Image Processing Algorithm for Virtual Chromoendoscopy (Tone Enhancement) in Clinical Decision Support System

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***Abstract*—Virtual chromoendoscopy is one of the demanded modern direction for increasing the diagnostic value of medical images. The most famous technics are I-SCAN and FICE, and image-processing algorithms that can leverage the unique characteristics of different spectral response in the endoscopic image are actual and relevant, such as TRI-SCAN. The new method of virtual chromoendoscopy based on digital processing of images obtained in the white light was proposed. The main feature of method is local nonlinear processing each color plane. Proposed method was tested on open database of endoscopic images KVASIR. Experiment shows that method can effectively improve color contrast. Proposed method realizes visual effect corresponding visual effect of images obtaining with modern technologies of virtual chromoendoscopy (I-SCAN and FICE) and give possibility to get visual effect superior than modern method of tone enhancement TRI-SCAN.**

I. Introduction

Modern endoscopes play a significant role in diagnosing various gastrointestinal (GI) tract related diseases where the visual quality of endoscopic images helps improving the diagnosis.

The need for improving the differentiation of malignant and inflammatory lesions by endoscopy has fueled research to accelerate the development of novel types of endoscopy systems based on new optical technologies. The recently developed 'image-enhanced endoscopy' (IEE) encompasses various means of enhancing contrast during endoscopy using dye, optical, and/or electronic methods. Therefore, IEE provides easier assessment and specificity of the morphology of a lesion by highlighting the mucosal microstructure and microvasculature features that are needed for adequate and accurate GI cancer diagnosis and treatment.

IEE can be classified into dye-based CE and electronic CE methods.

Dye-based CE is an endoscopy technology that consists of spray application of dyes, which are harmless to the human body, onto the mucosal surface of interest. The application of dye improves visualization of the microstructure and vascular patterns of lesions under investigation. Therefore, the main purpose of CE in the screening of malignant and premalignant lesions is to enhance diagnostic accuracy by clearly delineating the boundaries of a lesion to determine the adequate region for biopsy. The CE is equipped with only a spray catheter, providing a relatively simple and cost-effective method of dye application. Despite these advantages, the application of CE to screening programs remains limited due to absence of standardized methods and analysis, resulting in uncertainty in lesion identification.

Electronic endoscopes obtain images in the form of electronic signals that can be analyzed using various image-processing techniques. Image enhancement is an image processing technique commonly used to improve diagnostic accuracy by converting color and structure-based diagnostic information into more objective and quantitative indicators. Electronic CE, therefore, eliminate the need for time-consuming methods of CE, including spraying and suctioning of dyes and the disadvantage of solution pooling in depressed-type lesions that obstruct visual inspection.

There are two types of electronic endoscopes that may be used to enhance certain mucosal or vascular characteristics: in-chip and off-line. Two new in-chip technologies, providing the enhancement with in-chip processor, are known as narrow band imaging (NBI) and auto-florescence imaging (AFI).

NBI is a novel endoscopic technique that may enhance the accuracy of diagnosis using narrow-bandwidth filters in a red-green-blue (RGB) sequential illumination system.

NBI was first developed by Olympus Medical Systems using these characteristics. The NBI system (EVIS LUCERA SPECTRUM system, CV-260SL; Olympus Medical Systems Co. Ltd., Tokyo, Japan) has a filter that transmits only wavelength of specific bandwidths: 415±15 and 540±15 nm.

AFI is based on the detection of natural tissue fluorescence emitted by endogenous molecules (fluorophores), such as collagen, nicotinamide, adenine dinucleotide, flavin, and porphyrins. After excitation by a short-wavelength light source, these fluorophores emit light of longer wavelengths (fluorescence). These metabolites may be responsible for the observed differences in the auto fluorescence spectra of normal and diseased tissues.

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A number of filters with specific wavelengths are used in these technologies that eventually increase the hardware complexity and power consumption of the endoscopic system [1], [2].

Among off-line techniques that provide enhancement in post-processing stage the most famous example of virtual chromoendoscopy are FICE (flexible spectral imaging color enhancement) [3] and i-SCAN [4], [5].

Fuji Intelligent Color Enhancement (FICE) is often used that can simulate an infinite number of wavelengths in real time. Here, the software applies an algorithm to the real-time endoscopic image, which is reconstructed to determine a wavelength for each of the three colors (red, green, blue). The image is instantaneously reconstructed after changing the wavelengths with virtual electronic filters.

I-scan by PENTAX modifies pixel sharpness, hue and contrast in real-time. Studies showed that i-SCAN technology could improve the diagnostic accuracy.

It is necessary to stress that FICE and I-scan technologies are rather closed technologies. Moreover, FICE method is most closely to hardware realization. Because it has rather complete calibration procedure, which gives possibility to estimate images at three wavelengths, or spectral images, by using the following 3*3 matrix. The aim of calibration procedure to find matrix H which is defined by a correlation matrix for the spectral radiance and camera output, and an auto-correlation matrix for the camera output. In calibration procedure the special devices such as spectrometer is used.

On the other hand, i-SCAN and FICE exploit the color tone enhancement to extract unique features from the different spectral response. Similarly, image processing algorithms that can leverage the unique characteristics of different spectral response in the endoscopic image, can provide better enhancement in terms of better visualization of the anomaly in the image. So there are additional methods of virtual chromoendoscopy with the aim to make endoscopy images more easy for visual analysis and interpretation by means image processing algorithms, the most famous example is TRI –SCAN [6].

TRI-SCAN has three stages: tissue and surface enhancement (TSE), mucosal layer enhancement (MLE) and color tone enhancement (CTE). TSE is employed using modified linear unsharp masking (MLUM); MLE is performed in red (R) plane of the sharpened color image using adaptive sigmoid function. Finally, in CTE the pixels of three color planes are uniformly distributed to increase the contrast level and to create an enhanced color tone.

MLE and CTE steps of TRI-SCAN method are based on global contrast enhancement methods. These methods apply the same transformation to all image pixels. Although global contrast enhancement methods are simple, they cannot be used successfully to all images, since they tend to exhibit degraded appearance, amplified noise or other annoying artifacts. The main reason for this is that the global methods cannot adapt to local features because they use the same transformation over the whole image. Thus, TRI-SCAN approach has some problems with endoscopic images with very dark and very bright areas in the same image, and for such images it is not effective.

Thus, the aim of our investigation was to develop a method based on digital processing of images obtained in the white light. Method must realize visual effect corresponding visual effect of images obtaining with modern technologies of virtual chromoendoscopy (I-SCAN and FICE) and must give possibility to get visual effect superior than modern methods of tone enhancement, for example TRI-SCAN

According to results of investigation the new method of tone enhancement in virtual endoscopy was proposed. The principle new feature of this method is nonlinear local enhancement in each plane (R, G, B). Method based on digital processing of images obtained in the white light and realizing visual effect corresponding or superior visual effect of images obtaining with modern technologies of virtual chromoendoscopy.

The paper has next structure. Part II is devoted to review of modern technologies of virtual chromoendoscopy, which are used as methodology base of our research. Part III includes detail description of proposed method. Part IV experimental investigation and it results.

II. The Main Virtual Chromoendoscopy Technologies Review

A. *Fuji intelligent color enchancement (FICE)*

FICE can produce 60 types of spectral images in the visible light band of 400 to 695 nm at 5-nm intervals, with the possibility of further refining each spectral image into five intensities.

In FICE the spectral reflectance of an object is determined on the basis of the Wiener estimation.

When an object (such as the gastric mucosa) with a spectral reflectance of is illuminated with a light source having a spectral emissivity of through a filter with a spectral transmittance of (i = R, G, B), and an image obtained through a lens and fiber with a spectral transmittance of is recorded with camera with a spectral sensitivity of camera output Vi (i = R, G, B) can be expressed by the equation (1) (for simplicity, noise is ignored).

$$V_i = \int_{400}^{700} E(\lambda) f_i(\lambda) L(\lambda) S(\lambda) O(\lambda) d\lambda, \quad i = R, G, B \qquad (1)$$

Equation (1) can be expressed with a vector as follows:

$$\mathbf{V_i} = \mathbf{f_i^t} \cdot \mathbf{E} \cdot \mathbf{L} \cdot \mathbf{S} \cdot \mathbf{O} = \mathbf{H_i^t} \cdot \mathbf{O} \qquad (2)$$

where $\mathbf{H_i^t}$ is the system's spectral product $\mathbf{H_i^t} = \mathbf{f_i^t} \cdot \mathbf{E} \cdot \mathbf{L} \cdot \mathbf{S}$ and *t* indicates transposition.

When the system's spectral product is not known, the Wiener estimation may be used to estimate the spectral reflectance of an object. The pseudo-inverse matrix $\mathbf{H}^{-1}$ of the

system matrix should be computed to obtain $\mathbf{O}$ from the equation (2). For determination of the estimation matrix, an endoscope is used to capture sample color charts corresponding to spectral radiance $\mathbf{O}$ as shown in Fig. 1, and the camera output $\mathbf{V}$ should be measured.

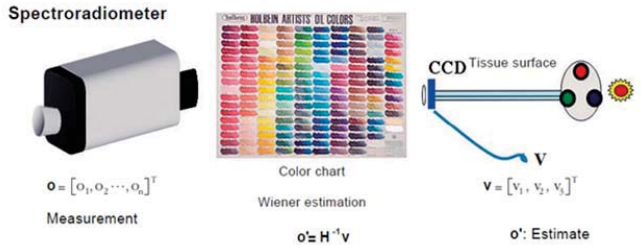

Fig. 1. Structural calibration scheme

In this case, the estimate of spectral radiance of sample k can be expressed with the camera output as shown below.

$$\mathbf{O}'_k = \mathbf{H}^{-1}\mathbf{V}_\mathbf{k}$$

According to the Wiener estimation method, the pseudo-inverse matrix $\mathbf{H}^{-1}$ that minimizes the error $\left|\mathbf{O}'_\mathbf{k} - \mathbf{O}_\mathbf{k}\right|$ between the actual spectral radiance $\mathbf{O}_\mathbf{k}$ and the estimate $\mathbf{O}'_\mathbf{k}$ for all sample data can be obtained from the following equation

$$\mathbf{H}^{-1} = \mathbf{R}_{\mathbf{fg}}\mathbf{R}_{\mathbf{gg}}^{-1}$$

where $\mathbf{R}_{\mathbf{fg}}$ is a correlation matrix for the spectral radiance and camera output, and $\mathbf{R}_{\mathbf{gg}}$ is an auto-correlation matrix for the camera output.

So, FICE has pre-calculated coefficients in a look-up table and estimates images at three wavelengths $(\lambda_1, \lambda_2, \lambda_3)$, or spectral images, by using the following 3*3 matrix.

$$\begin{bmatrix}\lambda_1\\ \lambda_2\\ \lambda_3\end{bmatrix} = \begin{bmatrix}k_{1r} & k_{1g} & k_{1b}\\ k_{2r} & k_{2g} & k_{2b}\\ k_{3r} & k_{3g} & k_{3b}\end{bmatrix}\begin{bmatrix}R\\ G\\ B\end{bmatrix}$$

For example, the matrix coefficients for determination of wavelengths (λ_1 = 500 nm, λ_2 = 620 nm, λ_3 = 650 nm) are as follows:

$$\begin{bmatrix}\lambda_1\\ \lambda_2\\ \lambda_3\end{bmatrix} = \begin{bmatrix}-0.00119 & 0.002346 & 0.0016\\ 0.004022 & 0.000068 & -0.0097\\ 0.005152 & -0.00192 & 0.000088\end{bmatrix}\begin{bmatrix}R\\ G\\ B\end{bmatrix}$$

Thus, FICE assigns estimated spectral images to RGB components in a display device and allows reproduction of color images at a given set of wavelengths in real time. Fig. 2 shows a FICE block diagram.

Fig. 3 shows an example of an endoscopic image of the esophagus taken with this endoscopy system. Fig. 3(a) shows an image produced with conventional RGB data, and Fig. 3(b) shows an example of an image in which RGB components are replaced with spectral components (R, 500 nm; G, 450 nm; B, 410 nm). In Fig. 3(b) blood vessels and the contours of inflammatory tissue associated with reflux esophagitis are highlighted.

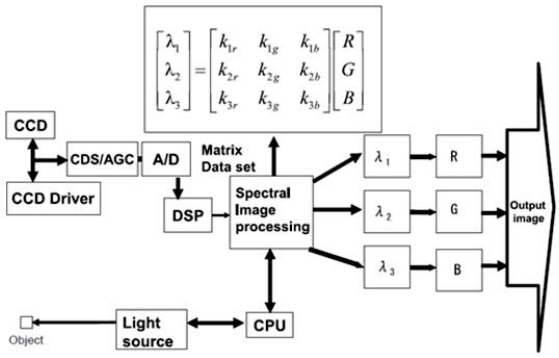

Fig. 2. FICE block diagram

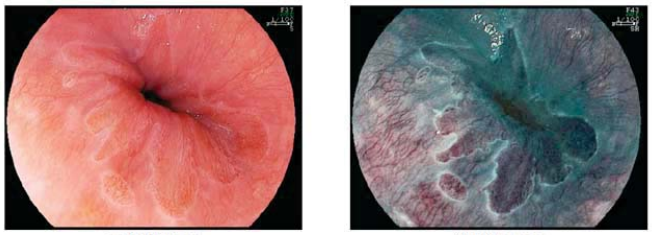

Fig. 3. Endoscopic image of the esophagus taken with FICE endoscopy system

B. I-SCAN

I-SCAN is a software-based digital post-processing image-enhanced technology developed by PENTAX (Tokyo, Japan). I-SCAN performs three functions: surface enhancement (SE), contrast enhancement (CE), and tone enhancement (TE). Of these three functions, SE enhances light-dark contrast on the basis of luminance intensity data obtained from each pixel. This SE function is useful for visual inspection of subtle changes in the mucosa and improving the identification and examination of lesions. This function is comparable to the structure enhancement feature of Olympus endoscopes (Tokyo, Japan), and can yield similar outcomes to spraying of acetic acid in CE, which highlights changes in the mucosal surface by adding blue hue to darker regions based on the luminance intensity data obtained from each pixel.

TE divides the images obtained using normal white light into its RGB components, and subsequently converts and resynthesizes them into a new image to produce images in which subtle hue differences highlight vascular patterns or subtle changes in the mucosa. TE can be implemented in six different modes (TE p, TE v, TE b, TE e, TE g, and TE c) that vary the degree of conversion of each color component to optimize imaging to target organs. TE v and TE p were the original main modes of TE, with TE b, TE e, TE g, and TE c modes more recently added to the TE suite. TE p highlights relatively dark tone red to distinguish the mucosal surface and, therefore, is suitable for observing pit pattern. TE v in contrast is tailored to the observation of vessel morphology by highlighting lesser red regions with the use of faded red color. Therefore, TE p and v perform similarly to NBI in filtering red coloring. TE b is similar to TE p in that it highlights dark red

but it was designed specifically to facilitate detection of Barrett's esophagus. TE e is the best-suited mode for esophagus observation as it highlights reddish and whitish mucosal regions by fading the red color.

C. Tri-Scan

Tri – Scan has three stages: tissue and surface enhancement (TSE), mucosal layer enhancement (MLE) and color tone enhancement (CTE).

The endoscopic image is divided into three primary color planes: R, G, and B. These color planes are normalized between 0 and 1. In TSE stage, each of these color planes is treated as a grayscale image. The mucosa structures, tissue and vascular characteristics, and pit patterns in each plane are enhanced using modified linear unsharp masking (MLUM) [7].

In MLE stage, the superficial layers of mucosa, and size and pattern of micro-vessels are enhanced and highlighted using contrast manipulation techniques. An adaptive sigmoid function (ASF) to enhance mucosal layer information is used.

As the R plane carries the spatial characteristics of superficial layers of mucosa, and size and pattern of microvessels (as previously mentioned), ASF is applied only on the R plane of the sharpened color image.

In general, a sigmoid function is real-valued and differentiable, have either a non-negative or non-positive bell shaped first derivative. Using x for the input, the sigmoid function is given below:

$$S(x)=\frac{1}{\left(1+e^{x}\right)}$$

To control the exponent, two coefficients in the sigmoid function were introduced. Using x for the input, g for gain and k for cutoff, the modified sigmoid function is expressed below:

$$S(x)=\frac{1}{\left(1+e^{g(k-x)}\right)}$$

The cutoff value determines the midpoint of the input curve, and the gain controls the amount of bending. These parameters (gain and cut-off) can also control the overall brightness and contrast level of the input image respectively.

In CTE stage three-dimensional (3-D) uniform distributions to modify the pixels of R, G and B planes is applied.

Let, f is a given image represented as m by n matrix of integer pixel intensities of three dimension ranging from 0 to $L-1$. Let, p denotes the normalized values of f. Then,

$$P_n=\frac{\text{Number of pixels with intensity } n}{\text{total number of pixels}}$$

The 3-D uniform distribution is expressed in equation (3), where *floor*() rounds the pixel value down to the nearest integer. In CTE, the 3-D uniform distribution of pixels of R, G and B plane have been done by flatting the cumulative distribution function (CDF).

$$\psi_{r,g,b}=\begin{cases} floor\left((L_r-1)\sum_{n=0}^{fr_{ij}} p_{rn}\right), \text{R plane} \\ floor\left((L_g-1)\sum_{n=0}^{fg_{ij}} p_{gn}\right), \text{G plane,} \\ floor\left((L_b-1)\sum_{n=0}^{fb_{i,j}} p_{bn}\right), \text{B plane} \end{cases} \quad (3)$$

III. Proposed method

The RGB planes carry different spectral responses of the surface. These spectral responses are mainly dependent on the camera sensor and its spectral sensitivity. From the observation of spectral sensitivities ranging from 300 nm to 700 nm of CMOS and CCD cameras and their effect on endoscopic images, it can be noticed that R plane dominates higher wavelength, G plane dominates mid-wavelength, and B plane dominates shorter wavelength regions. As a result, these individual spectral responses of R, G and B planes carry different spatial characteristics.

For example, the subtle blood vessels and microvessels located deeper in the mucosal layer are better visible in R plane, primarily carrying information related to deep mucosa layer than the other plane. It is possible to highlight these subtle features by enhancing these different spatial characteristics separately. The proposed enhancement method works on each plane separately to highlight these subtle features to help the gastroenterologists to inspect the tissue characteristics, mucosa structures, and abnormal growths better than the original image.

Proposed algorithm is based on idea to divide the initial images obtained using normal white light into its RGB components, and subsequently converts and re synthesizes them into a new image to produce images in which subtle hue differences highlight vascular patterns or subtle changes in the mucosa. For the better blood vessels visualization, we used enhancement only in red channel, and then resynthesizes new images. For R channel processing, we proposed to use nonlinear local method of contrast enhancement – Multi Scale Image Contrast Enhancement (MSICE) [8].

Multi-Scale Image Contrast Enhancement method employs the following adjustable non-linear transformation functions,

$$G(x)=\frac{(B+A)\cdot x}{A+x} \qquad \forall x\in[0,B], \qquad A,B\in R \quad (4)$$

$$H(x)=\frac{A\cdot x}{A+B-x} \qquad \forall x\in[0,B], \qquad A,B\in R \quad (5)$$

where x is the input data, B is the maximum value of x and A is the factor that regulates the degree of the non-linear transformation. B is defined according to the range of input data, varying A can result to different nonlinear curves, controlling the transformation between the input x and output $G(x)$ or $H(x)$. In this method, since the input data will be intensity values, the input range is [0,255] and thus B=255.

For every pixel (*i,j*) of the original image, the difference between the pixel Y_{ij} and its mean surrounding intensity S_{ij} should increase. If $Y_{ij} > S_{ij}$, equation (4) is employed in order to calculate a new pixel value $G(Y_{ij}) \geq Y_{ij}$ and, thus, increase the intensity difference with its surround S_{ij}. Similarly, if $Y_{ij} < S_{ij}$, equation (5) is employed in order to calculate a new pixel value $H(Y_{ij}) \leq Y_{ij}$ and, thus, increase the intensity difference with its surround S_{ij}.

The mean surrounding intensity S^K_{ij} for scale K is calculated as follows:

$$S_{ij}^{K} = \frac{1}{(2d_k+1)^2} \sum_{y=i-d_K}^{i+d_K} \sum_{x=j-d_K}^{j+d_k} Y_{yx}, \qquad (6)$$

where d_K is the size (in pixels) of the surrounding region for scale K. Factor A, which determines the degree according to which the original pixel value Y_{ij} is either increased or decreased, should be adjusted by the initial difference between Y_{ij} and S^K_{ij}. Small differences should result to greater changes in the pixel values, in order to increase the local contrast. On the contrary, large differences should result to smaller changes, since the contrast in these cases is already satisfactory. The regulation of the non-linearity factor A, as well as the combination of equations (4), (5) and (6), are described by the following equations, which are the contrast enhancement function of this method.

$$Out_{ij}^{K}(Y,S) = \begin{cases} \dfrac{\left[B + A\left(Y_{ij} - S_{ij}^{K}\right)\right]Y_{ij}}{A\left(Y_{ij} - S_{ij}^{K}\right) + Y_{ij}} & \text{if } Y_{ij} \geq S_{ij}^{K} \\ \dfrac{A\left(Y_{ij} - S_{ij}^{K}\right)Y_{ij}}{A\left(S_{ij}^{K} - Y_{ij}\right) + B - Y_{ij}} & \text{if } Y_{ij} < S_{ij}^{K} \end{cases}$$

$$A(x) = \begin{cases} \dfrac{M}{x} & \forall x \in [1, B] \\ M & \text{if } x = 0 \end{cases}$$

where Out^K_{ij} is the new intensity value of pixel (*i, j*) for scale K, and M is a constant value that determines the degree of contrast enhancement. Small M values result to strong enhancement, while high values result to moderate enhancement. Since image contrast enhancement can be a rather subjective application, the M value should be determined by the user, according to the enhancement degree that he/she wants to apply. The recommended value for medicine images for M is 5000 (obtained from experiments).

The proposed method is applied independently to three different spatial scales and the final result is the average between their results.

The second part of proposed method is tone enhancement. It includes separate enhancement in each channel. We proposed used for separate processing of R, G, B channel the Contrast–limiting adaptive histogram equalization (CLAHE) algorithm [9].

CLAHE based on the classical contrast enhancement technique Histogram Equalization (HE) and it advanced variant Adaptive Histogram Equalization (AHE). HE is global method, so it has good performance in ordinary images. This method increases the contrast of an image globally by spreading out the most frequent intensity values. HE has been generalized to a local histogram equalization – AHE. AHE formulates each histogram of sub-image to redistribute the brightness values of the images.

CLAHE differs from ordinary AHE in contrast limiting. The CLAHE introduced clipping limit to overcome the noise amplification problem. The CLAHE limits the amplification by clipping the histogram at a predefined value before computing the Cumulative Distribution Function (CDF).

In CLAHE technique an input original image is divided into non-overlapping contextual regions called sub-images, tiles or blocks.

The CLAHE has two key parameters: Block Size (BS) and Clip Limit (CL). The CLAHE method applies histogram equalization to each contextual region. The original histogram is clipped pixels are redistributed to each gray level. The redistributed histogram is different with ordinary histogram, because each pixel is limited to a selected maximum. But the enhanced images and the original image have the same minimum and maximum gray levels.

Thus, proposed method has next main steps presented in the Fig. 4. The endoscopic image is divided into three primary color planes: R, G, and B. For R-plane we apply Multi Scale Image Contrast Enhancement. Than we realize separate processing of R, G, B channel with the CLAHE algorithm.

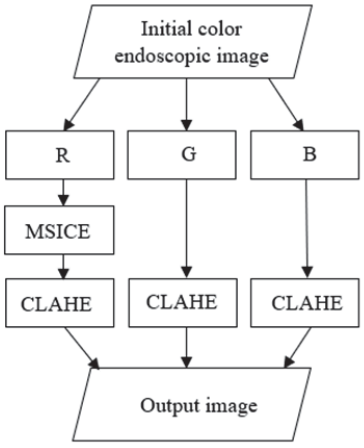

Fig. 4. Block diagram of proposed method

IV. Results of Experimental Investigation

The experiments were carried out with the KVASIR open database of endoscopic images [10]. The dataset consists of 4000 images with different resolution from 720x576 up to 1920x1072 pixels. The images are separated on eight types, represent different endoscopic cases. The rich variability of the data allows to comprehensively investigate the proposed method in various conditions.

The Fig. 5 – 8 show the initial images of different cases and the results of TRI-Scan and proposed method application.

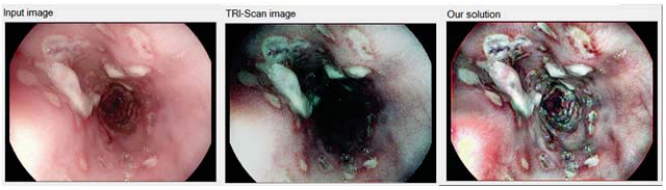

Fig. 5. The results of proposed method and TRI-Scan

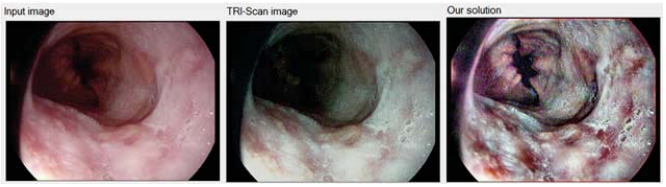

Fig. 6. The results of proposed method and TRI-Scan

Fig. 7. The results of proposed method and TRI-Scan

Fig. 8. The results of proposed method and TRI-Scan

On the Fig. 9-10 there are comparative results with the pictures from FICE atlas.

Fig. 9. The results of proposed method and FICE

Fig. 10. The results of proposed method and I-Scan

In our research we used focus value (*Fv*) as a quantitative measure of image enhancement. *Fv* represents the ratio of AC and DC energy of a Discrete Cosine Transform (DCT) image [11]. The results of tone enhancement obtained using Kvasir database for different types of pathologies are presented in the Table I.

TABLE I. THE RESULTS OF CONTRAST ENCHANCEMENT

Type of pathology	Initial image	Processed image
Esophagitis	0.015	0.043
Dyed lifted polyps	0.031	0.069
Dyed resection margins	0.033	0.072
Normal seccum	0.025	0.067
Normal pylorus	0.014	0.043
Normal z-line	0.015	0.042
Polyps	0.025	0.059
Ulcerative colitis	0.031	0.075

The experiments show that the proposed method has several very important advantages:

- It normalizes image brightness, reveals the information from dark areas and retrieves some data from overexposed fragments;
- It provides the most sharpness images with highlighted small details and pit patterns;
- It overcomes the analogs in highlighting of vessels and vascular patterns;
- As a result of contrast enhancement and color manipulation the subtle image features to be voluminous – this provide an excellent visual quality for image under observation.

V. CONCLUSION

The new method of virtual chromoendoscopy based on digital processing of images obtained in the white light was proposed.

The method is based on nonlinear separate contrasting of RGB channels. It emphasizes the structural differences in the areas of the tissues to be examined.

The method provides high color contrast between the vascular structures and tissues.

The method highlights the mucosa features.

The proposed solution provides image enhancement with characteristics at least similar or even superior than state-of-the-art technologies.

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