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Dynamic Band Imaging: Image Enhancement for Endoscopic Diagnosis

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Abstract. *In this study the authors propose an endoscopic image enhancement technique named dynamic band imaging (DBI) which temporally changes the color conversion matrix. DBI is based on the estimation of multispectral band images to enhance the endoscopic color images in order to distinguish the slight color difference of early stage cancer more clearly. Since this method can be implemented by using only a software approach, it is easy to upgrade the devices, whereas the narrow band technique requires hardware upgrading. From the results of fundamental analysis by subjective evaluations, the effectiveness of DBI for image enhancement in comparison with the typical still image evaluation is demonstrated. In addition the authors have developed a user interface to determine the six required parameters of this method easily. By using this device, appropriate parameters for practical endoscopic diagnosis have been obtained. DBI is found to be a new, effective method to enhance color endoscopic images. © 2008 Society for Imaging Science and Technology.*
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INTRODUCTION

Color images taken by electronic endoscopes provide important information for diagnosis of various kinds of digestive diseases; in these images it is important to observe the fine structure of the mucous membrane wall in detail. Color reproduction of electronic endoscopes, however, is insufficient for diagnosis the early stage of disease. Therefore, it is necessary to improve color reproduction of electronic endoscopes in order to distinguish the slight color difference of early stage cancer more clearly.[1]

To this end, several methods have been proposed in the past. Based on the report that index of hemoglobin (IHb) correlates well with mucosal microcirculation, the adapted IHb color enhancement system has been developed.[2] Because this method can be implemented by a real-time software approach, it is widely used in commercial endoscopes. Although the efficacy of this technique for the digestive systems has been reported,[3,4] a disadvantage has been also reported, namely that it would increase the number of false positives for non-polypoid lesions.[5] Autofluorescence endoscopy exploits either autofluorescence characteristics of naturally occurring molecules in the tissue, or fluorescence caused by an exogenously administered fluorescent drug.[6–8] By use of this technique, the detection of abnormal lesions depends on changes in the concentration or depth distribution of the endogenous fluorophores that can affect the fluorescence intensity or spectral distribution. In 2002, Gono et al. have proposed the narrow band imaging technique[9–11] to improve the image quality with regard to such fine structure, by adjusting the spectrum feature in consideration of the wavelength dependence of the light penetration depth into the tissue. This method is quite significant and has received remarkable acceptance from medical doctors.[12,13] However, because the NBI and autofluorescence endoscopy require dedicated hardware, their costs are very high and they cannot perform optimal analysis for certain diseases because of the fixed wavelength.

To overcome such problems, Miyake et al. in 2005 proposed the image enhancement technique using multispectral images,[14] which is based on the spectral analysis as follows. In 1988, they first developed the endoscope spectrophotometer[15] to measure the spectral reflectance of gastric mucous membrane directly and precisely. Many measured spectra of the gastric and rectal mucous membrane have been analyzed by principal component analysis, and these investigators showed that the reflectance spectra can adequately be described by only three principal components. Based on this 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 con-

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ventional electronic endoscopes. In the study of Miyake et al.,[14] three of estimated single band images were chosen from estimated multiband images and were reassigned to RGB channels. Although some endoscopic images are improved effectively by using this method, since it is essentially only a simple color conversion using a 3×3 matrix, its capacity for enhancement has limitations.

Therefore, in the present study we propose a new image enhancement technique based on estimated multispectral imaging and named dynamic band imaging (DBI). Human perception has more sensitivity to a changing stimulus than to a static stimulus. In order to distinguish a slight color difference, it can be thought that color-enhanced movies are more effective than still images. DBI is an extension of Miyake's synthesizing method and exploits temporal change of the color conversion matrix based on the above hypothesis. Since DBI can be implemented by only using software postprocessing, it is very easy to realize in conventional endoscopes, whereas conventional color-enhancement techniques require hardware upgrading. In this study, we first examine the fundamental effectiveness of DBI by performing subjective experiments, and the results are analyzed by employing logistical regression analysis.

Actually, DBI can have many parameters, whose change can be designed freely. In this study we focus on six example cases to confirm the basic efficacy of the temporal parameter change and evaluate these cases by using logistical regression analysis. Further, we implement DBI for the practical medical application in endoscopic diagnosis. Because DBI has many parameters which need to change simultaneously, it is a very difficult task to find the best way of changing parameters using a conventional user interface. Therefore, we have developed an interface which can adjust six parameters in real-time. Finally, the efficacy of the DBI system for the medical application is evaluated by a medical doctor who is a specialist for endoscopic diagnosis.

IMAGE ENHANCEMENT BY SPECTRAL PROCESSING

Spectral estimation from RGB values

The color reproduction characteristics of electronic endoscopes depend on many optical factors with wavelength λ (nm) such as spectral radiant distribution of illuminant $E(\lambda)$, spectral sensitivity of charge coupled device (CCD) $S(\lambda)$, spectral transmittance of color filters $f_i(\lambda)$, $i=\{r,g,b\}$, and spectral transmittance of imaging lenses $L(\lambda)$. The output signal v_i at position (x,y) can be calculated as

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

where $r(\lambda,x,y)$ is a spectral reflectance of the surface. For mathematical convenience, each spectral characteristic with wavelength λ is expressed as a vector or a matrix with the discrete form, and further for the sake of simplicity, (x,y) from v_i,r are omitted. Equation (1) can be rewritten as follows:

$$\mathbf{v} = [v_r \ v_g \ v_b]^T = \mathbf{Ar},$$

$$\mathbf{r} = [r(400) \ r(405) \ \cdots \ r(700)]^T, \tag{2}$$

where T denotes a transposition and matrix $\mathbf{A}$ is called system matrix that represents entire characteristics of imaging system. In order to discretize the wavelength in the visible range, we calculate from 400 to 700 nm at intervals of 5 nm. Here, the imaging system is assumed to have linear characteristics. The method of Munzenmayer et al.[16] can be used to to handle nonlinear characteristics of the imaging system. The estimation of reflectance spectra $\tilde{r}$ can be obtained as follows:

$$\tilde{\mathbf{r}} = \mathbf{Gv}, \tag{3}$$

where G is called a estimation matrix figured out by using an estimation method. In this study we employ the Wiener estimation for $\mathbf{G}$. Wiener estimation method minimizes the overall average of the square error between the original and estimated spectral reflectance.[17] For this method, the estimation matrix $\mathbf{G}$ is given as follows:

$$\mathbf{G} = \mathbf{R}_{rr}\mathbf{A}^T(\mathbf{A}\mathbf{R}_{rr}\mathbf{A}^T + \mathbf{R}_{nn})^{-1}, \tag{4}$$

where $\mathbf{R}_{rr}$ represents the self-correlation matrix of original spectra $\mathbf{r}$, and $\mathbf{R}_{nn}$ represents the self-correlation of noise. Hence, Eq. (4) can be rewritten as

$$\mathbf{G} = \mathbf{r} \cdot \mathbf{v}^T(\mathbf{v} \cdot \mathbf{v}^T + \mathbf{R}_{nn})^{-1}. \tag{5}$$

In order to calculate $\mathbf{G}$, it is needed to take number of samples by the CCD. In this study, we use Macbeth Color Checker which has 24 of different color samples, and each spectral distribution is first measured by using a spectrophotometer. Thus, 24 sets of measured spectral distributions are used for $\mathbf{r}$ in Eq. (5), and 24 sets of $\mathbf{v}$ are given by the output signal of the CCD from the Macbeth Color Checker.

Image enhancement by estimated spectral information

In 2005, Miyake et al. proposed the image enhancement method by assigning three single band images of arbitrary wavelength to R, G, B image planes.[14] For example, by choosing 500 nm for the R plane, 450 nm for the G plane, and 410 nm for the B plane from an estimated 61-band spectral image, a synthesized example is shown in Figure 1. The edge of the tumor area is clearly emphasized by using this method. This color transformation is just multiplying a 3×3 matrix with the pixel values of the CCD output $\mathbf{v}=[v_r \quad v_g \quad v_b]^T$ as follows:

$$\mathbf{p} = \mathbf{FG} \cdot \mathbf{v},$$

$$= \mathbf{M} \cdot \mathbf{v}, \tag{6}$$

where $\mathbf{p}$ is the output RGB vector and $\mathbf{F}$ is selection and filtering matrix which converts from 61-band spectral data to RGB data. $\mathbf{M}$ actually used in Fig. 1 is

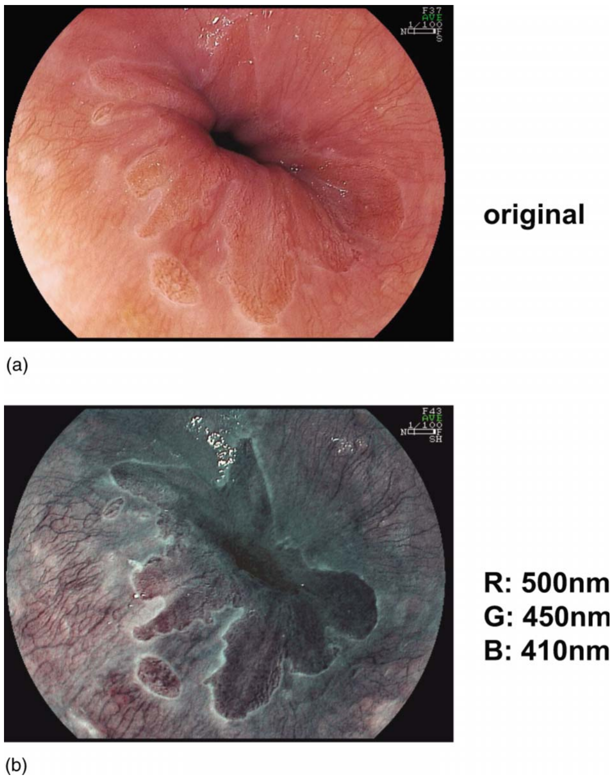


Figure 1. (a) Ordinary endoscopic image, (b) Synthesized image by assigning spectral images at 500, 450, and 410 nm to R, G, B planes, respectively.

$$\mathbf{M}=\begin{bmatrix}-0.00119 & 0.002346 & 0.001600\\ 0.004020 & 0.000068 & -0.000970\\ 0.005152 & -0.001920 & 0.000088\end{bmatrix}. \tag{7}$$

Since this operation is very simple, it is easy to implement it in the conventional endoscope system as software enabled postprocessing in real-time.

In the practical diagnosis, medical doctors have to diagnose the hundreds kinds of tumors on the mucous membrane which have different spectral properties. When a tumor has a particular reflectance spectrum which is clearly different from the reflectance spectra of mucous membrane, the conventional method is adequate to emphasize the edge. There are, however, many tumors which have quite similar reflectance spectra to the membrane. In order to enhance such slight difference of spectral properties, we propose the new method named dynamic band imaging.

Dynamic Band Imaging (DBI)

Human perception has greater sensitivity to temporally changing stimuli than to a still stimulus, e.g., small involuntary eye movement. In order to distinguish slight color difference, color-enhanced movies may be more effective than still images. Since endoscopic diagnoses are conventionally performed by evaluating still images, in this study we generate the color enhanced movie from the still image based on the spectral processing described above.

In this method, for designing the matrix **F** we define three kinds of time-varying parameters such as center wavelength $c_i(t)$ (nm), bandwidth $w_i(t)$, and intensity coefficient $n_i(t)$, where t is the time and i represents color channels, $i=\{r,g,b\}$. This method is equivalent to changing the transformation matrix **M** dynamically; hence, we call it DBI. By use of estimated reflectance spectra $\tilde{r}(\lambda)$ calculated with **G**, output digital values can be synthesized by using the Gaussian distribution as follows:

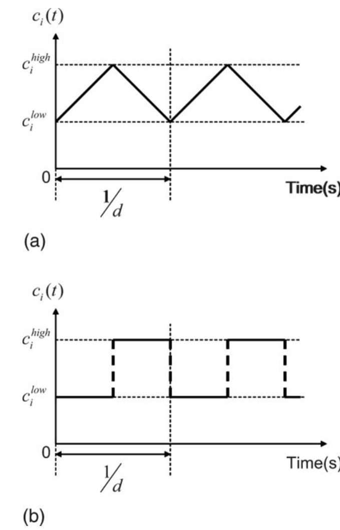


Figure 2. Temporally changing functions of the center wavelength $c_i(t)$ (a) triangular wave form and (b) square wave form.

$$p_i = n_i(t)k_i \sum_{\lambda=\{400,405,\cdots,700\}} \frac{1}{\sqrt{2\pi}w_i(t)} \times \exp\left(-\frac{(\lambda-c_i(t))^2}{2w_i(t)^2}\right)\tilde{r}(\lambda). \tag{8}$$

Coefficient k_i is determined to give $(p_r,p_g,p_b)=(255,255,255)$ when the camera records a perfectly reflecting diffuser as follows:

$$k_i \sum_{\lambda=\{400,405,\cdots,700\}} \frac{1}{\sqrt{2\pi}w_i(t)} \exp\left(-\frac{(\lambda-c_i(t))^2}{2w_i(t)^2}\right)=255. \tag{9}$$

In this method, we have infinite degrees of freedom to define these time-varying functions. In order to analyze the fundamental efficacy of DBI, we prepare two kinds of changing functions to vary the parameters. The first one is

$$c_i(t)=\begin{cases} c_i^{\mathrm{low}}+2dt(c_i^{\mathrm{high}}-c_i^{\mathrm{low}}) & \text{if } 0\leqslant t<\dfrac{1}{2d},\\ c_i^{\mathrm{low}}+2(1-dt)(c_i^{\mathrm{high}}-c_i^{\mathrm{low}}) & \text{if } \dfrac{1}{2d}\leqslant t<\dfrac{1}{d},\end{cases}$$

$$w_i(t)=10,$$

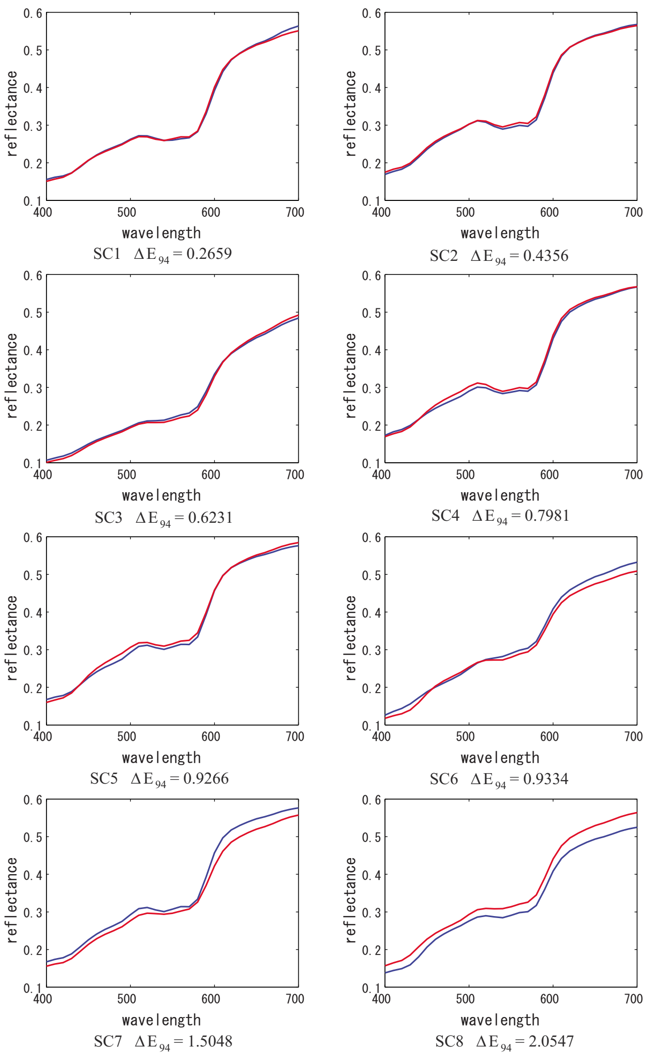


Figure 3. Eight sets of reflectance spectra used in the subjective experiment. Each color difference ΔE_{94} is calculated under D65 illumination.

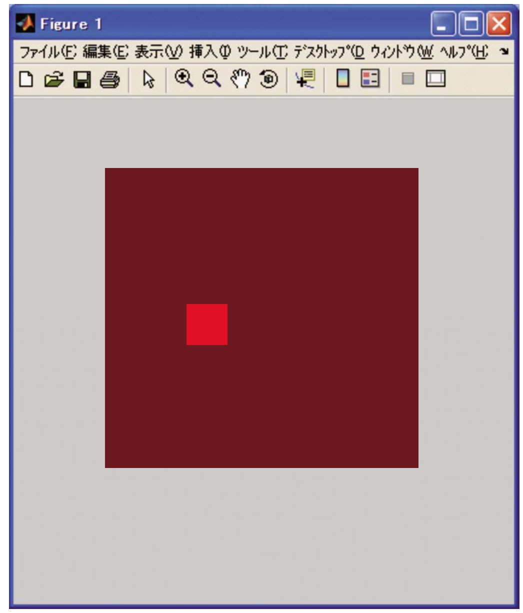


Figure 4. Display image of the subjective experiment. A small color patch is placed on a random position over the large color patch.

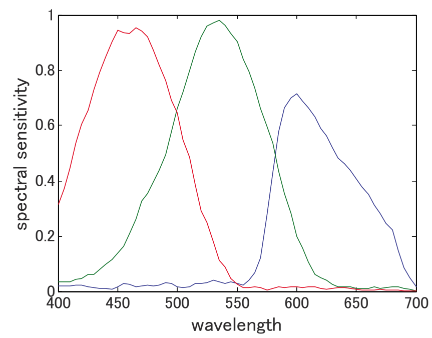


Figure 5. Spectral sensitivity $Q_i(\lambda) = S(\lambda) f_i(\lambda) L(\lambda)$ of the camera simulator.

$$n_i(t) = 1, \tag{10}$$

where $c_i^{\mathrm{low}}, c_i^{\mathrm{high}}$ (nm) are the lower and higher boundaries of the oscillation of the center wavelength respectively and d (Hz) represents the frequency of the oscillation. Then $c_i(t)$ is the triangular wave function as shown in Figure 2(a). In this study, we investigate the efficacy of center wavelength time-variation and leave bandwidth and intensity coefficient constant. The second changing function is as follows:

$$c_i(t) = \begin{cases} c_i^{\mathrm{low}} & \text{if } 0 \leqslant t < \dfrac{1}{2d}, \\ c_i^{\mathrm{high}} & \text{if } \dfrac{1}{2d} \leqslant t < \dfrac{1}{d}, \end{cases}$$

$$w_i(t) = 10,$$

$$n_i(t) = 1. \tag{11}$$

This shape is a simple square wave as shown in Fig. 2(b). On the basis of these examples the effectiveness of dynamic band imaging can be evaluated in comparison with still image evaluation.

EXPERIMENTS

Dynamic band imaging has been proposed based on the hypothesis that color-enhanced movies may be more effective than still images to distinguish slight color difference. Therefore, in order to investigate the fundamental effectiveness of DBI, we have conducted a basic experiment by way of subjective evaluation. In this experiment, we have prepared images comprising eight sample combinations of regions exhibiting similar reflectance spectra. Each combination consists of two kinds of reflectance spectra extracted from an arbitrary human skin color database. The color differences ΔE_{94} under D65 illumination between them and all reflectance spectra are shown in Figure 3. A small square patch which is colored by the first reflectance spectra is placed on a random position over the large square patch colored by the second reflectance spectra as shown in Figure 4. The efficacy of the image enhancement is evaluated by judging whether the small patch can be found or not.

Table I. DBI parameters of test cases B–F.

Case	Wave form	Frequency (Hz)	c_r^{low}	c_r^{high}	c_g^{low}	c_g^{high}	c_b^{low}	c_b^{high}
B	**Triangular**	**2**	**600**	**680**	**500**	**580**	**420**	**500**
C	Triangular	**1**	600	680	500	580	420	500
D	Triangular	2	**620**	**660**	**520**	**560**	**440**	**480**
E	**Square**	2	600	680	500	580	420	500
F	Triangular	2	600	680	500	580	420	500

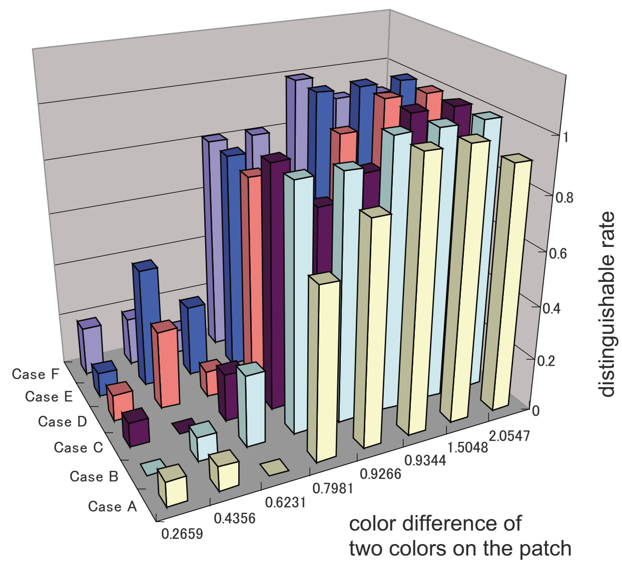


Figure 6. Results of subjective evaluation. Distinguishable rates of each case are shown.

These color patches are taken by a camera simulator which has the typical spectral sensitivity $Q_i(\lambda)=S(\lambda)f_i(\lambda)L(\lambda)$ as shown in Figure 5. By using this camera simulator, we first calculate the estimation matrix **G** which gives $\tilde{r}(\lambda)$ from v_i by means of Wiener estimation, as described above. Dynamic band imaging described in Eq. (8) is performed with the triangular wave function (Eq. (10)) and the square wave function (Eq. (11)). For subjective evaluation, we prepare six kinds of imaging schemes as follows:

Case A: Color patches are displayed as taken by the camera simulator.

Case B: DBI with 2 Hz triangular wave form using estimated reflectance spectra $\tilde{r}(\lambda)$. This is set as base line.

Case C: DBI with slower frequency than case B.

Case D: DBI with smaller amplitude of wave oscillation than case B.

Case E: DBI with square wave form.

Case F: DBI using original reflectance spectra $r(\lambda)$.

Actual DBI parameters used in cases B–F are shown in Table I. For the subjective evaluation, 48 movie patches (eight sets of skins colors times six cases) are displayed on the liquid crystal display monitor for 5 s each in random order. Subjects are asked whether they could find the small square patch inside the large square patch or not (Fig. 4). The distinguishable rates of the six cases evaluated by eleven subjects (21–30 years old) are shown in Figure 6.

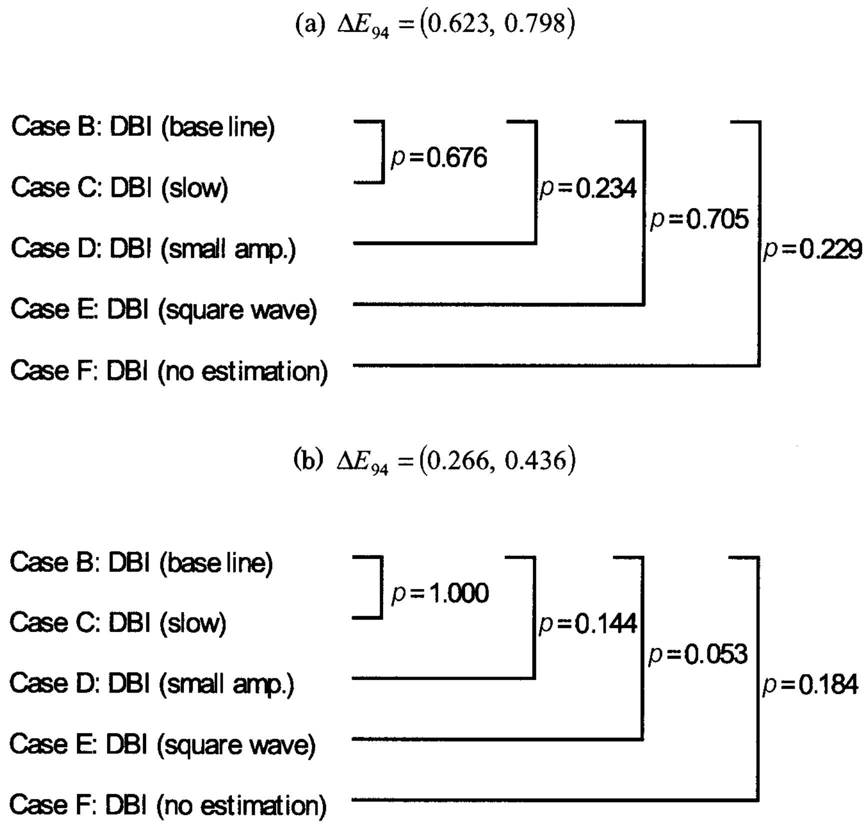
Table II. Results of logistical regression analysis by varying the range of color difference. ($p<0.05$) represents significant difference between results of static image (case A) and DBI (cases B–F). We obtain significant efficacy of DBI in the range of $\Delta E_{94}=(0.623, 0.798)$.

Range 1	$dE94=(0.266, 2.055)$	$p=0.210>0.05$
Range 2	$dE94=(0.266, 0.934)$	$p=0.242>0.05$
Range 3	$dE94=(0.266, 0.798)$	$p=0.051>0.05$
Range 4	$dE94=(0.266, 0.436)$	$p=0.479>0.05$
Range 5	$dE94=(0.623, 0.798)$	$p=0.025<0.05(^*)$
Range 6	$dE94=(0.623, 0.934)$	$p=0.328>0.05$
Range 7	$dE94=(0.927, 0.934)$	$p=0.355>0.05$

To examine the efficacy of the proposed method, the logistical regression analysis is employed. First we compare the static image (case A) with DBI (cases B–F) by varying the range of color difference, and the results appear in Table II. We see from Table II that significant efficacy ($p=0.025<0.05$) is obtained in the range of $\Delta E_{94}=(0.623, 0.798)$, but not for $\Delta E_{94}\leqslant 0.436$ and $\Delta E_{94}\geqslant 0.927$. This means that $\Delta E_{94}\geqslant 0.927$ represents enough large color difference and most of subjects could distinguish two colors in this range, and $\Delta E_{94}\leqslant 0.436$ is actually too small difference to enhance by DBI. Hence, DBI is effective to improve the distinguishable rate of color difference around $\Delta E_{94}=(0.623, 0.798)$.

Next we examine the difference between parameters of DBI by using the logistical regression analysis as shown in Table III. The p value for each combination is calculated between results of base line case (B) and each cases (C–F). Table III(a), which shows results in the range of $\Delta E_{94}=(0.623, 0.798)$, actually reveals no significant difference, whereas we can see high efficacy ($p=0.053$) of case E against case B in the range of $\Delta E_{94}=(0.266, 0.436)$. We infer that the square wave form has the possibility to emphasize the very small color difference.

Table III. Results of logistical regression analysis between results of base line case (B) and each case (C–F) in the range of (a) $\Delta E_{94}=(0.623,0.798)$ and (b) $\Delta E_{94}=(0.266,0.436)$. Data show no significant difference in the range of $\Delta E_{94}=(0.623,0.798)$, whereas case E shows a significant difference ($p=0.053$) in the range of $\Delta E_{94}=(0.266,0.436)$.



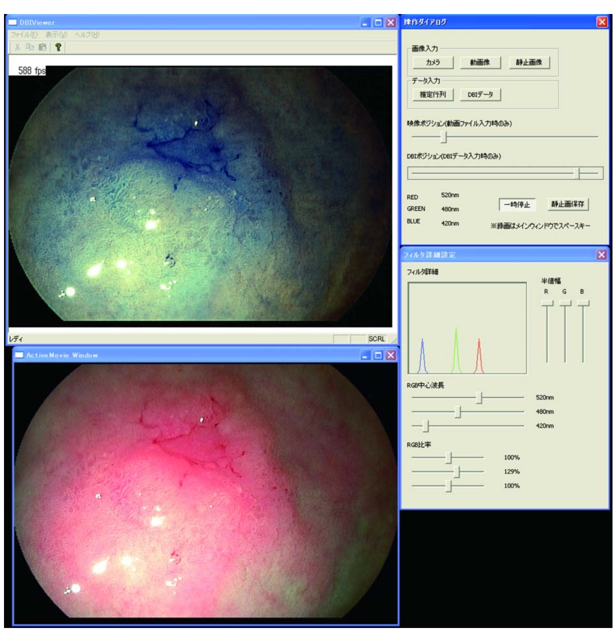


Figure 7. DBI application software for endoscopic diagnosis.

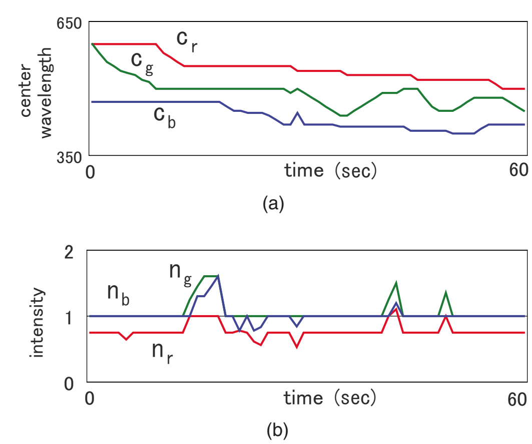


Figure 8. An example change of (a) center wavelength, $c_i(t)$, and (b) intensity, $n_i(t)$, determined by a medical doctor using PHANTOM®.

ENDOSCOPIC DIAGNOSIS

As the practical application of DBI, we implement the real-time DBI system for endoscopic diagnosis as shown in Figure 7. Because DBI has many parameters which need to change simultaneously, it is a very difficult task to determine the best change of parameters using a conventional man-machine interface, such as an ordinary mouse and keyboard. Therefore, we propose to use PHANTOM® (SensAble Technologies) in order to determine the best parameters of DBI, which is an input interface having six degrees of freedom. Six parameters of DBI (center wavelength $c_i(t)$ and intensity $n_i(t)$) are assigned to the X, Y, Z coordinate, and roll, yaw, pitch angles of PHANTOM®'s stylus, respectively.

Medical doctors can seek the best way of changing the six parameters while displaying the endoscopic image in real-time. Figure 8 shows a sample change determined by a medical doctor who a specialist for endoscopic diagnosis in order to enhance the slight cancer on the mucous membrane of the stomach. The endoscopic image used in this evaluation is shown in Fig. 7. After the evaluation of DBI by the medical doctor, he commented that DBI is a new, effective method to enhance the image for medical diagnosis and the interface is very useful to determine many parameters at the same time.

CONCLUSION

In this study, we propose a new image enhancement technique named dynamic band imaging (DBI) for endoscopic diagnosis. This method is based on the hypothesis that color-enhanced movies may be more effective than still images to distinguish a slight color difference. Therefore, at first, in order to investigate the fundamental efficacy of DBI, we conducted subjective experiments with six cases of parameters of DBI. From the results of logistic regression analysis, we found that DBI with a triangular wave form is significantly effective for improving the distinguishable rate of color difference around $\Delta E_{94}=(0.623, 0.798)$; in comparison the square wave form has the possibility to emphasize very small color difference $\Delta E_{94}=(0.266, 0.436)$. Because the parameter variation in DBI can be designed freely, we need to analyze the efficacy by accumulating results of fundamental experiments, and we need to find more effective parameters by evaluating many practical medical images. In order to determine many time-varying parameters at the same time, we adopted the PHANTOM® interface which has six degrees of freedom input. According to the medical doctor who evaluated the DBI system with this interface, it is effective for practical diagnosis.

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