Color Enhancement of Multispectral Images for Effective Visualization

Noriaki Hashimoto*, Yuri Murakami**, Masahiro Yamaguchi**, Takashi Obi*, Nagaaki Ohyama**

* Tokyo Institute of Technology, Department of Information Processing, Yokohama, Japan

** Tokyo Institute of Technology, Imaging Science & Engineering Laboratory, Yokohama, Japan

Abstract

The color enhancement of multispectral images is a useful tool to visualize their spectral features. Previously, a color enhancement method which enhances the feature of specified spectral band without changing the average color distribution was proposed. However, the enhanced feature is sometimes unapparent or invisible, when the wavelength range of the specified band is visually insignificant. In this paper, we propose a modified method for more effective visualization capability in the color enhancement for multispectral images. In the proposed method, a user specifies both the spectral band for extracting the spectral feature and the color to be visualized, respectively. Then, the spectral feature in the multispectral image is enhanced by arbitrary color. The proposed method of the color enhancement was experimentally applied to multispectral images, such as a human skin image and microscopic images of pathological tissue specimen. As a result, we verified that the proposed method can effectively visualize the spectral features.

Introduction

Multispectral imaging uses more than 3 spectral filters to capture images that include spectral information which is useful for color reproduction [1,2] and image analysis [3-7]. High fidelity color reproduction becomes possible by using multispectral images; moreover, invisible information can be also captured and employed for object detection, recognition, or quantification.

Color enhancement is an effective tool to explore the spectral features contained in multispectral images. For example, Gillespie et al. [4], Ward et al. [5] and other papers proposed color enhancement methods of multispectral images. The enhancement has been applied to pseudo color images in many cases, but original color of object is also important to interpret the spectral features of the multispectral images that include visible spectral range.

Mitsui et al. [6,7] proposed a multispectral color enhancement method, in which the enhanced results are overlaid with the natural color reproduction images. In this method, the differences between the original image and its approximation by a few principal components are amplified in the spectral regions of the specified spectral band. Then, the spectral feature veiled in the multispectral image is visualized without changing the average color distribution. However, the enhanced feature is sometimes unapparent or invisible, when the specified spectral band is not visually significant, for example, near ultraviolet or

infrared. Also when the number of spectral bands is very large, enhanced results are not clear.

In this paper, we propose a method for more effective visualization capability in the color enhancement for multispectral images. In the proposed method, the spectral band to extract the spectral feature and the color to be visualized are independently specified by the user, so that the spectral feature in the multispectral image is enhanced in the specified color. For such purpose, we present two methods to determine the color for visualization. In the experiment, we apply the proposed methods to a skin image and microscopic images, and verify that the proposed method is effectively enhance the feature in the multispectral images.

Multispectral Color Enhancement Method

The color enhancement presented in this paper is mainly based on the method proposed by Mitsui et al. [6]. This method enhances the color difference from dominant Karhunen-Loéve (KL) component without changing the color determined by dominant component. The algorithm of the color enhancement procedure is shown in fig. 1.
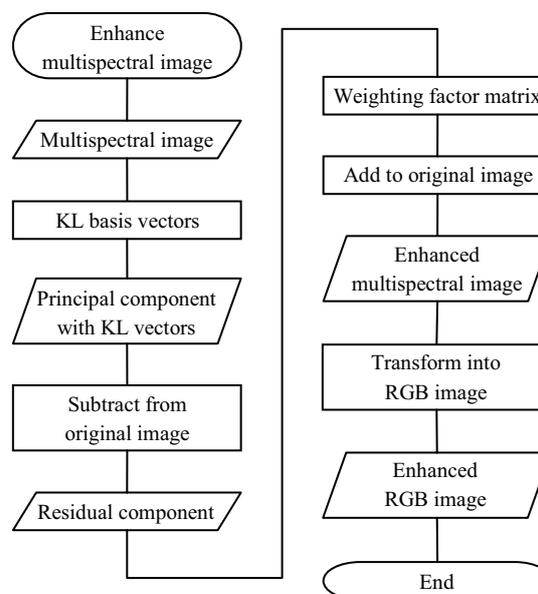
Figure 1. *Flow of the color enhancement*

First, sample pixel data are extracted from the image in order to derive the dominant component. The extraction can be done from entire image, or a part of the image, for example normal region if the intent is to enhance abnormality, depending

on the requirement from the application. Then, a covariance matrix is generated from the extracted samples and KL basis vectors are calculated.

In the N-band multispectral image, the enhanced signal value vector for j-th pixel $\mathbf{g}_{e_j}$ (N-dimensional vector) is represented as,

$$\mathbf{g}_{e_j} = \mathbf{W}(\mathbf{g}_j - \mathbf{s}_j) + \mathbf{g}_j, \qquad (1)$$

where $\mathbf{W}$ is a matrix which generates the enhanced image, $\mathbf{g}_j$ is the original multispectral signal value of j-th pixel and $\mathbf{s}_j$ is the signal value estimated with dominant KL vectors, and is written as,

$$\mathbf{s}_j = \sum_{i=1}^{m} \alpha_{ij} \mathbf{u}_i + \overline{\mathbf{g}}, \qquad (2)$$

where m is the number of basis vectors used in the estimation, $\mathbf{u}_i$ is i-th KL basis vector (N-dimensional vector) and $\overline{\mathbf{g}}$ is the average vector. $\mathbf{g}_j - \mathbf{s}_j$ is considered to be a residual component. Here, i-th KL coefficient for j-th pixel α_{ij} is represented as,

$$\alpha_{ij} = \mathbf{u}_i^t \left(\mathbf{g}_j - \overline{\mathbf{g}} \right). \qquad (3)$$

$\mathbf{W}$ is a $N \times N$ matrix for the enhancement process. In ref. 6, element in p-th row and q-th column $[\mathbf{W}]_{pq}$ is given by,

$$[\mathbf{W}]_{pq} = \begin{cases} k & p = q = n \\ 0 & otherwise \end{cases}, \qquad (4)$$

where n is an index for the enhanced band and k is a coefficient to amplify residual component. Therefore, the coefficient k is multiplied to the residual component in n-th band, which is added to the original signal value in n-th band according to eq. (1).

In addition, from the relationship of eqs. (1), (2) and (3), we have

$$\mathbf{g}_{e_j} = \left\{ \mathbf{W} \left(\mathbf{E} - \mathbf{U}\mathbf{U}^t \right) + \mathbf{E} \right\} \mathbf{g}_j - \mathbf{W} \left(\mathbf{E} - \mathbf{U}\mathbf{U}^t \right) \overline{\mathbf{g}}, \qquad (5)$$

where $\mathbf{E}$ is a $N \times N$ identity matrix, and $\mathbf{U}$ is a $N \times N$ matrix which has KL basis vectors as column vectors and each vector for q-th column of $\mathbf{U}$ is written as,

$$[\mathbf{U}]_q = \begin{cases} \mathbf{u}_q & q \le m \\ \mathbf{0} & otherwise \end{cases}. \qquad (6)$$

In eq. (5), the second term of right side is a constant vector. Thus, it is easy to calculate enhanced result with matrices for multiplication and addition.

The enhanced multispectral image $\mathbf{g}_{e_j}$ is transformed into the spectral reflectance or transmittance with spectral estimation technique [8], and the color image is generated by using a color-matching function (CMF), such as CIE 1931 XYZ CMF and a matrix for XYZ to RGB transform.

Modification of Weighting Factor Matrix

In the above method, the enhanced feature is sometimes unapparent or invisible when the enhanced band is visually insignificant. For example, the enhanced band is near invisible bands like ultraviolet or infrared, or the number of bands is very large, such as hyperspectral images. In such cases, the enhanced feature cannot be emphasized well when the enhanced image is visualized by transformation into a RGB color image because a color-matching function has low magnitude. So we propose a new design of the weighting factor matrix for more effective visualization of multispectral color enhancement.

Modified design of weighting factor matrix

In contrast to the conventional method, in which the difference from principal component is added to the signal value of the specified spectral band, we extend the method of ref. 6, such that the band to extract spectral features and the color for visualization can be specified independently. For this purpose, the weighting factor matrix given in eq. (4) is modified as follows.

The column vectors of modified weighting factor matrix for q-th column are represented as,

$$[\mathbf{W}]_q = \begin{cases} k(\mathbf{g}_d - \mathbf{g}_a) & q = n \\ \mathbf{0} & otherwise \end{cases}, \qquad (7)$$

where $\mathbf{g}_d$ is the spectral data of target color to be visualized and $\mathbf{g}_a$ is the spectral data of the background in the image. According to eq. (1), spectrum $\mathbf{g}_d - \mathbf{g}_a$ amplified to residual component in each pixel is added to original signal value using eq. (7). Setting the proper coefficient k allows the color of enhanced region to change toward the target color determined by $\mathbf{g}_d$ with reducing the background color $\mathbf{g}_a$.

Determination of parameters

There can be considered several approaches to determine $\mathbf{g}_d$, the spectral data of target color; two examples are shown in this paper as follows.

Method I

In the first example of the weighting matrix design, arbitrary color or spectrum is specified based on a user's intent. A user can choose a color to be visualized with a tool like a color picker, then the spectrum corresponding to the chosen color is calculated by using a technique of spectrum estimation. If a user desires the color or the spectrum of a physical object as the enhanced result, the spectrum of the target object can be selected from a spectral image with a tool of spectrum-picker.

Method II

The relationship between the wavelength of the multispectral image and the color for the visualization is defined. Then the spectrum of the color assigned to n-th band derived by the spectral estimation technique, and is used as $\mathbf{g}_d$ when n-th band is specified for the enhancement. For example, hue between blue through red is assigned to the band between the shortest and the longest wavelengths of the multispectral image. The spectral data of background color, $\mathbf{g}_a$, can be the average spectral data of entire image.

Experiment

In the experiment, we applied the proposed color enhancement method to the multispectral images of a human skin captured by filter-wheel multispectral camera [7] and pathological slides captured by multispectral microscopy [9].

Application to the skin image

In the application to the skin image, we used the image of the palm captured by a 16-band multispectral camera which has the center wavelengths and bandwidths of each spectral band for the multispectral camera shown in table 1. The image used in the experiment is shown in fig. 2, and its image size is 1000×750 pixels, reduced and trimmed from the original image in 2048×2048 pixels.

Table 1: Center wavelength and bandwidth of each spectral band for the multispectral camera

Band	Center wavelength [nm]	Bandwidth [nm]
1	425	30
2	450	20
3	470	20
4	480	15
5	500	20
6	515	15
7	535	15
8	550	20
9	565	15
10	585	20
11	600	20
12	620	20
13	645	20
14	665	20
15	690	25
16	720	30

Figure 2. The multispectral image of a human skin
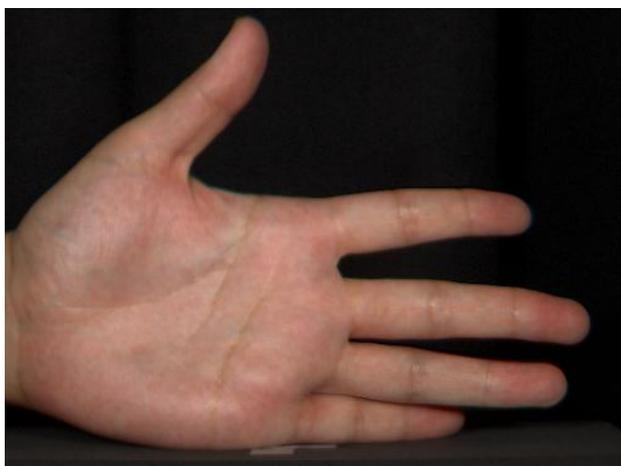
Figure 3. The result of color enhancement with the conventional method (n=16, k=50)

It has been reported that the vein has spectral features in long wavelength because the long wavelength light penetrates relatively deeper and is affected by the absorption of the deoxy-hemoglobin in the vein. In the previous method of multispectral color enhancement [6], however, the result of color enhancement was sometimes unapparent range if a band of long wavelength (16th band, center wavelength = 720nm) was enhanced in the conventional method, as shown in fig. 3.

Color mapping to spectral bands

In this experiment, the method II explained in the previous section is applied; each wavelength in visible range is assigned to every hue between blue ($h = 240°$) through red ($h = 0°$) in L^*C^*h color space. And the spectrum of the selected hue is used as $\mathbf{g}_d$. The spectrum corresponding to each hue is derived with using spectral estimation technique, as follows; Lightness and chroma are fixed and hue is changed at an interval of Δh , to calculate L^* , a^* and b^* corresponding to each wavelength. Calculated L^* , a^* and b^* are transformed into XYZ color space and the spectral data is estimated from this XYZ tristimulus values by wiener estimation using the sensitivity of a multispectral camera for capturing the image.

In this instance, hue is sampled with the spacing of 16 degrees for equable hue spacing because the number of spectral bands of the multispectral camera used in this experiment is 16 bands, namely h = 240, 224, 208 ⋯ and 0 corresponds the band 1, 2, 3, ⋯ and 16, respectively. In addition, lightness and chroma are defined as $L^* = 80$ and $C^* = 80$.
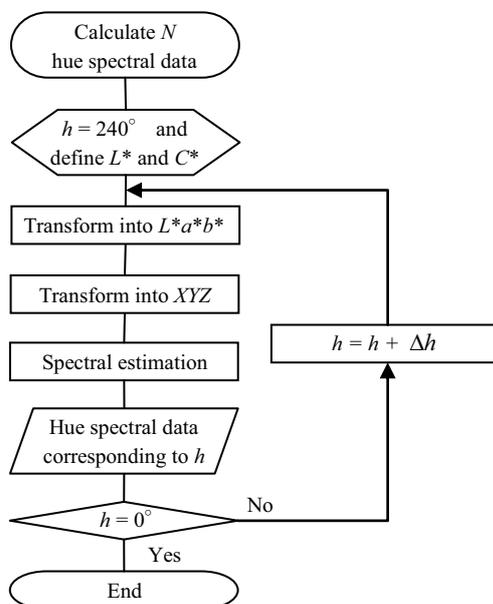
Figure 4. Flow of the color mapping method to each spectral band

Result of color enhancement for a skin image

The result of the color enhancement of the skin image with the proposed method is shown in fig. 5. In this experiment $n = 16$, that is, we set $h = 0°$ as the hue value from which the spectrum for visualization $\mathbf{g}_d$ is calculated, and the average vector of the image is used as the spectrum of the region enhanced $\mathbf{g}_a$.

In the result of this experiment, the feature in the long wavelength region which did not appear in the conventional method was successfully enhanced and the structure of the vein is apparently observed. The artifacts in the edge of fingers occurred from the motion of the object during the image capture using filter-wheel multispectral camera.

Figure 5. *The results of color enhancement with the proposed method (n=16, k=50)*

Application to pathological images

In the application to the pathological image, we took attention to the fiber region of an HE (Hematoxylin-Eosin) stained liver tissue specimen and applied color enhancement to a 16-band multispectral and a 63-band hyperspectral images.

Application to a multispectral pathological image

In this experiment, the color enhancement was applied to the 16-band image captured using multispectral microscopy [9] which has the center wavelengths and the bandwidths shown in table 2. The fiber region is not visible in HE staining shown in fig. 6, but MT (Masson-Trichrome) staining technique is normally used to see the fiber region as shown in fig. 7. And it has been reported that the spectral imaging provides the information for discriminating the fiber region in an HE stained specimen [9]. So we applied color enhancement to the HE stained tissue specimen, and the spectrum $\mathbf{g}_d$ for the visualization was determined from the color of the fiber region of an MT stained tissue specimen according to method I. The size of images used in the experiment is 2048×2048 pixels.

Table 2: Center wavelength and bandwidth of each spectral band of the multispectral camera for microscopy

Band	Center wavelength [nm]	Bandwidth [nm]
1	425	25
2	450	20
3	470	20
4	480	15
5	500	20
6	515	15
7	535	15
8	555	20
9	565	15
10	585	20
11	600	20
12	620	20
13	645	20
14	665	20
15	685	25
16	720	30
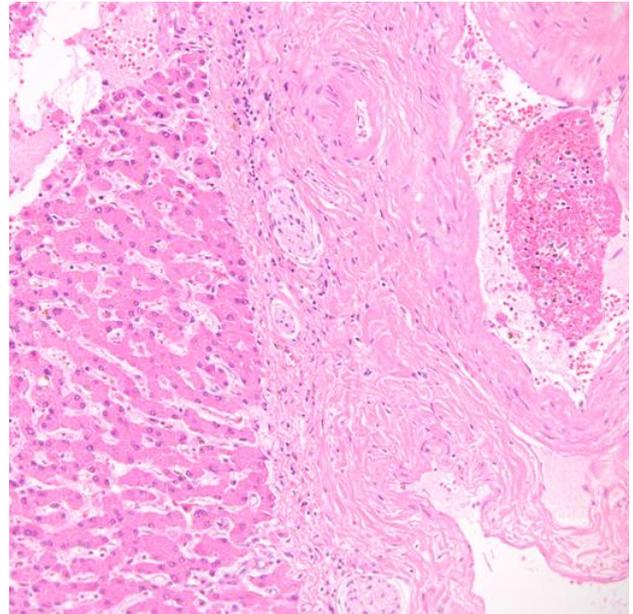
Figure 6. *HE stained liver tissue specimen (x20)*
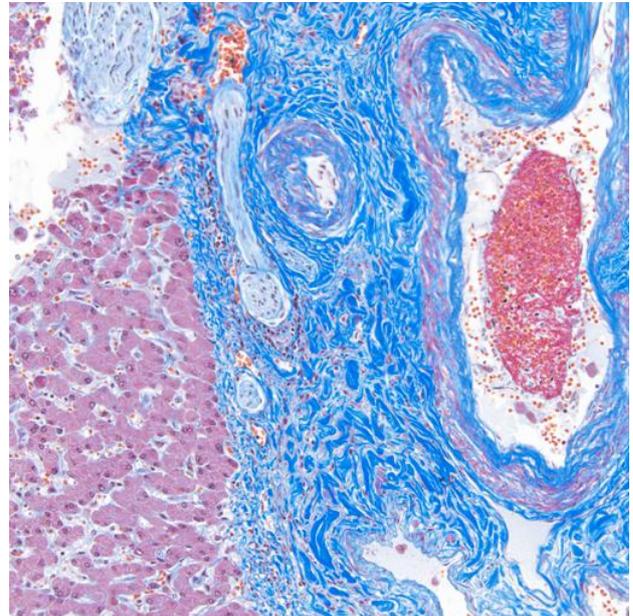
Figure 7. *MT stained liver tissue specimen (x20)*

Result of color enhancement for the multispectral image

The sample data for generating a covariance matrix were selected from the regions of cytoplasm, nucleus, red blood cell and glass, and a hundred samples were obtained for each tissue with averaging in 5×5 pixels ROI. The average vector of sample data were used as the spectral data of background color $\mathbf{g}_a$. The spectrum of fiber region in MT stained specimen shown in fig. 8 was employed for the spectrum $\mathbf{g}_d$ for the visualization.
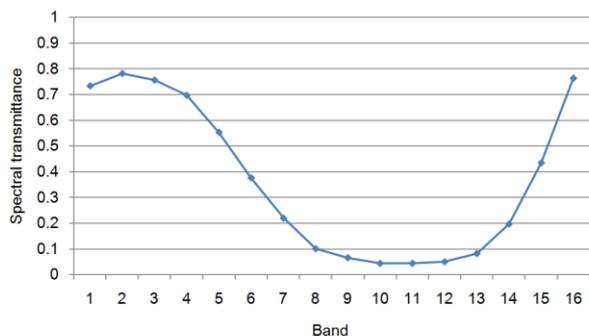
Figure 8. The spectral transmittance of fiber in an MT stained tissue

Here, color enhancement method was implemented in spectral transmittance space for removing the illumination nonuniformity. Spectral transmittance is calculated as follow,

$$t(\lambda) = \frac{i(\lambda)}{i_g(\lambda)}, \qquad (8)$$

where $i(\lambda)$ is signal value of tissue and $i_g(\lambda)$ is that of glass. Fig. 9 shows the average residual component for each tissue when using six KL basis vectors.
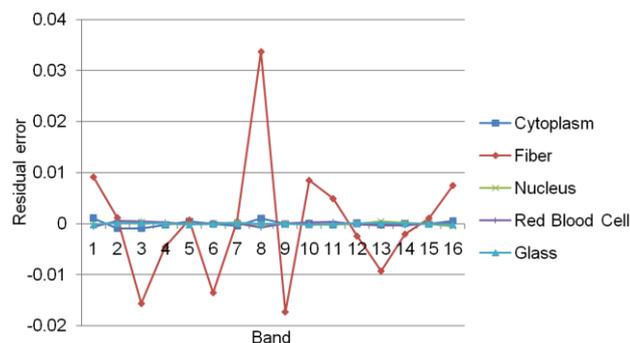
Figure 9. The residual component of each tissue

From this graph, it is realized that the fiber region has a large residual in 8th band. So we determined the band to be enhanced as $n = 8$. The resultant images of the color enhancement are shown in fig. 10.

Although enhanced feature did not appear visually in the conventional method, the fiber region of the HE stained image was enhanced to blue, which is similar to the color of the MT stained specimen in the proposed method. Moreover, since the color is visualized similar to that of MT stained tissue specimen, it seems to be easier for pathologists to evaluate the result comparing with the conventional physical staining technique.
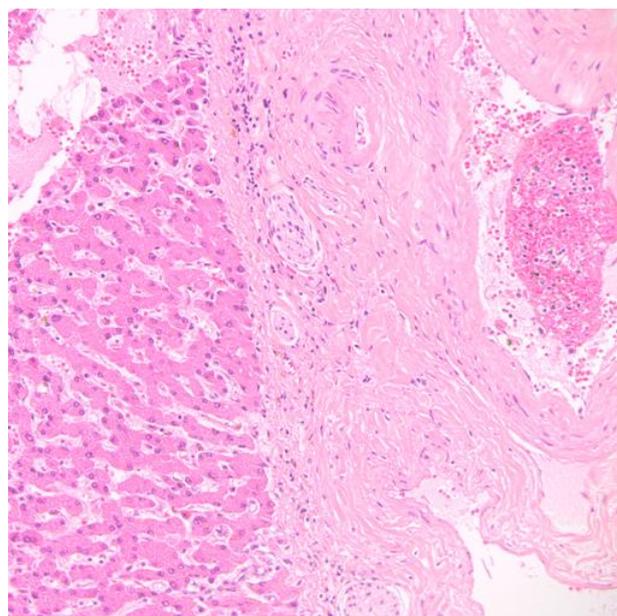
(a) The conventional method
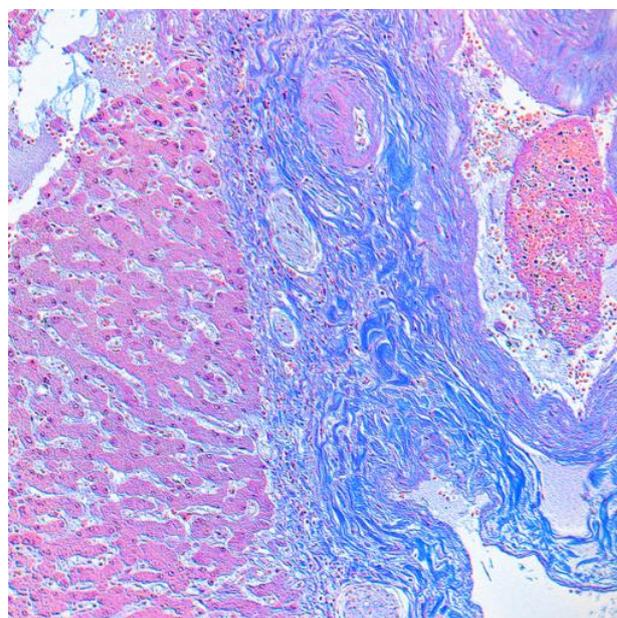
(b) The proposed method

Figure 10. The enhanced result of the HE stained tissue (n=8, k=30)

Application to a hyperspectral image

It is thought that the proposed method is also effective to images which have more spectral bands, such as hyperspectral images.

We also applied the color enhancement method to a hyperspectral image shown in fig. 11, which is a slide of HE stained liver tissue specimen. The image was captured with a liquid crystal tunable filter, (VariSpec) and the number of spectral bands was 63 bands within visible wavelength range sampled at five nm intervals from 410 nm to 720 nm. The image size was 1370×1030 pixels trimmed from 1434×1050 pixels.
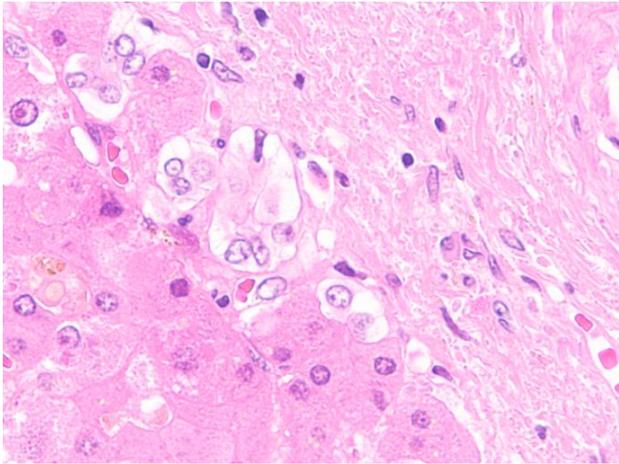
Figure 11. *The HE stained liver tissue specimen (x40)*
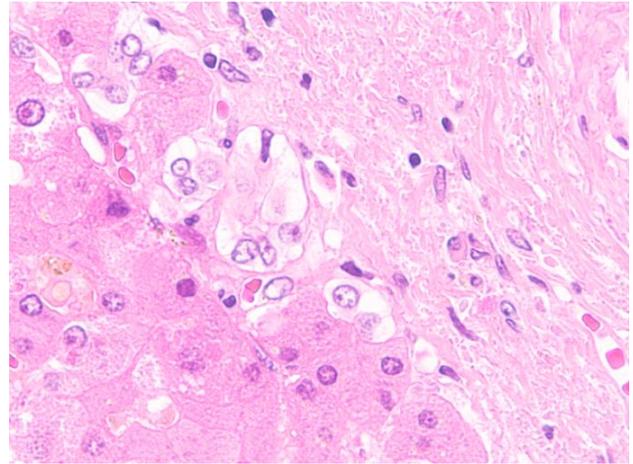
(a) *The conventional method*

Result of color enhancement for the hyperspectral image

Similarly to the previous experiment, the spectrum of the fiber region of another MT stained liver tissue specimen shown in fig. 12 was used as the color $\mathbf{g}_d$ for visualization. KL basis vectors were calculated by using the spectra of cytoplasm, nucleus, red blood cell and glass, which were obtained 100 samples about each tissue with an average in 3×3 pixels ROI. The spectral band of 545 nm ($n = 28$) had the spectral feature which was found in residual component obtained with using seven KL basis vectors, and the 545 nm component was enhanced to visualize the spectral feature. The average of sample data was used as the background spectral data $\mathbf{g}_a$.

The results of color enhancement of the hyperspectral image are shown in fig. 13. In the enhanced result, the color of fiber region became blue like that of MT staining with the proposed method, while the fiber region was not enhanced visually with the conventional method. The conventional method is not effective for the application to hyperspectral images which have large number of spectral bands, because signal value of single band barely affect the transformed color image. The proposed method is visually effective even if the number of spectral band is very large.
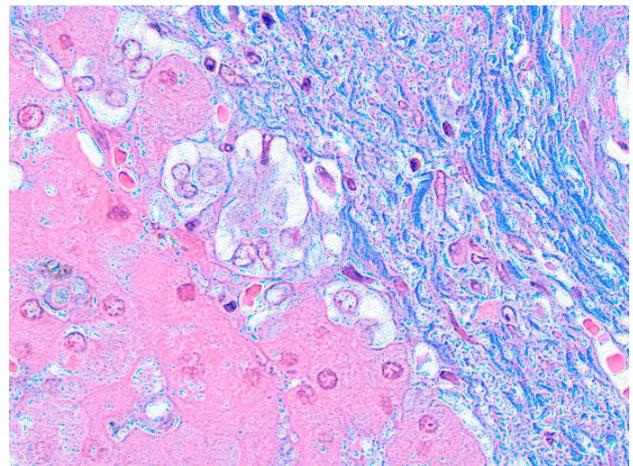
(b) *The proposed method*

Figure 13. *The enhanced result of the HE stained tissue (n=28, k=30)*

Conclusion

This paper proposes a method for the effective visualization in the multispectral color enhancement, in which the design of a weighting factor matrix is modified so that the enhanced feature appears in arbitrary color. Even if an image has a spectral feature in invisible wavelength range or has too many spectral bands, the spectral feature can be visually well enhanced with the proposed method. Moreover, it becomes possible to apply the spectral color enhancement technique even to the multispectral image outside of visible wavelength range. The method will be useful in the exploration of the spectral features contained in the multispectral or hyperspectral images.

Figure 12. *The MT stained liver tissue specimen (x20)*

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Author Biography

Noriaki Hashimoto received his B.S. degree in engineering from Tokyo Metropolitan University (2008) and his M.S. degree in engineering from Tokyo Institute of Technology (2010). Since 2010 he attends a doctor's course in Tokyo Institute of Technology and his work has primarily focused on the analysis of pathological images by using multispectral imaging. He is a member of IS&T, IEEE, IEICE and JSAP.