Optimum design of spectral characteristic of light source for an optical endoscope

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Abstract

The design of spectral characteristic of the light source in an optical endoscope is discussed. First, two criteria are introduced for the evaluation of the light source and the evaluation result for two CIE standard illuminants and 15 light sources commercially available is presented. Next, an optimization method using POCS (projection onto convex set) is proposed for the design of the light source. It is shown that the optimum light source achieves much better score for the introduced criteria than the 17 light sources. Simulation of image reproduction of mucous membrane under an arbitrary light source is also described.

Introduction

In endoscopic diagnosis, an optical endoscope (OE) with fiber bundle is widely used as well as an electronic endoscope (EE) with CCD area sensor. The OE has some advantages; it is less expensive than EE and the observed color is more stable because it is composed of optical elements only. As a shortcoming, the OE available now can hardly enhance the color variation of mucous membrane which is important in diagnosis, while the EE can easily do that by changing some parameters of video circuits. However, we considered that the OE can potentially have a similar effect of color enhancement by optimizing its light source.

In this paper, we first formulate the color observed in an optical endoscope. Then we present two criteria for evaluation of the light source and actually evaluate 17 kinds of light sources. Next, we propose a technique to optimize the spectral characteristic of the light source of OE. In this optimization, three conditions corresponding to two criteria introduced and a physical constraint are expressed mathematically and a solution holding those conditions simultaneously is found by POCS algorithm. The effectiveness of the optimized light source is confirmed through the criteria introduced. Finally, we briefly introduce a simulation of image reproduction under an arbitrary light source.

Formulation

Fig. 1 shows a schematic illustration of an optical endoscope. The light emitted from the light source passes through the light guide fiber and illuminates the object surface. The intensity distribution of the light on the object surface is transmitted through the image guide fiber and observed by a physician. Letting the spectral radiance of the light source be $e(\lambda)$, the overall spectral transmittance of transmissive optical elements $t(\lambda)$, spectral reflectance of mucous membrane $o(\lambda)$, the observed light is given by the spectral product of these characteristics, $e(\lambda)t(\lambda)o(\lambda)$. The tristimulus values of this light are expressed as,

$$
\begin{aligned}
X &= \int \bar{x}(\lambda)e(\lambda)t(\lambda)o(\lambda)d\lambda \\
Y &= \int \bar{y}(\lambda)e(\lambda)t(\lambda)o(\lambda)d\lambda \\
Z &= \int \bar{z}(\lambda)e(\lambda)t(\lambda)o(\lambda)d\lambda
\end{aligned}
\tag{1}
$$

where $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ are the color matching functions.

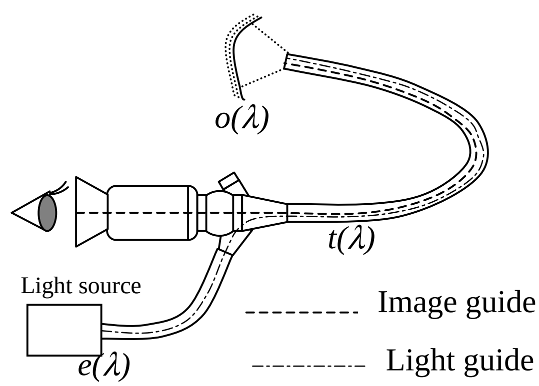

Figure 1: Schematic illustration of an optical endoscope.

For the mathematical expression used in later sections, we express each spectral characteristic discretely by a vector or a matrix as follows.

Reflectance of mucous membrane:

$o(\lambda) \Rightarrow \mathbf{o} = [o_1,\ldots, o_n]^T$

Radiance of xenon lamp (conventional lamp):

$e_x(\lambda) \Rightarrow \mathbf{e}_x = [e_{x1},\ldots, e_{xn}]^T$

Radiance of test light source:

$e(\lambda) \Rightarrow \mathbf{e} = [e_1,\ldots, e_n]^T$

Overall transmittance of optical elements:

$t(\lambda) \Rightarrow \mathbf{T} = \mathrm{diag}[t_1,\ldots, t_n]^T$

Color matching functions of the CIE standard observer:

$\bar{x}(\lambda) \Rightarrow \mathbf{x},\ \bar{y}(\lambda) \Rightarrow \mathbf{y},\ \bar{z}(\lambda) \Rightarrow \mathbf{z}$

Here, $[\ ]^T$ denotes the transposition of vector or matrix and diag[ ] denotes a diagonal matrix whose diagonal elements are given by the array inside [ ].

The total amount of the radiance of the light source is also a factor affecting color perception. However, we assume that the total amount of the radiance is the same between the conventional and designed light source and focus on only the relative spectral shape of the light source.

Criteria for Evaluation of Light Source

Color variance criterion

Since subtle color variation of mucous membrane is significant for early detection of diseases, the ability to enhance such color variation is desired for the light source of OE. We used 307 reflectance spectra of gastric mucous membrane measured before[1] and introduced a criterion to evaluate such color variation. If the spectral radiance of the light source is given, the tristimulus values, XYZ, of the observed color for each gastric mucous membrane can be calculated by Eq. (1). Then those values are transformed to the uniform color space, CIELUV according to the definition[2]. The criterion for color variation is defined as the sum of the variance for each variable, L^*, u^*, v^* of CIELUV color space as,

$$S = \frac{1}{307}\sum_{k=1}^{307}\{(L_k^* - \bar{L}^*)^2 + (u_k^* - \bar{u}^*)^2 + (v_k^* - \bar{v}^*)^2\} \tag{2}$$

Here L_k^*, u_k^*, v_k^* denote the color of k-th sample under the test light source, $L^*, \bar{u}^*, \bar{v}^*$ denote the mean color of all samples. We regard the light source with greater value of V as the light source more suitable for diagnosis. We call V the color variance criterion.

Whiteness criterion

Physicians are used to the color of mucous membrane under xenon lamp because of their long experience of diagnosis with that light source. Thus, the color of designed light source should be similar to that of xenon lamp. To evaluate this characteristic, the similarity between the color of the xenon lamp and that of test light source was introduced as another criterion. The similarity of these colors was measured by the distance between them on CIE u'-v' color plane:

$$D = \|\mathbf{w}_x - \mathbf{w}\| \tag{3}$$

where $\mathbf{w}_x$ and $\mathbf{w}$ represent the color vector of xenon and test light source, respectively. We call D the whiteness criterion and regard the light source with smaller value of D as the better light source.

Preliminary Evaluation for Typical Light Sources

Before optimizing the light source, two standard illuminants and 15 kinds of light sources commercially available were first evaluated with the introduced criteria. The evaluated light sources are listed below.

#1	Xenon
#2	Standard A
#3	Standard D65
#4	Mercury
#5	Metal Halide
#6	Sodium
#7	Tungsten
#8-17	Fluorescent

The result of the evaluation is shown in Fig. 2. Sodium and tungsten lamp showed good performance with respect to the color variance criterion. However, these light sources are colored significantly. The fluorescent #17 marks relatively high score of color variance criterion and moderate score in whiteness criterion. However any light source did not show significant superiority to xenon lamp.

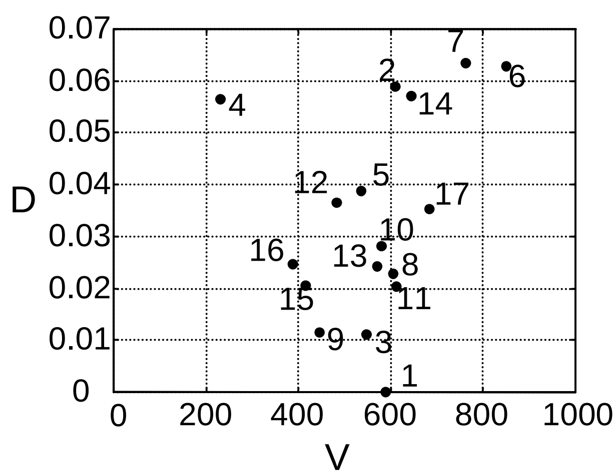

Figure 2: Evaluation result for 17 typical light sources.

Design of Optimum Light Source using POCS

We used a POCS method to design the spectral radiance of light source of OE. POCS is an iterative algorithm to obtain a solution which holds simultaneously some predetermined conditions[3][4]. Each condition must be defined so that its solution space forms a convex set. The solution is obtained by repeating projections onto each subspace.

In our design the following three conditions are used:

(1) Color variation of 307 mucous membrane samples is beyond a predetermined value.

(2) The light source has exactly the same whiteness as xenon lamp.

(3) The spectral radiance of the light source is non-negative.

We formulate these conditions and the projection operation onto each subset.

Condition (1)

The condition that Eq. (2) is greater than a proper value is ideal, but such condition does not form a convex set. Thus we introduced an alternative criterion:

$$S = \int \{\bar{x}(\lambda) + \bar{y}(\lambda) + \bar{z}(\lambda)\} e(\lambda) t(\lambda) v(\lambda) d\lambda \tag{4}$$

Here $v(\lambda)$ denotes the variance of 307 reflectance spectra at each wavelength and is shown in Fig. 3. The discrete expression of Eq. (4) is given by

$$S = [\mathbf{VT}(\mathbf{x} + \mathbf{y} + \mathbf{z})]^T \mathbf{e} \tag{5}$$

where $\mathbf{V} = \mathrm{diag}[v_1, ..., v_n]$ is a discrete expression of $v(\lambda)$.

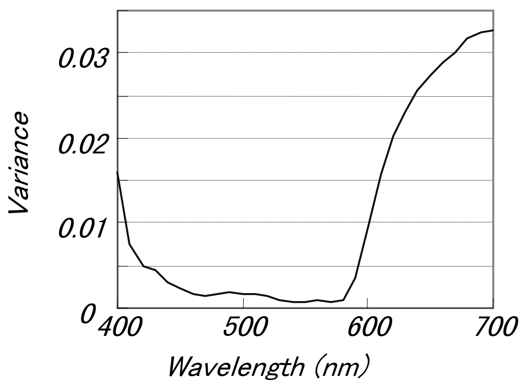

Figure 3: Spectral variance $v(\lambda)$ of the 307 reflectance spectra of gastric mucous membrane.

To confirm the correlation between V and S, each value was calculated for 17 light sources mentioned above. As a result, we found that two values correlates well.

The introduced condition C_c is expressed as

$$C_c = \{\mathrm{e} \mid [\mathbf{VT}(\mathbf{x} + \mathbf{y} + \mathbf{z})]^T \mathbf{e} \geq S_0\} \tag{6}$$

where S_0 is a proper threshold.

The projection **e'** from an arbitrary light source **e** onto the above solution space is given by

$$\mathbf{e'} = \mathbf{e} + (S_0 - \mathbf{g}^T\mathbf{e})\, \mathbf{g} / (\mathbf{g}^T\mathbf{g}). \tag{7}$$

Condition (2)

The second condition C_w is expressed as

$$C_w = \{\mathbf{e} \mid \mathbf{He} = \mathbf{t}_x, \text{ where } \mathbf{t}_x = \mathbf{He}_x\} \tag{8}$$

where $\mathrm{H} = [\mathbf{x}, \mathbf{y}, \mathbf{z}]^T\mathbf{T}$. The solution is generally given by the following equation.

$$\mathbf{e'} = \mathbf{H}^+\mathbf{t}_x + (\mathbf{I} - \mathbf{H}^+\mathbf{H})\mathbf{f}. \tag{9}$$

Here **f** is an arbitrary vector in spectral space. $\mathbf{H}^+$ is called Moore-Penrose generalized inverse of **H** and gives a minimum norm solution for the equation $\mathbf{He} = \mathbf{t}_x$. The first term of right hand side means the subspace which is transmitted through the matrix **H**. On the contrary, the second term means the subspace which is not transmitted through the matrix **H**. All color represented by this equation is perceived by human observer as the same color even if its spectral characteristic is different.

The projection **e'** form an arbitrary light source **e** onto this solution space, C_w is given by,

$$\mathbf{e'} = \mathbf{H}^+\mathbf{t}_x + (\mathbf{I} - \mathbf{H}^+\mathbf{H})\mathbf{e}. \tag{10}$$

Condition (3)

The solution space which holds the third condition C_n is expressed as follows.

$$C_n = \{\mathbf{e} \mid \mathbf{e} \geq \mathbf{0}\} \tag{11}$$

Here **0** means zero vector. The projection onto this space is a simple operation that only negative elements are replaced by zero.

Result of Optimization and Evaluation

The above mentioned projections were coded and the optimum spectral radiance was calculated with MATLAB. The result is shown in Fig. 4. The value of V for the optimized light source was 1162 which is nearly twice of xenon lamp. The value of D is zero as theory. This result is clearly much better than those shown in Fig. 2. The color distribution of 307 mucous membrane under xenon lamp and optimum lamp on u*-v* color plane is shown in Fig. 6. The distribution under the optimum light source is wider than xenon lamp.

The resultant spectral characteristic of the optimum light source can be interpreted by considering the shape of the spectral variance $v(\lambda)$. The reflectance spectra have large variance in long wavelength region beyond 600nm and moderate variance in short wavelength region below 450nm. In the other region, the variance is relatively small. Thus, the optimum light source also has remarkable energy in long wavelength regions and small peak in short wavelength region. It is considered that energy around 520nm is essential to produce the whiteness similar to xenon lamp.

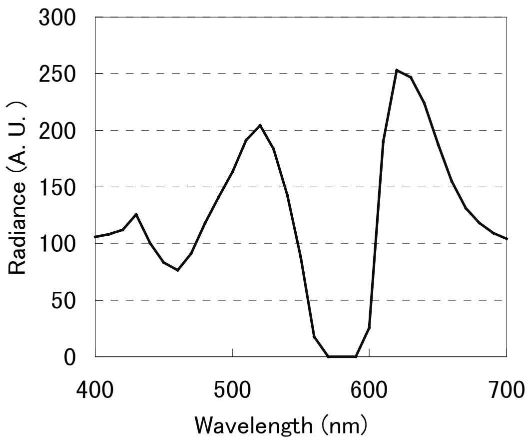

Figure 4: Spectral radiance of the optimum light source.

The calculated spectral characteristic is relatively smooth. The light source with such a characteristic can be implemented using xenon lamp and a few bandpass filters. If the use/not use of such filters are easily switched by physicians, the real time color enhancement would be realized even in the OE.

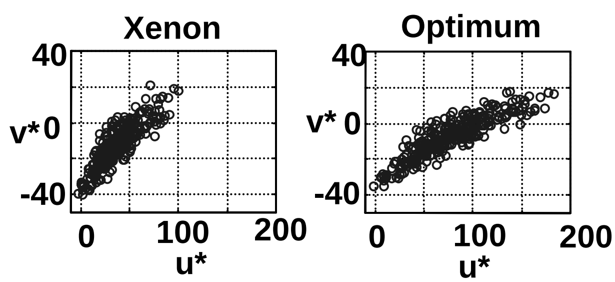

*Figure 5: Distribution of CIE u*v* chromaticities of 307 gastric mucous membrane illuminated by xenon and optimum lamp.*

Simulation of Image Reproduction

It would be useful if we evaluate how the designed light source is effective for diagnosis before making it actually. As we have reported already[5], two dimensional spectral reflectance of gastric mucous membrane can be estimated from R, G, B color image captured by an electronic endoscope based on the knowledge that spectral reflectance of the gastric mucous membrane can be represented from three principal components with high precision.

We built a simulation system that first estimates 2D spectral reflectance images and then reproduces color images to be observed under a light source with an arbitrary spectral radiance. Fig. 6 shows sample images corresponding to xenon lamp and optimum lamp. Original color images show different appearance. Currently we are preparing the evaluation experiment with these simulation images by physicians.

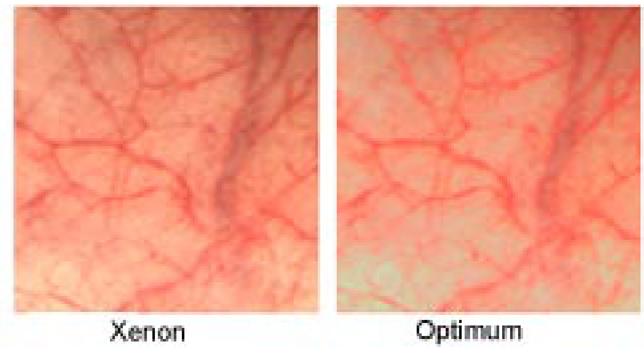

Figure 6: Simulated images.

Conclusion

In this paper, we first have introduced two criteria to evaluate the light source of optical endoscope. Next we have proposed a method for optimizing the spectral radiance of the light source. We found that the designed light source potentially has much better performance than xenon lamp or the other lamps commercially available.

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