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1 Introduction

Gastric cancer is the second most frequent cause of cancer-related death worldwide, and the number of deaths due to gastric cancer is about 15% of the total cancer deaths in Japan. Esophagogastroduodenoscopy (EGD) is widely used for the screening of gastric cancer in Japan; however, skill is required to detect small gastric cancers by this method. Such cancers are often missed by EGD; the reported miss rate for gastric cancers is approximately 20%. Although image-enhanced endoscopic technologies such as narrow-band imaging (NBI) and flexible spectral imaging color enhancement (FICE) have been developed, they are not sufficient to improve the detection rate of gastric cancers.

Hyperspectral imaging (HSI) represents a hybrid modality of optical diagnostics that obtains spectroscopic information and renders it in image form. This technology has been used in the field of remote sensing. The HSC1700 hyperspectral camera (HSC; EBA JAPAN Co., Ltd., Tokyo, Japan) is equipped with HSI technology, and the images recorded by the HSC1700 include spectral reflectance (SR) at 72 spectral bands in the wavelength range from 400 to 800 nm, at wavelength intervals of approximately 5.6 nm. Satori et al. reported that at these intervals, it was possible to distinguish slight changes of color with a high degree of accuracy.

We developed a new, easy, and objective method to detect gastric cancer using hyperspectral imaging (HSI) technology combining spectroscopy and imaging. A total of 16 gastroduodenal tumors removed by endoscopic resection or surgery from 14 patients at Yamaguchi University Hospital, Japan, were recorded using a hyperspectral camera (HSC) equipped with HSI technology. Corrected spectral reflectance was obtained from 10 samples of normal mucosa and 10 samples of tumors for each case. The 16 cases were divided into eight training cases (160 training samples) and eight test cases (160 test samples). We established a diagnostic algorithm with training samples and evaluated it with test samples. Diagnostic capability of the algorithm for each tumor was validated, and enhancement of tumors by image processing using the HSC was evaluated. The diagnostic algorithm used the 726-nm wavelength, with a cutoff point established from training samples. The sensitivity, specificity, and accuracy rates of the algorithm’s diagnostic capability in the test samples were 78.8% (63/80), 92.5% (74/80), and 85.6% (137/160), respectively. Tumors in HSC images of 13 (81.3%) cases were well enhanced by image processing.

Differences in spectral reflectance between tumors and normal mucosa suggested that tumors can be clearly distinguished from background mucosa with HSI technology. The authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: 10.1117/1.JBO.18.2.026010]

Keywords: corrected spectral reflectance; esophagogastroduodenoscopy; hyperspectral camera; hyperspectral imaging; flexible spectral imaging color enhancement; spectral reflectance.

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640 × 480 pixels. A representative HSC image and SR data for each wavelength in tumorous and normal mucosae from Case 1 are shown in Fig. 1. The SR at all pixels in the image can be evaluated with HSC analysis software (HSD Analyser; EBA JAPAN Co.). The obtained SR is normalized to one on the basis of white reference data.

2.3 Recording Procedure with the HSC

The 16 resected specimens were washed with buffered saline and as much of the mucus as possible was removed; then the specimens were pinned on blackboards and immediately recorded with the HSC. All specimens were illuminated equally using the diffused light of three 250-W halogen lamps. The distance between the HSC and the specimen was 50 cm (Fig. 2). Images of the tumors and surrounding normal mucosa could be obtained for all specimens.

2.4 Pathological Evaluation of the Resected Specimens

After being recorded by HSC, the resected specimens were fixed in 10% buffered formalin. We followed the 14th edition of the Japanese Classification of Gastric Carcinoma with regard to the handling of resected specimens.7 The fixed specimens were sectioned at 2-mm intervals and stained with hematoxylin and eosin. The border between the tumor and normal mucosa was diagnosed by histopathological examination. All lesions were curatively resected with a sufficient margin.

2.5 Analysis of the SRs of Tumors and Normal Mucosae

The method of supervised learning was used to establish a diagnostic algorithm and evaluate its diagnostic capability.8 The 16 cases were divided into eight training cases and eight test cases. The training cases were used to determine the optimal wavelength and cutoff point to discriminate between normal and tumorous mucosae. The test cases, which were independent of the training cases, were used to evaluate the diagnostic capability for tumors.

The SRs were obtained from 15 samples (pixels) of normal mucosae and 10 samples (pixels) of tumors from each case. Artifacts of electric cauterization and surgical margins were omitted from the measured samples. Because the SR varied in each case, the mean SR from five normal samples was used as a control for normalization. For each case, corrected spectral reflectance (cSR) was defined as follows:

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\text{Corrected spectral reflectance (cSR) = SR-mean SR of 5 normal samples}
\]

Table 1 Characteristics of the cases recorded by HSC.

| Group | Case no. | Sex | Age (y) | Treatment method | Location | Histopathologic diagnosis | Depth | Macroscopic type | Color       | Tumor size (mm) |
|-------|----------|-----|---------|------------------|----------|--------------------------|-------|------------------|-------------|----------------|
| Training | 1       | F   | 76      | ER               | M        | Adenoma                  | m     | Protruding       | Discolored  | 20             |
|        | 2       | F   | 76      | ER               | M        | Adenoma                  | m     | Protruding       | Discolored  | 10             |
|        | 3       | M   | 71      | ER               | M        | Tub1                     | m     | Protruding       | Reddish     | 20             |
|        | 4       | F   | 79      | ER               | L        | Pap                      | m     | Depressed        | Reddish     | 6              |
|        | 5       | M   | 76      | ER               | L        | Tub1                     | m     | Protruding       | Discolored  | 22             |
|        | 6       | F   | 67      | ER               | L        | Adenoma                  | m     | Protruding       | Same        | 12             |
|        | 7       | M   | 86      | ER               | M        | Tub1                     | m     | Protruding       | Same        | 18             |
|        | 8       | M   | 84      | ER               | M        | Tub1                     | m     | Depressed        | Reddish     | 10             |
| Test   | 9       | M   | 81      | ER               | L        | Adenoma                  | m     | Protruding       | Same        | 10             |
|        | 10      | M   | 70      | ER               | L        | Tub1                     | m     | Depressed        | Reddish     | 12             |
|        | 11      | M   | 64      | ER               | L        | Tub1                     | sm   | Protruding       | Discolored  | 38             |
|        | 12      | M   | 68      | ER               | L        | Tub1                     | m     | Depressed        | Reddish     | 8              |
|        | 13      | M   | 68      | ER               | L        | Tub1                     | m     | Depressed        | Reddish     | 8              |
|        | 14      | F   | 65      | ER               | U        | Tub2                     | m     | Depressed        | Reddish     | 28             |
|        | 15      | M   | 59      | Surgery          | D        | Tub1                     | m     | Protruding       | Discolored  | 20             |
|        | 16      | M   | 78      | Surgery          | M        | Pap                      | ss   | Protruding       | Reddish     | 20             |

Note: ER, endoscopic resection; U, upper third of the stomach; M, middle third of the stomach; L, lower third of the stomach; D, duodenum; Tub1, well-differentiated adenocarcinoma; Tub2, moderately differentiated adenocarcinoma; Pap, papillary adenocarcinoma; m, mucosa; sm, submucosa; ss, subserosa; Same, same color as normal mucosa.
2.6 Image Enhancement of Tumors by Image Processing

By using the HSD Analysiser, we processed the images of all lesions with 20 levels of color gradation on the basis of the SR of the optimal wavelength. Each pixel of the image was displayed in blue if the SR of the pixel was low and red if it was high. The enhanced images were classified by two endoscopists (J. Nishikawa and T. Okamoto) into the following three grades: A, the entire tumor was enhanced; B, the tumor was partially enhanced; and C, the tumor was not enhanced at all. The

![Image from Case 1 obtained with the HSC and SR. Each individual pixel in the image recorded with the HSC has an SR in the wavelength range from 400 to 800 nm. By selecting any pixel, the SR of the spot can be extracted.](https://www.spiedigitallibrary.org/journals/Journal-of-Biomedical-Optics)

![Schematic of the recording procedure using the HSC. All specimens are illuminated equally using the diffused light of three 250-W halogen lamps. The distance between the HSC and the specimen is 50 cm.](https://www.spiedigitallibrary.org/journals/Journal-of-Biomedical-Optics)

![Flowchart of the analysis of SR. The SR is obtained from 15 samples (pixels) of normal mucosae and 10 samples (pixels) of tumors from each case. The mean SR from 5 normal samples is used as a control for normalization, and then the cSR from 10 normal mucosa samples and 10 tumor samples of each case are obtained. The 16 cases are divided into eight training cases and eight test cases. The training cases are used to determine the optimal wavelength and cutoff point to discriminate between normal and tumorous mucosae. The test cases are used to evaluate the diagnostic capability for tumors.](https://www.spiedigitallibrary.org/journals/Journal-of-Biomedical-Optics)
cases classified as A or B were defined as “enhanced,” and we examined the cases of enhancement.

3 Results

3.1 Establishment of the Diagnostic Algorithm with Training Cases

The mean cSR of each wavelength from the 10 tumor samples and 10 normal samples of Case 1 is shown in Fig. 4. In the range of 600 to 800 nm, the mean cSR in the tumors tended to be higher than that in normal mucosae in the training cases. Consequently, the cutoff point was set at the intermediate value between the mean cSR of 80 tumor samples and the mean cSR of 80 normal mucosal samples from the eight training cases. We hypothesized that a cSR higher than the cutoff point indicated a tumor, and a cSR lower than the cutoff point indicated normal mucosa. To determine the optimal wavelength and cutoff point, we set a cutoff point for each wavelength and compared the sensitivity, specificity, and diagnostic accuracy. The accuracy rate using the cutoff point of 726 nm was the highest for the 72 wavelengths, and its cutoff point was 0.05084. The sensitivity, specificity, and accuracy rates were 76.2% (61/80 samples), 78.8% (63/80), and 77.5% (124/160), respectively (Fig. 5).

3.2 Validation of the Diagnostic Algorithm with Test Cases

To evaluate the diagnostic capability using the cutoff point of the optimal wavelength (726 nm) determined in training cases, we used 160 blind samples (80 tumor samples and 80 normal mucosa samples) from the test cases, independent of the training cases. The sensitivity, specificity, and accuracy rates were 78.8% (63/80 samples), 92.5% (74/80), and 85.6% (137/160), respectively, in the test cases (Fig. 6).

3.3 Evaluation of Images Enhanced by SR Data at 726 nm

HSC images of the 16 cases were processed on the basis of the SR of the wavelength of 726 nm. An image from Case 1 is shown in Fig. 7. Endoscopist J. Nishikawa classified them as follows: A, 8 cases; B, 6 cases; and C, 2 cases, whereas T. Okamoto considered the classifications to be as follows: A, 3 cases; B, 11 cases; and C, 2 cases. The number of cases evaluated as enhanced (A or B) by both endoscopists was 13 (81.3%).

4 Discussion

Previous applications of optical spectroscopy to detect gastrointestinal cancer have been attempted. Sambongi et al. measured the spectral intensities of tumors and normal mucosae of the stomach and the colon using a fiber probe through an endoscope. They analyzed the SR in the range of 400 to 600 nm normalized to an SR of 640 nm, but the difference in SR between tumors and normal mucosae was not clearly identified. The usefulness of autofluorescence for cancer detection has been reported. Mayinger et al. measured the fluorescence...
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