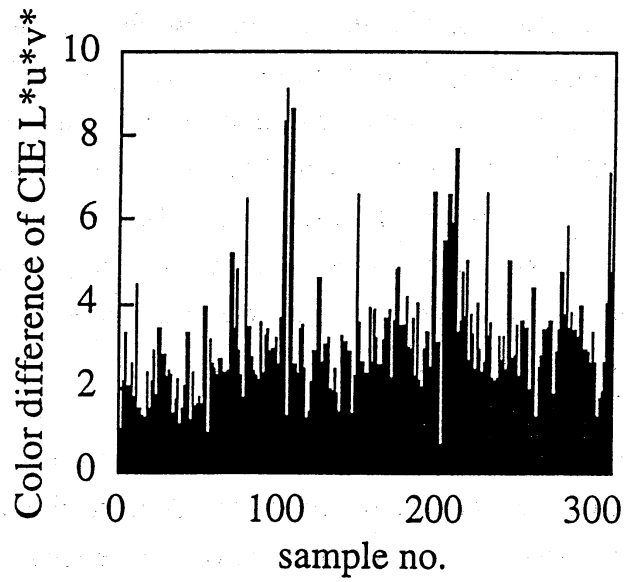


Figure 7. Color differences of CIEL*u*v* between measured and estimated reflectance spectra.

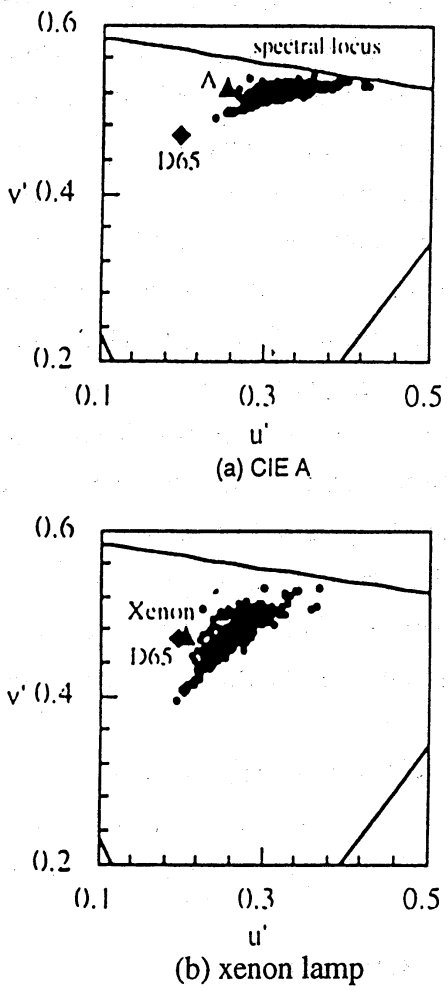


Figure 8. The u'v' chromaticity of a polyp image under two kinds of illuminants:(a)CIE A, (b) xenon lamp.

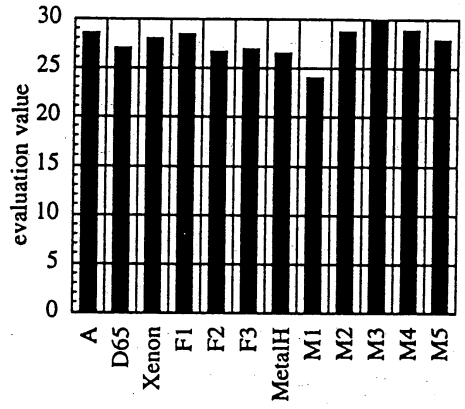


Figure 9. Results of the calculated evaluation values.

Table 1. The color temperatures of the 12 illuminants used

Illuminant	Color temperature
CIE standard A	2856 K
CIE standard D65	6500 K
CIE fluorescent F1	about 3000 K
CIE fluorescent F2	about 4000 K
CIE fluorescent F3	about 6500 K
Xenon	about 5100 K
Metal Halogen	4274 K
Fluorescent lamp M1	6245 K
Fluorescent lamp M2	7763 K
Fluorescent lamp M3	2766 K
Fluorescent lamp M4	5150 K
Fluorescent lamp M5	6758 K

4. Conclusion and Discussion

In this paper, we showed that the spectral reflectance of gastric mucous membranes can be estimated with high accuracy using only three principal components. On the basis of the analysis, the spectral reflectance of 270 x 270 pixels were estimated from the R, G, B signals of gastric mucous membrane taken by practical electronic endoscopes. The color reproduction characteristics of eight kinds of membranes with different disorders under the 12 different illuminants were estimated by computer simulation. Those images were rated by physicians, and the color reproduction of the image taken by xenon lamp was most preferred, however, in the diagnosis of vascular pattern, another illuminant was better than the xenon.

In this paper, we only considered the improvement of color reproduction of electronic endoscopes based on colorimetric color reproduction under various illuminants. The perceived colors, however, are different in practice from the colorimetric color reproduction, that are caused by the chromatic adaptation of human vision. The color appearance can be predicted using chromatic adaptation models[6,7,8] such as the von Kries, Fairchild, RLAB , Hunt, etc.. Therefore, furthermore research considering color appearance models for the optimum color reproduction should be performed for each of the various diagnosis and viewing condition.

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