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Video-Telemedicine with Reliable Color Based on Multispectral Technology

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1. Introduction

Videos and still-images play quite important role in telemedicine, such as dermatology, teleconsultation, endoscopy, and surgery video. However, one of the problems is the lack of color reproducibility, since it is difficult to reproduce the original color of the object in conventional color imaging systems based on RGB (red, green, blue). Although the color management technology enables to deal with color as device independent information, the color reproduced on the monitor still does not agree with the original object.

For the solution to such problem, the spectrum-based technology, instead of conventional RGB based methods has been developed aiming at high-fidelity color reproduction in both video and still image systems. By using multispectral image capture, illumination spectrum measurement, spectrum-based color conversion, and multiprimary color display, the colors of real object can be faithfully reproduced on a display. The technology is called "natural vision (NV)" (Yamaguchi et. al., 2008). The advantages of multispectral technology in various possible applications, such as telemedicine, digital archives of historical heritage or art works, electronic commerce, educational video contents, and high-quality color printing, have been shown in the literature.

In this chapter, we introduce the system developed for video-based telemedicine with reliable color, and demonstrate the results of experimental evaluation for the telemedicine applications including dermatology, surgery video and the video-based teleconsultation between a general hospital and a clinic.

2. Related works

The color of the medical images was not paid strong attention until now, but the color information is quite important in many cases. In dermatology, the color of skin has critical information for diagnosis (Numahara, 2001), and attempts to calibrate the color imagnig device have been presented (Herbin et. al., 1990; Haeghen et. al., 2000; Maglogiannis, 2004). In 2008, American Telemedicine Association published practice guidelines for teledermatology, in which the technique to maintain the color quality was described Krupinski et. al., 2008).

Color video are also used in telemedicine; both store-and-forward and real-time teleconferencing, such as teledermatology (Loane et. al., 2000; Maglogiannis, 2004), telesurgery (Demartines, et. al., 2000; Rafiq, et. al., 2004; Augestad, et. al., 2009), tele-endoscopy (Wildi et. al., 2004), emergency telemedicine (Gállego, et. al., 2005; Bolle, et. al., 2009), telecare for chronic disease (Nilsson, et. al., 2009), and telepsychiatry (Yellowlees, et. al., 2010). Image quality issues in video telemedicine have been studied (Hanna and Cuschieri, 2001), such as the dependence on the image compression (Broderick, et. al., 2001; Duplaga, et. al., 2008) or the comparison of different equipments (Berci, et. al., 1995). However, no report is found on the quantitative analysis of color fidelity in video.

It has been pointed out that there is a limitation in the color reproduction capability of RGB-based imaging system, and the application of multispectral imaging have been suggested (Burns and Berns, 1996; Hill, 1998; Yamaguchi, et. al., 1997). There have been proved that the high accuracy can be achieved by applying multispectral imaging. In the display industry, the multiprimary color approach becomes one of the choices for expanding color gamut (Ueki, et. al., 2009), but it is difficult to take full advantage of multiprimary color technology with conventional RGB image capture, because a wide gamut image is not available by RGB cameras. There have been proposed the systems for color management including spectral information for hardcopy applications (Rosen, et. al., 2001; Derhak and Rosen, 2004) and image displays (Hill, 1998; Yamaguchi, et. al., 2008). Using spectrum-based color management, the color of the original object can be reproduced in high-accuracy. As for medical application, the multispctral imaging was applied to dermatology (Tomatis, et. al., 2003; Yamaguchi et. al., 2005) and pathology (Levenson, et. al., 2003; Abe, et. al., 2005), providing the benefit of color reproducibility as well as the quantification of color information in the medical color images.

The applications of multispectral video for color reproduction have been studied in our group; such as apparels, video production especially for science and art, and videoconferencing (Yamaguchi, et. al., 2008) It enables high-fidelity and wide-gamut video creation and will enhance the visual communication in both professional and consumer applications. Telemedicine is one of the most important application areas of multispectral video technology, and this research focuses on the application of multispectral video to the color reproduction in dermatology, surgery, and rural patient care. Through the experiments in these fields, this work addresses the question: does the use of multispectral technology provide any benefit from the viewpoint of color reproducibility? For this purpose, both objective and subjective evaluations of color reproducibility were performed. There was no such report on the evaluation of the color reproducibility of multispectral imaging in telemedicine.

3. Spectrum-based color reproduction system

3.1 Overcoming the limitation of RGB trichromatic scheme

The color of images we see on display is based on the "additive color mixture," and all the conventional color imaging technology stands on trichromatic color system, especially using RGB. There are however, limitations of conventional RGB trichromatic systems, and it is quite difficult to realize high-fidelity color reproduction in the video or still-image communication systems. An approach to overcome such limitations and to realize high-fidelity color reproduction is going beyond RGB, namely, adopting a spectrum-based system instead of RGB. NV provides the method for systematizing the multispectral and multiprimary color imaging technologies, including image capture, processing, storage, printing, and display. Followings are the details of how the spectrum-based approach can overcome the limitation of conventional RGB scheme.

1. The RGB values in conventional systems have different meanings, depending on the device characteristics or color processing. For example, consumer color cameras are usually designed for user preference, and the RGB values do not represent objective color information. In order to deal with the color information independent on the devices, the color management technology should be employed, such as the color conversion using ICC (International Color Consortium) profile. However, there still remains the problem; since the spectral sensitivity of a color camera is different from that of human vision, the RGB signal does not have one-to-one correspondence to the tristimulus values perceived by human vision. Using MS image capture and appropriate color processing, it becomes possible to realize the spectral sensitivity that is equivalent to human vision.
2. When the illuminant of the image capture environment is different from that of display observation, white balance adjustment is performed in conventional color imaging systems. The white balance can adjust white, but other colors often change, since the spectral reflectance of object and the illuminant spectrum are required in principle in order to derive the color under the different illuminant. In such case, it is reasonable to reproduce the color as if the object were placed at the site of the observer. The reproduction of the color under different illuminant is possible based on the spectrum-based color conversion.
3. In the color image display, the color gamut is usually inside the triangle spanned by RGB primary colors, and does not cover all the existent colors; thus some high-saturation colors cannot be reproduced. Recently wide-gamut displays are commercially available, with using purer RGB primaries or multiprimary colors. Even if the display gamut is enlarged, the color signals represented in conventional color space, such as sRGB (equivalent to the color space defined in ITU-R BT.709) do not support a wider gamut. Wide gamut color spaces have recently become available, such as AdobeRGB and xvYCC, but most of the color input devices cannot capture high-saturation colors correctly, because the error described in (1) tends to large in high-saturation colors.
4. It is known that the spectral sensitivity of human vision, or color matching function, varies depending on individuals (Alfvin and Fairchild 1997). Therefore, when the color displayed on a monitor is compared with the real object, the perceived colors may disagree with each other even if the colorimetric accuracy is high. Such phenomenon is called observer metamerism. The multispectral and multiprimary approach can solve this problem by reproducing the spectral color reproduction (Murakami, et. al., 2004).
5. In most RGB-based color imaging systems, RGB does not represent the color attribute of an object, because the RGB values depend on the illumination light and/or the device characteristics. Thus the utilization of color information is limited in the image analysis, archive, or database. In contrast, the spectral information can represent the original attribute of an object that generates color. The quantitative spectral attributes of object, useful for the analysis or the recognition of object, are captured and preserved. Moreover, the exploration of invisible features becomes possible from spectral images.

3.2 The principle of spectrum-based color reproduction system

In this subsection, let us briefly review the principle of spectrum-based color reproduction (Yamaguchi, et. al., 2008). In the spectrum-based color reproduction system, the spectral radiance, reflectance, transmittance, or colorimetric tristimulus values under arbitrary illumination are estimated from the camera signal with using the input device profile and the spectral information of illuminant, as shown in fig.1. Using multispectral cameras with larger number of bands for the image capture, higher accuracy can be realized.

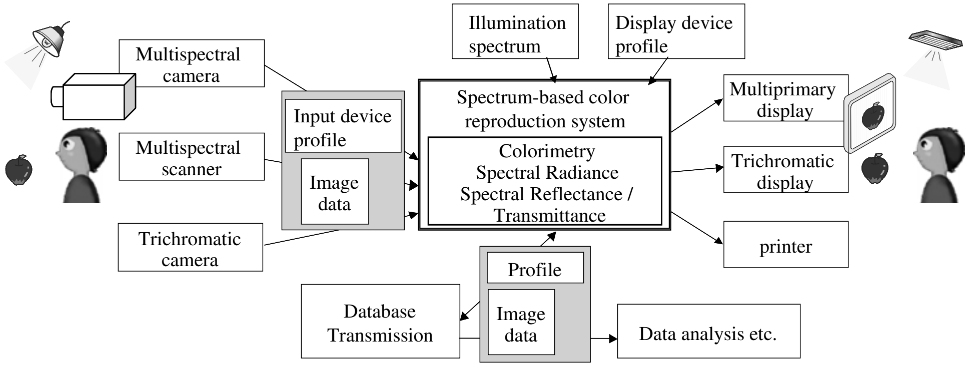


Fig. 1. The spectrum-based color reproduction scheme

Consider a certain point on the object, and its spectral reflectance sampled and denoted as **f**, which is an *L*-dimensional column vector. *k*-th element of **f** represents the reflectance of *k*-th wavelength λ_k, where

$$\lambda_k = \lambda_{\min} + k\Delta\lambda, \tag{1}$$

and $\lambda_{\min}$ and $\Delta\lambda$ are the minimum wavelength of visible range and the sampling interval in wavelength, respectively. Assuming linear response of the image sensor, the observed MS image **g**, represented by *N*-dimensional column vector, is given by

$$\mathbf{g} = \mathrm{S}\,\mathrm{E}_c\,\mathbf{f} + \mathbf{n}\,, \tag{2}$$

where S is a matrix with *N*x*L* elements and each row of S holds the discretized spectral sensitivity of the color camera, E_c is a diagonal matrix with *L*x*L* elements, and the diagonal elements corresponds sampled version of spectral radiance of illumination light at the image capture, **n** is a column vector which represents the noise in the observed image **g**, respectively. For the color reproduction under arbitrary illuminant, the colorimetric tristimulus values, such as CIE (Commission Internationale de l'Eclairage) 1931 XYZ, are required. Let a 3-dimensional column vector **x** be the XYZ values of the corresponding object under certain illuminant E_r, which is called rendering illuminant hereafter, then **x** is given by

$$\mathbf{x} = \mathrm{C}\,\mathrm{E}_r\,\mathbf{f}\,, \tag{3}$$

where C is a matrix with 3x*L* elements, where each row represents CIE 1931 XYZ color matching function. Then the task for high-fidelity color reproduction is to derive **x** from **g**. There have been reported various methods for this purpose, and one of the common approaches is a linear estimation, like

$$\hat{\mathbf{x}} = \mathrm{Q}\mathbf{g}\,, \tag{4}$$

where $\hat{\mathbf{x}}$ is the estimated tristimulus values, and Q is an estimation matrix with 3xM elements. Also a typical way to determine Q is Wiener estimation, given by

$$\mathrm{Q} = \mathrm{C}\mathrm{E}_{\mathrm{r}}\mathrm{R}_{\mathrm{f}}\mathrm{E}_{\mathrm{c}}\mathrm{S}^{t}(\mathrm{S}\mathrm{E}_{\mathrm{c}}\mathrm{R}_{\mathrm{f}}\mathrm{E}_{\mathrm{c}}\mathrm{S}^{t} + \mathrm{R}_{\mathrm{n}})^{+}\,, \tag{5}$$

where R_{f} is the correlation matrix of **f** in LxL elements, R_{n} is the correlation matrix of noise in NxN elements, respectively. Additionally Q_{s} can be defined as,

$$\begin{aligned} &\mathrm{Q} = \mathrm{C}\mathrm{E}_{r}\mathrm{Q}_{\mathrm{s}} \\ &\mathrm{Q}_{\mathrm{s}} = \mathrm{R}_{\mathrm{f}}\mathrm{E}_{\mathrm{c}}\mathrm{S}^{t}(\mathrm{S}\mathrm{E}_{\mathrm{c}}\mathrm{R}_{\mathrm{f}}\mathrm{E}_{\mathrm{c}}\mathrm{S}^{t} + \mathrm{R}_{\mathrm{n}})^{+} \\ &\hat{\mathbf{f}} = \mathrm{Q}_{\mathrm{s}}\mathbf{g} \end{aligned} \tag{6}$$

$\hat{\mathbf{f}}$ is the estimate of the spectral reflectance of the object, namely, Q_{s} is the matrix for spectral estimation.

In order to estimate the tristimulus values from the camera output using the eqs. (4) and (5), we need S, E_{r}, E_{c}, R_{f}, and R_{n}. The spectral sensitivity of the camera, S, can be obtained by using monochrometer and spectroradiometer. For example, a standard white diffuser is irradiated with the monochromatic light of every wavelength generated by the monochrometer, and is captured by the camera and the spectroradiometer. By normalizing the output signal value of each band of the camera, the spectral sensitivity is obtained. E_{c} and E_{r} are the spectral radiance of illumination light, measured by spectrometer at the image capturing and observation sites. As the correlation matrix R_{f} of the object spectral reflectance, there are several choices; if it is measured from the real object, the estimation accuracy is high, but is not always possible to get it. Instead, sometimes the correlation matrix derived from a color chart, such as GretagMacbeth ColorChecker, is used, and it gives fairly good performance. Another design of R_{f} is based on the 1st order Markov random field (MRF) model for the spectral reflectance. Since the spectral reflectance of most objects is smooth in the wavelength axis, MRF also gives good performance (Platt and Mancill, 1976). The noise correlation, or the covariance R_{n}, can be usually substituted with diagonal matrix, where each diagonal element is the noise variance of corresponding spectral channel. Another choice is to assume the noise variance to be constant over all channels, or just it can be omitted if the noise level is satisfactory low.

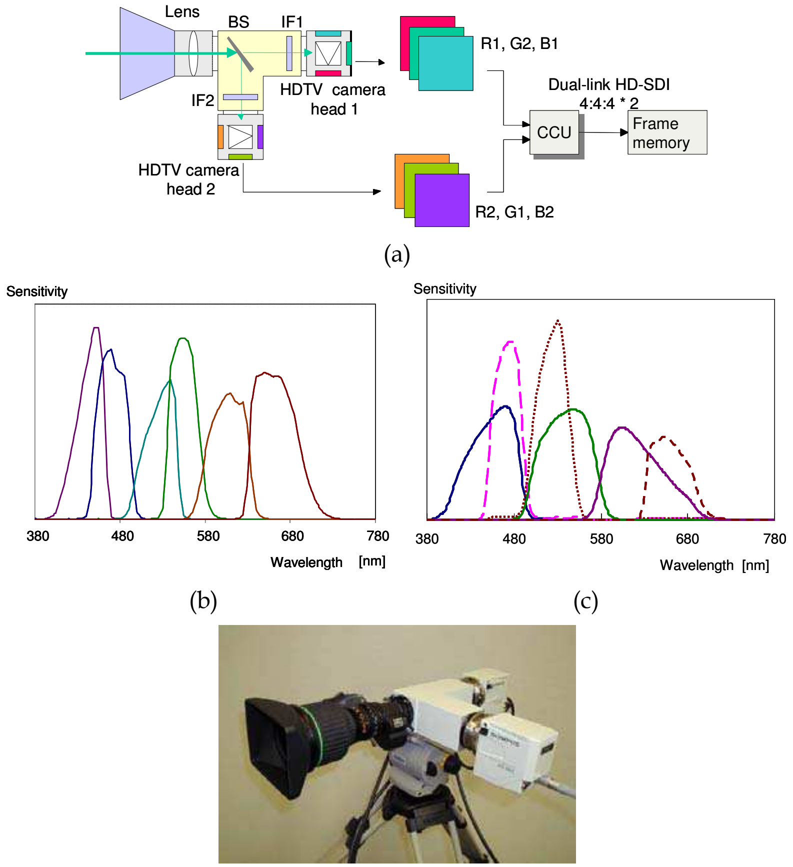
In the imaging model of eq.(2), the camera output is assumed to be linear to the light energy. In fact, when the input-output characteristics of the camera cannot be treated as linear, the tone reproduction curve of the camera is measured by capturing the gray-scale chart. The dark current of the sensor, such as CCD (Charge Coupled Device), should be also considered. It can be measured by placing a cap to the camera lens, and the average signal level is subtracted.

For the color image display, the characterization of display device is also required. It can be performed by using the commercial tool for making ICC profile, though the accuracy depends on the devices (both display device and characterization device). In the spectrum-based system, it is required to reproduce the XYZ tristimulus values regardless of the white point setting of the display device. For this purpose, the chromaticity coordinates of three primary colors and the tone reproduction characteristics of the RGB channels are measured, and we can obtain the 3x3 matrix and lookup tables for color conversion. As an alternative way, the white point of the display device can be set to the ambient illumination, such as the standard D65 illuminant, and then the commercial color management scheme using ICC profile can be employed. The case of multiprimary color displays is discussed later.

Based on the above theory for spectrum-based color reproduction, the color under the illuminant of observing environment can be faithfully reproduced, and the observer perceives realistic color images as if the object were placed at the observer's site.

3.3 Multispectral image capture

Using multispectral image capture, i.e., using more than 3-bands, is beneficial for higher accuracy in spectral and color estimation. Some multispectral input devices suitable for color reproduction have been developed in several groups, and it has been shown to realize the color estimation in high-accuracy a. In the work explained in this paper, 6-band HDTV camera shown in fig.2 was developed for the acquisition of multispectral motion picture (Ohsawa, et. al., 2004).



(a)

(b)

(c)

(d)

Fig. 2. Six-band video camera. (a) System configuration, (b) spectral sensitivities of 6-bands, and (c) photograph of the camera. BS: beam splitter, IF1, IF2: interference filters.

The 6-band camera consists of two 3-CCD HD cameras, a single imaging lens system, a beam splitter, and two different spectral filters (interference filters) that trim the spectral sensitivities of RGB channels. Two cameras output 3-band images of different RGB sensitivities, and combining them yields 6-band images. Two different versions are experimentally developed; one that is shown in fig.2(a) and (b), and another one IF2 in fig.2(a) is removed so that the spectral sensitivity becomes different as shown in fig.2(c). In the latter camera, a set of three channels has the spectral sensitivity identical to original RGB camera, and was used for the comparison of 6-band and 3-band capabilities.

It was reported that the average and maximum error (CIELAB ΔE) of GretagMacbeth ColorChecker estimated from the 6-band camera image (the case of fig.2(b)) were 1.43 and 4.24, while they were 4.12 and 8.22 in 3-band camera. The colorimetric accuracy is considerably improved by 6-band system, almost less than the color discrimination capability of human vision. The spectral sensitivities and the tone reproduction curves of the 6-band camera (camera profile) were measured in advance, as shown in fig.2(b), for spectrum-based color reproduction.

3.4 Multispectral video conferencing system

Fig.3 shows the system configuration for multispectral video recording and conferencing with high-fidelity color reproduction, especially employed in the experiments presented in the sections 5 and 6 (Yamaguchi, et. al., 2009). For the image input, a 6-band HD (high-definition) camera, a 3-band video camera, and a 6-band still camera were employed. In addition to the multispectral camera with more than 3-band, 3-band camera can be also employed in NV color reproduction even though the color accuracy is lower than 6-band case. The spectral sensitivities and the tone reproduction curves of these cameras (camera profile) were measured in advance, for spectrum-based color reproduction. The colorimetric signal for transmission was generated by the color converter set-top box, using the camera profile and the illumination spectrum measured by a compact spectrometer shown in fig.4.

The spectral reflectance of the object was estimated by Wiener estimation technique, which can be implemented with 6x3 or 3x3 matrix multiplication. The gray levels of video signal of camera output is encoded by 10-bit, where the color conversion process is operated with 12-bit signal. The output of color converter was a colorimetric signal in wide-gamut color space, and encoded by the H.264/AVC encoder. The maximum rate determined by the encoder is 15Mbps. Flat-panel liquid crystal displays (LCDs) are used in this experiment, while multiprimary color displays are considered to be applied in the future.

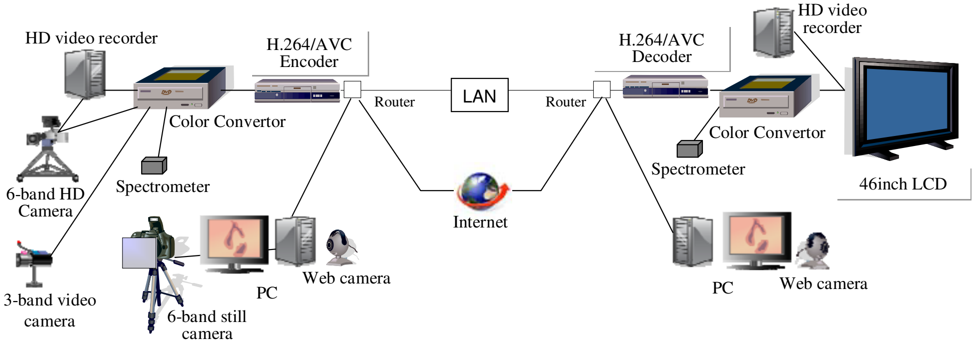


Fig. 3. System overview used in the experiments.

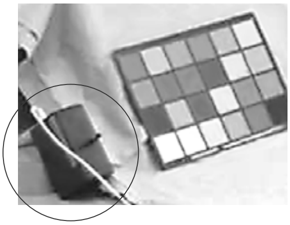
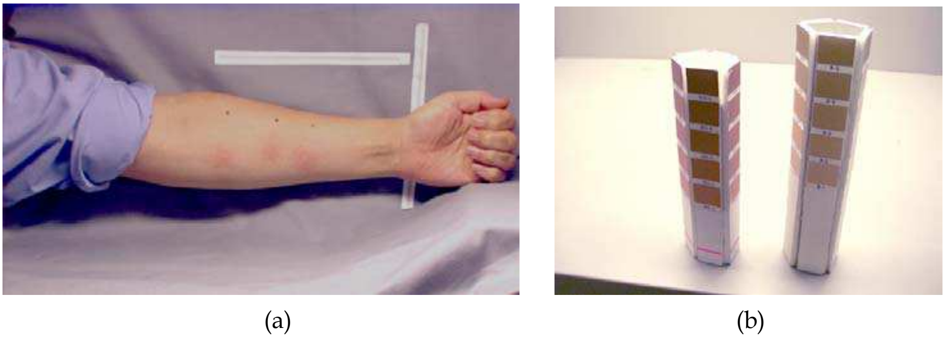


Fig. 4. Compact spectrometer for illumination spectrum measurement.

4. Experimental evaluation for the color reproducibility of skin lesions

This section briefly introduces the experiments, performed to evaluate the spectrum-based system in the dermatology department, Yokohama-city University Hospital, Yokohama, Japan (Yamaguchi, et. al., 2006). Instead of real patient, the erythema artificially produced by prick test was used, as its color can be considered as a good replication of typical flare such as urticaria. Fig.5(a) shows an example of the target arm with erythema. Prick tests of histamine, cedar pollen and mite allergens are performed onto 18 arms from 9 healthy volunteers. The experiment is composed of following 4 steps;



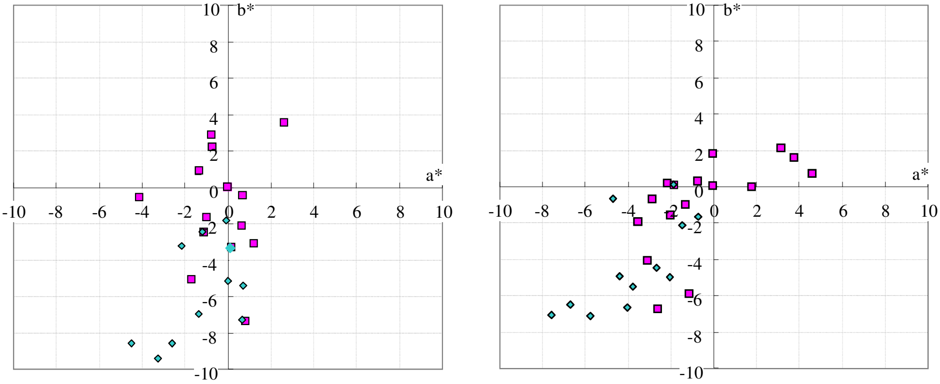
(a) (b)

Fig. 5. (a) Photograph of target arm with erythema by prick test. (b) Skin color chips on pentagonal cylinders used in the experiment.

1. Colorimetric evaluation, in which the colors of target skin and reproduced images were measured by a spectroradiometer to check the colorimetric accuracy. The CIELAB (ΔE^*ab) color differences between corresponding points were calculated, but it was confirmed that good color reproducibility is realized in 6-band system, i.e., average $\Delta E^*ab = 3.5$, where $\Delta E^*ab = 11$ in 3-band case, for both normal skin and flare regions.
2. Visual evaluation by dermatologists.
   For the color matching between the reproduced image and the real object, we prepared 25 color chips, printed by an inkjet printer and attached on a handy pentagonal cylinder as shown in fig.5(b). The colors are selected from the preliminary measurement of skin colors; they are distributed around the normal and flare skin colors. The average spacing between the neighboring color chips is $\Delta E^*ab = 3 - 5$ in CIELAB color space.
   In the first step of this experiment, the real skin was observed at first, and a best-matched color chip was determined by the mutual agreement among three

dermatologists. Next, the erythema was shot by 6-band camera and the image for 6-band and conventional RGB system are prepared. In this case the camera shown in fig.2(c) was used and a set of three channels corresponds to the conventional RGB signal.

The colors of target skin and reproduced images from 6-band and conventional RGB cameras were visually compared with a set of color chips by dermatologists to find the best-matched color chip. Then to see if the dermatologists perceive identical color from the reproduced image, the color difference between the color chips matched with the reproduced image and the real skin is illustrated in fig.6. The color chips selected from the observation of 6-band system distribute within ΔE*ab < 4 - 5 range, while in the observation of RGB system, the center of distribution is shifted and the color difference becomes about ΔE*ab = 7 - 8. As the tristimulus values of color chips matched to the target skin and reproduced images are satisfactory close each other, it can be said that the dermatologist perceives almost same color in the case of 6-band system.



(a) (b)

Fig. 6. CIE a*-b* color difference between the color chips matched with the real skin and the reproduced images. (a) normal skin, (b) erythema. Square and diamond plots correspond the results by 6-band and RGB systems, respectively.

3. For the purpose to investigate the influence of color reproducibility to diagnosis, the dermatologists were asked to measure the size of erythema when it was found, with using a micrometer caliper, from the real skin and the reproduced image. Although no significant difference was found in the erythema size measurement between 3-band and 6-band systems, oversights of lesions were observed; in some cases the sizes were not measured from the observation of RGB system because the erythema was not found. Three dermatologists dealt with 60 cases in total, and 8 cases were not judged as flare, though they were found in direct observation. This indicates the possibility that the natural color reproduction capability reduces the oversights of skin lesions.
4. After the overall evaluation with observing the real-time video reproduction, following comments were obtained from the participated dermatologists;
   a. The color reproduction by RGB system is not sufficient especially in reddish colors, and is not suitable for the diagnosis of subtle flare such as measles, virus infection, and drug allergy.

b. The image color in 6-band system looks natural, and the reddish and yellowish colors can be easily discriminated. Then the profile of the erythema is clearer in the image of 6-band system.
c. The dilatation of blood capillary can be clearly observed in 6-band system.

	6-band	Conventional HDTV
Oversight	0	8
Total Obsrvation (3 Dermatologists)	80	60

Table 1. Oversight in the conventional HDTV system (Erythema sizes were not measured).

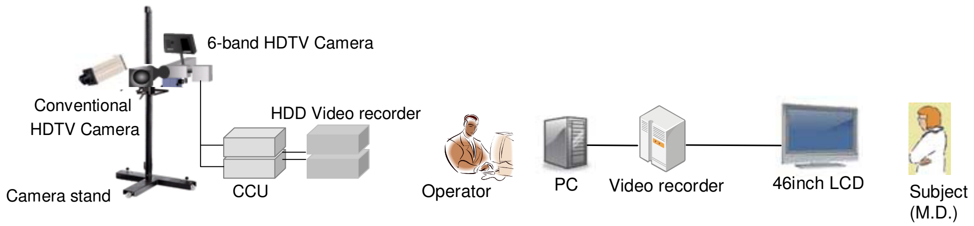
5. Evaluation for the color reproducibility in surgery video

5.1 The system for surgery video recording and evaluation

The NV technology was also applied to the video capture of open surgery and medical doctors visually evaluated the reproduced image quality (Yamaguchi, et. al., 2010). The system configuration used in the experiment is shown in fig.7. For the image input, a 6-band HD camera of fig.2(b) was used. The 6-band camera was installed on a camera stand and set in the operation room as shown in fig.8(a). Seven cases of hand operations were captured and recorded in a hard disk video recorder in an uncompressed format. The spectrum-based color conversion was applied in the manner explained in the section 2. The illumination in the operation room was a mixture of fluorescent and surgical light (Stryker, Visum Surgical Light, halogen lamp mounted). Its spectral energy distribution is shown in fig.8(b), which was measured by a spectroradiometer (Topcon SR-3) and a standard white diffuser.

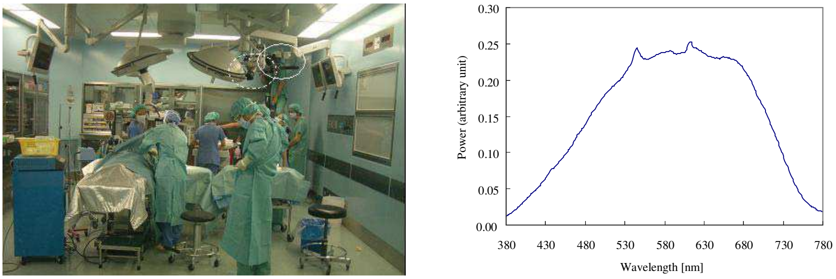
For the image display, a flat-panel LCD (liquid crystal display, Sharp, Information Display PN-455) was used. The resolution of the LCD panel was HD format (1920×1080 pixels). The ambient illumination of the viewing environment was fluorescent lamp, and the irradiance around the monitor was about 300 lx, which is almost equivalent to the typical office environment. In the subjective evaluation, the observation distance was 5H, where H is the height of the image displayed on the monitor. Although the standard observation distance is 3H in HD television system, the standard for SD (standard-definition) was used here since the image resolution was almost equivalent to SD image. In the second experiment subsection 5.3, the observation distance was 3H since the image was HD format. For the evaluation of compressed video, H.264/AVC software codec (MainConcept H.264 Encoder / Decoder) was applied to the signal after the color conversion from the 6-band image.

For comparison with the 6-band images, a consumer HD digital camcoder of high-end specifications was simultaneously used as shown in fig.7(a). Both the 6-band and RGB camera were mounted on the camera stand and operated by two engineers to adjust the image. After the observation of captured image, the images of conventional video showed apparently different color, it was difficult to be employed for the subjective evaluation in comparison with 6-band image. Thus the image captured by operating room camera was used as the conventional image in the evaluation experiment described in the subsection 5.3. The camera was attached to the flexible arm and its position was occasionally adjusted by a nurse to keep the best view. The video sequence was compressed about 1/70 by the encoder included in the camcoder product.



(a) (b)

Fig. 7. The system configuration used in the experiment for (a) image capture and (b) subjective evaluation. CCU: Camera control unit.



(a) (b)

Fig. 8. (a) The operation room after the 6-band video camera installed. (b) The illumination spectrum of the operation room.

5.2 The color distribution of organs and tissues

The image data captured by 6-band camera have quantitative spectral information, which can be utilized for the tissue classification or visualization. As a preliminary investigation, the colorimetric information captured by 6-band camera with high accuracy was derived. Fig.9 shows the colors of the tissue elements on CIE xy-chromaticity coordinates. The colors of tissues distributes from red to yellowish white. Tendon, fat and fascia are yellow-white, and muscle and blood are reddish, while the slightly different red colors of muscle and blood are myoglobin and hemoglobin. The colors were also affected by the deeper organs because some of the tissues are semitransparent.

This shows the possibility of discriminating the tissue elements using the spectral information in the image data for the support of the observation. It is observed that the color of blood exceeds the color gamut of conventional RGB space. It is expected to employ a wide color-gamut display especially in the deep red region for reproducing blood color. In the following experiment, however, we used a flat-panel LCD with normal color gamut, since practical wide-gamut display suitable for this experiment was not available.

5.3 Evaluation of subjective image quality

The videos captured by 6-band (raw and 1/70 compression) and conventional RGB (1/70 compression) cameras were reproduced on a 45inch LCD and the image qualities were evaluated based on Scheffe's paired comparison test. A HD video camera furnished in the

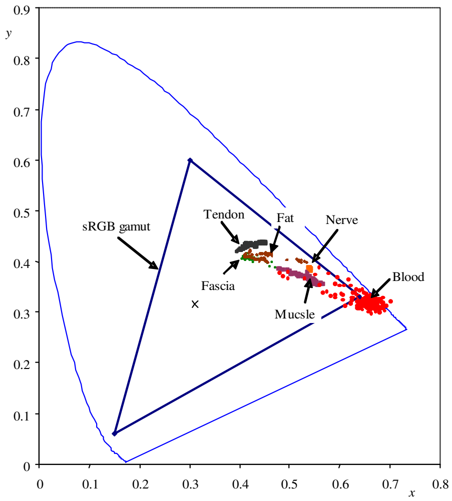


Fig. 9. The color coordinates of the tissues captured by 6-band camera (CIE xy chromaticity coordinates)

operation room was used as the conventional camera. Three doctors (a surgeon and dermatologists) participated in the experiment as the observers. The observers viewed a pair of video (A and B) sequentially and scored 8 items for evaluation into 6 levels (extremely A, much A, slightly A, slightly B, much B, extremely B). The result is summarized in fig.10. Among the evaluation items, 6-band systems were rated significantly higher in "color reproducibility," "fidelity," and "material appearance" at 95% confidence level. It shows that the appearance of the field of operation is superior for the doctors in the 6-band video reproduction than that of the conventional system.

5.4 Evaluation of perceptual color difference

In the experiment described in this section, it was tested if the color difference reproduced by video systems would be perceivable by the medical doctors. For this purpose, the image reproduced by a conventional RGB system was artificially generated from the 6-band image, where the color reproduction from the 6-band image was considered to be a gold standard. In addition, the spectrum-based color reproduction from 3-band camera was artificially generated and compared with 6-band.

In the evaluation, two images (6-band and RGB, or 6-band and 3band) were displayed side by side, without notifying the observer which was the 6-band image. Then the observer answered the color difference was perceivable or not, scoring into 5 levels (5:identical, 4:perceivable but not annoying, 3:slightly annoying, 2:annoying, 1:completely different). The resultant scores for every observer is shown in fig.11, and it can be seen that the differences in (6-band vs. RGB) and (6-band vs 3-band) are significant.

According to the comments from the participants, the most apparent difference was the color of skin. The color difference of tumor was noticeable as well. Human vision is generally sensitive to the skin color variation, and it was confirmed that the color reproduction of skin is quite difficult. Although it cannot be said whether the color difference would give rise to error in diagnosis or decision from this experiment, significantly noticeable errors were observed in the reproduced image. In order to find the cases in which the color accuracy is critical, much more cases should be acquired by multiband camera in future.

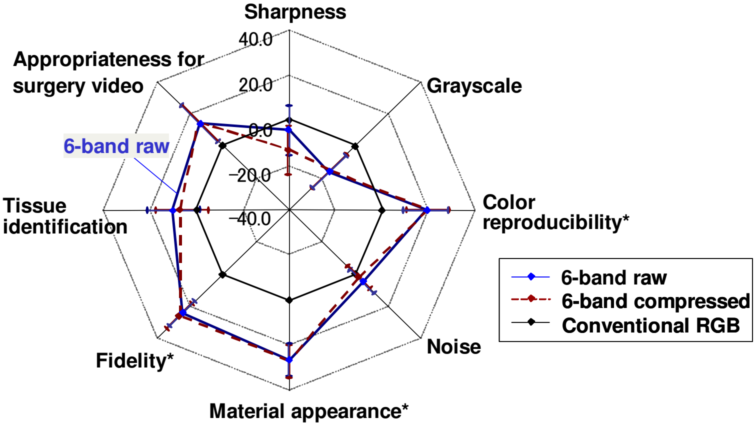


Fig. 10. Result of subjective evaluation. Each score is relative amount where the score of conventional RGB is zero.

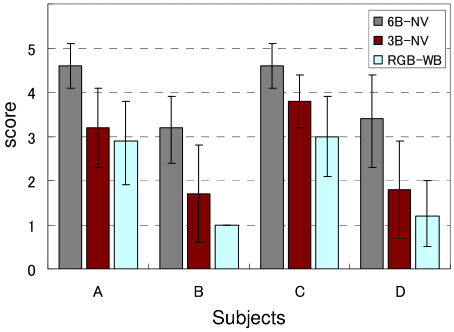


Fig. 11. Result of subjective evaluation of color difference. The error bars indicate the 95% confidence interval.

5.5 Transmission through LAN

To demonstrate the applicability of the high-fidelity color reproduction system using multiband camera to telemedicine, such as telementoring or telesurgery, the color video generated from 6-band data were transmitted through local network using the system shown in fig.3. HD size (1920×1080 pixels) 6-band video clips were stored in video recorder, and converted to the standard color signal (xvYCC color space) in real-time by the color convertor set-top box developed for 6to3 color conversion. The color signal was compressed by H.264/AVC hardware encoder and transmitted though local area network (LAN). The receiver was located in a different room in the same hospital. The received stream was decoded by a decoder, and the display RGB signal were generated by another color converter. The maximum bit-rate of transmission was limited by the encoder up to 15Mbps, and the compression rate could be varied. The image was reproduced on the same LCD of 1920×1080 pixels. Then the doctors observed the images for the informal evaluation, and followings are the discussions based on the comments from participated doctors;

The distortion due to the compression was not so problematic for the physicians when the transmission rate was 15 Mbps. In the case of 4 Mbps, the distortion considerably affected the image quality but it would be usable as the HD video, and the image strongly degraded in 2 Mbps case. Relatively lower bit-rates were accepted, as the motion in the image was small in the surgery video. As a result, it can be said that telementoring or telesurgery system with HD video would work with the transmission rate 10~15 Mbps approximately.

The delay due to the codec was 0.5~1.0 sec, which may obstruct real-time communication. The delay was caused by the color conversion, codec process, and network, and that by codec was considered to be dominant. The reduction of delay time and the investigation of acceptable delay time are one of the important issues.

The material appearance in the field of operation was evaluated to be much better than the conventional video and quite similar to the direct vision, and therefore the multiband system will be effective in case archives, conferences and demonstration. For the practical use, it is required to address some problems, such as the widespread monitors are not usually calibrated, and the H.264 codec is not implemented in the common PCs. The introduction of color management in the medical display is required.

In monitoring surgeries from remote site, in addition to the high-fidelity video of the field of operation, it is desired to view the image of whole operating room or the operator's situation, in which the image quality may not be high. Thus it is recommended that the conventional videoconferencing system for whole operating room and the high-fidelity video transmission for the field are concurrently used, and probably displayed PinP (picture in picture) mode. Moreover, though naturally, the system should be applied to the endoscopic and laparoscopic images.

6. Remote teleconsultation experiment

The system was also tested in the video-based teleconsultation experiment, in which the system was installed at real hospital and clinic sites (Kasaoka Daiichi Hospital and Manabeshima island clinic, Kasaoka, Okayama Pref., Japan) (Yamaguchi, et. al., 2009). Manabeshima island is located about 20km distant from mainland in Setonaikai sea. A doctor usually visits once a week to the clinic, thus improved care service is demanded, and a constant support through teleconsultation would be quite valuable.

The system configuration shown in fig.3 was used in the experiment. For low-bandwidth live-view, 3-band camera was also tested with spectrum-based color processing, along with the 6-band HD camera explained before. A still camera with 6-band capability was employed in addition to the video systems. It was an experimental system with using high-end commercial digital still camera (Olympus E-3), and two pictures were shot for an object; one is normal RGB image, and another one was captured with a color filter in front of the lens. The filter characteristics were similar to the ones shown in fig.2(c). The two pictures were synthesized into a 6-band image, and the spectrum-based color reproduction was applied. The image resolution was 3900x2616 pixels and the image was obsrved with changing the window and the magnification.

Before the remote teleconsultation experiment, a dermatologist tested the video-based teleconsultation by NV technology inside the hospital. The dermatologist overviewed a volunteer patient thoroughly with using the video, and high-resolution 6-band images were captured with 6-band still-camera when suspicious feature was found. Then the magnified still-image was carefully observed to give the final decision.

In the experiment at the real site, the network was provided by cable TV line, where the connection between the mainland and the island was radio transmission. The transmission rate was about 2-10Mbps depending on the weather condition. Ahead of the consultation, the images reproduced by NV and conventional system were compared as shown in fig.12 (left). Two identical skin color charts were kept at both sites, and the image of the color chart was reproduced on the monitors reproduced by NV technology and conventional RGB. In the case of NV, the color reproduced on the monitor almost agrees with the real chart, which was confirmed by the participated doctors. The color difference in the conventional system was evident. After that, a simulated patient at clinic site was consulted by doctors in the hospital through the NV video and still image transmission system [fig.12 (right)]. When using 3-band live-view system, a doctor in the hospital instructed the assistant in the remote clinic to show the part of interest, and high-resolution image was captured by 6-band still camera.

Doctors commented that the NV system provides more natural and realistic images. It was also pointed out that the combined use of normal-resolution video and high-resolution 6-band still image seemed to be practical to observe the patient situation in detail.

Fig. 12. Left: Hospital site. Doctors were viewing the images reproduced by NV and RGB schemes. Color charts were placed at the center for a reference. Right: Clinic site. A patient is showing his arm to the 6-band camera according to the doctor's direction in the hospital site. The person in front of the patient is a technical operator. The color chart is not seen in this photograph.

7. Conclusion

By the use of spectrum-based color reproduction technology, the color reproduced on a display is perceived almost identical to the original, and the advantage of the system was proved in dermatology, surgery video, and teleconsultation. Through the experimental evaluation, in addition to the color reproducibility, the reality, the discriminability of skin lesions and material appearance are significantly improved in the spectrum-based system. In the remote teleconsultation experiment, the video was transmitted through the internet with H264/AVC coding, and the reality of the reproduced image was highly evaluated by the participated medical doctors. For the practical use of the system, it is necessary to develop compact and high-quality multiband camera with better usability.

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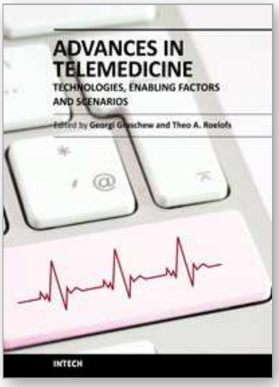

Advances in Telemedicine: Technologies, Enabling Factors and Scenarios
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