Color Retinal Image Enhancement Based on Luminosity and Contrast Adjustment

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Abstract*—*Objective: **Many common eye diseases and cardiovascular diseases can be diagnosed through retinal imaging. However, due to uneven illumination, image blurring, and low contrast, retinal images with poor quality are not useful for diagnosis, especially in automated image analyzing systems. Here we propose a new image enhancement method to improve color retinal image luminosity and contrast.** ***Methods:*** **A luminance gain matrix, which is obtained by gamma correction of the value channel in the HSV (Hue, Saturation, and Value) color space, is used to enhance the R, G, and B (Red, Green and Blue) channels, respectively. Contrast is then enhanced in the luminosity channel of L*a*b* color space by CLAHE (contrast limited adaptive histogram equalization). Image enhancement by the proposed method is compared to other methods by evaluating quality scores of the enhanced images.** ***Results:*** **The performance of the method is mainly validated on a dataset of 961 poor quality retinal images. Quality assessment (range 0-1) of image enhancement of this poor dataset indicated that our method improved color retinal image quality from an average of 0.0404 (standard deviation 0.0291) up to an average of 0.4565 (standard deviation 0.1000).** ***Conclusion:*** **The proposed method is shown to achieve superior image enhancement compared to contrast enhancement in other color spaces or by other related methods, while simultaneously preserving image naturalness.** ***Significance:*** **This method of color retinal image enhancement may be employed to assist ophthalmologists in more efficient screening of retinal diseases and in development of improved automated image analysis for clinical diagnosis.**

***Index Terms*—Contrast enhancement, gamma correction, L*a*b* color space, luminosity, retinal image.**

I. Introduction

RETINAL images are widely used by the ophthalmologists for early detection and diagnosis of common retinal diseases, including diabetic retinopathy, age-related macular degeneration, and glaucoma [1]. However, some retinal images are of a clinically unsatisfactory quality due to eye lesions and imperfect imaging processes [2], [3], such as opacity of refractive media, hemorrhages, exudates, and patients' eye movement. Uneven illumination, blurring, incorrect focus, and low contrast reduce the quality of retinal images, resulting in a loss of sensitivity and specificity for diagnostic purposes, and may even impair ophthalmologists' ability to interpret significant eye features or distinguish different retinal diseases [4]. Poor quality retinal images make it difficult for subsequent accurate segmentation and computer-aided diagnosis of retinal diseases [5], which are used to automate the detection process and to assist ophthalmologists. Therefore, it is necessary to overcome the challenges associated with poor quality retinal images. One effective method is to use image enhancement technology [6] to provide better visibility of the retinal anatomical structure.

In recent years, many new enhancement methods for retinal images have been proposed to augment the classical histogram equalization, including image luminosity and contrast normalization techniques [7], a multi-scale method based on the Contourlet transform [8], CLAHE (contrast limited adaptive histogram equalization) [9]-[11], Retinex-based enhancement algorithm [12], [13], blood vessel enhancement by multi-scale top-hat transformation and linear stretching with histogram Gaussian curve fitting [14] or via multi-dictionary and sparse coding [15], and some other combinatorial methods. These existing methods can broadly be divided into three types: histogram based, filter based, and transformation based. Most of these methods focus on enhancing retinal blood vessels to achieve better vessel segmentation through increasing the contrast between blood vessels and the retinal background in both grayscale and color retinal images. This method is especially useful for color retinal images, where the green channel of the color retinal image generally displays a high contrast between the vessels and the background. The enhanced retinal images can lose color information or other important image features (e.g., optic disc, macula lutea, and various types of lesions), which cannot directly improve the current status of diagnosis by ophthalmologists.

In order to obtain more image details as well as preserve image naturalness which means pleasing perceptual quality without color distortion and over-enhancement, we present a new enhancement method for color retinal images based on illumination and contrast adjustment. To avoid the common

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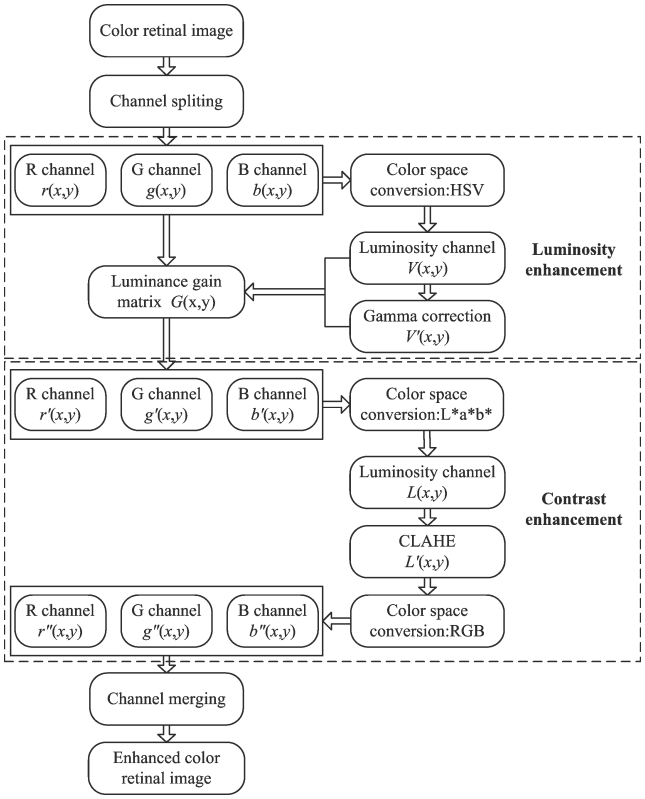

Fig. 1. Flow diagram of our proposed method for color retinal image enhancement.

problem of color distortion, all the processes are performed on the luminosity channel. The luminance gain matrix, which is obtained by a non-linear transformation of the value channel in the HSV (Hue, Saturation, and Value) color space, is used to enhance the R, G, and B (Red, Green and Blue) channels respectively. Subsequently, contrast is enhanced in the luminosity channel of L*a*b* color space [16], [17] by CLAHE, which specializes in improving local contrast and avoiding the non-homogeneous regions in retinal images (the optic disc region is significantly brighter than other regions) and enhances the image uniformly. The method is evaluated on a data subset of poor quality retinal images, as assessed by the human visual system-based fundus image quality assessment system [18] from our proprietary datasets, and a publicly-available dataset. A comparison with contrast enhancement in different color spaces and other related methods is also presented.

II. Materials and Methods

The proposed method includes two steps: luminosity enhancement and contrast enhancement. The flow diagram of our proposed method is shown in Fig. 1.

A. Retinal Image Datasets

The main color retinal image dataset used for evaluation of the proposed method is selected from a proprietary repository of retinal images. To collect our proprietary datasets, 4000 images with a resolution of 2144 ×1424 pixels were taken by a tabletop TRC-NW8 fundus camera (TopCon Medical Systems, Tokyo, Japan) at the Eye Center of Second Affiliated Hospital of Zhejiang University. A subset of 961 images with overall poor quality was selected automatically from the 4000 images. The automatic-selection system was implemented by our proposed algorithm [18] where three characteristics of the human visual system -- multi-channel sensation, noticeable blur, and the contrast sensitivity function -- were utilized to detect illumination and color distortion, blur, and low contrast distortion, respectively. The selected images in the subset have poor assessed scores which are below 0.1; the maximum possible score is 1. Clinical diagnosis on these retinal images is usually difficult as they are of very low contrast, blur, and uneven illumination. In addition, circular masks were drawn and the images were cropped to eliminate the area beyond the region of interest [18]. The preprocessing reduces the size of the image and hence less number of pixels is investigated in further computation, which can reduce the computational time. Four representative samples in our data subset are shown in Fig. 2. (No.104, No.134, No.145, No.854).

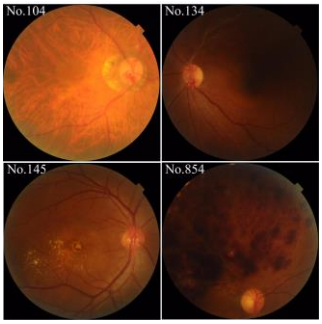

Fig. 2. Four retinal image samples from our data subset.

Meanwhile, to verify the effectiveness of the proposed method on normal dataset and make the result reproducible, the largest publicly-available Messidor dataset [19] is also used to test. The Messidor dataset contains 1200 retinal images, which were acquired at three different ophthalmology departments using a non-mydriatic 3CCD camera (Topcon TRC NW6) at 45° FOV with a resolution of 1440*960, 2240*1488 or 2304*1536 pixels and stored in TIFF format.

B. Luminosity Enhancement

Because insufficient or uneven luminance obscures visual perception of retinal images, making diagnostic details undetectable, it is essential to enhance the luminance effect first. However, for a color image, the color should not change for any pixel, to prevent image distortion. In general, color retinal images are stored and viewed using RGB color space. The R, G, and B channels simultaneously contain the luminosity information and the color information, which are correlated with each other. To enhance the luminosity and preserve the color, the R, G, and B channels should be adjusted by the same proportion [20]. Our solution is to obtain a luminance gain matrix $G(x, y)$ which is defined as follow:

$$\frac{r'(x,y)}{r(x,y)} = \frac{g'(x,y)}{g(x,y)} = \frac{b'(x,y)}{b(x,y)} = G(x,y) \quad (1)$$

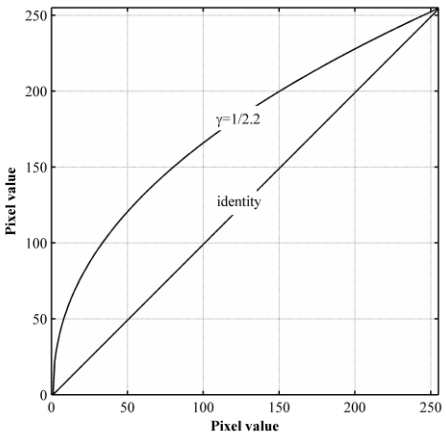

Fig. 3. Transformation curve of gamma correction and the identity line.

where $r'(x, y)$, $g'(x, y)$, and $b'(x, y)$ are the enhanced R, G, and B values in the pixel at (x, y) position, and the $r(x, y)$, $g(x, y)$, and $b(x, y)$ are the original R, G, and B values.

To obtain the color-invariant luminance gain matrix, the color image is transformed into the HSV color space where the luminosity channel (V) is decoupled from the two color components, hue (H) and saturation (S). The H and S channels are irrelevant to luminance, and both are ignored. The luminance intensity of a pixel at the (x, y) position is obtained as the maximum (max) of the R, G, and B values. Therefore, the luminance gain matrix can be inferred as

$$G(x,y) = \frac{V'(x,y)}{V(x,y)} = \frac{V'(x,y)}{\max(r(x,y), g(x,y), b(x,y))} \tag{2}$$

where $V(x, y)$ is the luminance intensity of a pixel at (x, y) position, and $V'(x, y)$ is the function of $V(x, y)$, which determines the effect of luminosity enhancement. We can see that the processing can be directly done in the RGB color space, which reduces the computational complexity.

For the $V'(x, y)$, we aim to significantly increase the dynamic range of the low gray level region, to slightly increase the moderate gray level region, and to maintain or compress the high gray level region. Gamma correction [21], [22], a popular imaging processing methods, is used to transform luminance nonlinearly. The transformation curve is expressed by

$$w = u^{\gamma} \tag{3}$$

where $u \in [0,1]$ denotes the normalized pixel value of the luminosity channel, w is the normalized output, and γ is a constant. The transformation has a simple pointwise operation form. Before undergoing the transformation, $V(x, y)$ is normalized as the input u. $V'(x, y)$ is the reversed normalization of the output w. The gamma, γ, is typically greater than 1.0 in a display device, and the standard of the National Television System Committee recommends a gamma of 2.2, which can be used to effectively recover an overexposed region. Whereas $\gamma <$ 1 has exactly the opposite effect, the usual setting is 1/2.2, which is also used in our method. The transformation curve of gamma correction is shown in Fig. 3. Compared with the identity line when $\gamma = 1$, the nonlinearity transformation can effectively enhance the luminosity. The values in the calculated luminance gain matrix $G(x, y)$ are always greater than or equal to 1. The gray level interval [0, 50] in the luminosity channel (V) is transformed to [0, 122], [100, 150] is transformed to [167, 200], and [200, 255] is transformed to [228, 255]. The transformation can increase the dynamic range of the low gray level and compress the high gray level, which can clarify the details of the retinal image.

Even more importantly, the luminosity enhancement in the HSV color space can effectively take care of the gamut problem [23]. Because the pixel value in the luminosity channel (V) is the maximum value in the R, G, and B channels and the gamma correction does not change the gray level range. The enhanced values $r'(x, y)$, $g'(x, y)$, and $b'(x, y)$ by multiplying the original R, G, and B values and $G(x, y)$ respectively cannot go out of bounds.

C. Contrast Enhancement

The luminosity enhancement above can balance the overall luminance, especially for retinal images with low luminosity. Image contrast can also be enhanced to some extent. However, if the retinal image is blurry and has moderate luminosity, there would be no significant improvement in contrast. To further enhance the contrast of retinal images, the CLAHE method is applied, which has been verified to be an effective method to uniformly enhance details of gray retinal images [10], [11]. The CLAHE divides the image into small regions called tiles; the histogram on each tile is equalized so that local contrast is enhanced. This local enhancement technique can result in noise dominating on individual local regions. Hence, a clip-limitation strategy is employed to prevent local contrast from hitting the maximum. In our method, the number of tiles is 8×8, and the clip limit is 0.01. Both derive from a public domain implementation of CLAHE in MATLAB. Optimization results of the two values showed that higher values generate blocking effects whereas lower values fail to enhance contrast.

For color retinal images, it is better to implement CLAHE on the luminosity channel to reduce color distortion. This contrast enhancement will only operate on the luminosity channel and can avoid the gamut problem. The L*a*b* color space (also called CIE LAB) [16], [17] based on the prior master space CIE 1931 XYZ color space can provide more uniform color differences in relation to visual differences. It has three orthogonal dimensions: luminosity, L* (dark-to-bright); chromaticity, a* (green-to-red); and b* (blue-to-yellow). The value of L* extends from 0 (black) to 100 (white), and the values of a* and b* both range from -128 to +127. The L*a*b* color space is able to better separate the luminosity and the color, and its L* component closely matches human perception of luminosity, which can be used to adjust the contrast. Thus, the retinal image in RGB color space by luminosity enhancement is converted into L*a*b* color space. The CLAHE is used to enhance the L channel. Then the processed

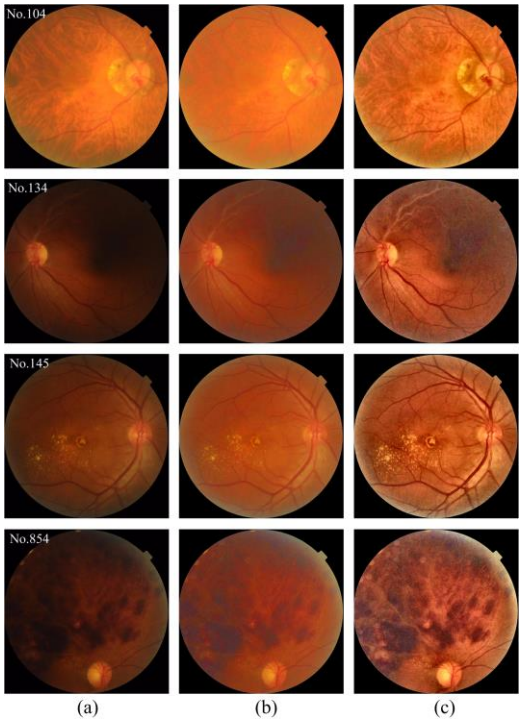

Fig. 4. Procedure of color retinal image enhancement by the proposed method, (a) Original images, (b) luminosity enhancement of original images, and (c) contrast enhancement of images in 4b.

image in the L*a*b* color space is transformed back into the RGB color space. However, there are no simple formulas for conversion between RGB and L*a*b*, because the RGB color space is device-dependent. To obtain device-independent data, the luminosity enhanced image in RGB color space is firstly transformed to the CIE 1931 XYZ color space and then transformed into L*a*b*. The forward transformation process of the L channel is described in (4)-(6) as follows.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.412453 & 0.357580 & 0.180423 \\ 0.212671 & 0.715160 & 0.072169 \\ 0.019334 & 0.119193 & 0.950227 \end{bmatrix} \cdot \begin{bmatrix} r'(x,y) \\ g'(x,y) \\ b'(x,y) \end{bmatrix} \tag{4}$$

$$L = 116 f(Y/Y_n) - 16 \tag{5}$$

$$f(t) = \begin{cases} t^{1/3} & t > \left(\frac{6}{29}\right)^3 \\ \frac{1}{3}\left(\frac{29}{6}\right)^2 t + \frac{4}{29} & others \end{cases} \tag{6}$$

where X, Y, and Z are the three components in CIE XYZ color space, and X_n, Y_n, and Z_n are the CIE XYZ tristimulus values of the reference white [24].

The value of L is proportional to Y in which the green channel is weighted largely. The green channel exhibits the highest contrast among the three channels of the RGB color space, therefore the L channel is also expected to have higher contrast. Enhancement in the L channel of the L*a*b* color space should further improve performance.

All the operations were implemented using MATLAB R2013b on a PC with Intel i5 processor at 2.30 GHz and 8 GB RAM and elapsed times were reported in seconds.

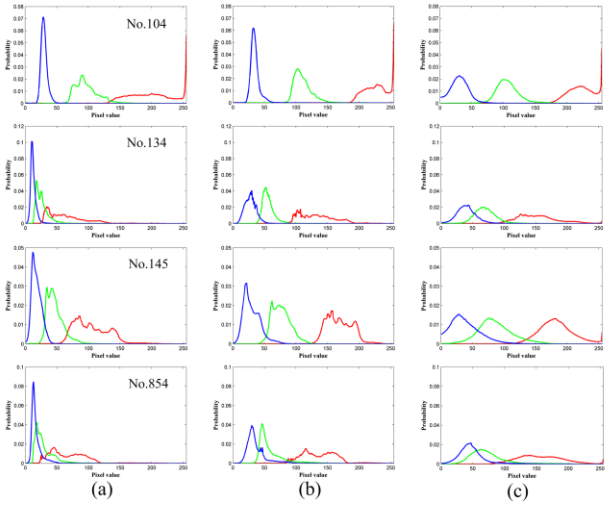

Fig. 5. Corresponding histograms of ROI of the color retinal images in Fig. 4. The red, green, and blue lines correspond to the R, G, and B channels respectively.

III. Results and Discussion

The performance of the color retinal image enhancement method based on luminosity and contrast adjustment was mainly analyzed and validated on our proprietary dataset of 961 color retinal images and further on the Messidor dataset. Quality of both original and enhanced images was quantitatively assessed by our assessment algorithm [18].

Initially, we applied our proposed enhancement method to four retinal images (Fig. 2).The stepwise process of color retinal image enhancement by the proposed method starting with the original image (Fig. 4a), proceeding to luminosity enhancement (Fig. 4b), and culminating with contrast enhancement (Fig. 4c) is shown for representative images. This process demonstrates that our method of luminosity enhancement achieves improvement in the luminance of retinal images without color distortion. Enhancement of luminance alone results in overall uniform and bright luminance (Fig. 4b), but the clarity of the retinal images is still insufficient. Subsequently applying CLAHE to the L channel of the L*a*b* color space results in significant enhancement of the contrast of the retinal images (Fig. 4c). The corresponding ROI histograms from the original and enhanced color retinal images in Fig. 4 verify the effectiveness of our method (Fig. 5). The images No.134, No.145, and No.854 have low gray-level values in whole and narrow dynamic range in the R, G, and B channels, especially in the B channel, which means low luminosity and contrast and is consistent with our visual perception. The image No.104 has moderate gray-level values, but it also has narrow dynamic range, and the highlight region around the optic disc makes some details indistinguishable. After luminosity enhancement, the whole gray-level values in all channels become greater due to the characteristic of luminance gain matrix $G(x, y)$ (Fig. 5b), which indicates better illuminance. And the dynamic range of histograms in the low gray-level interval is also stretched. It is an effective and conventional

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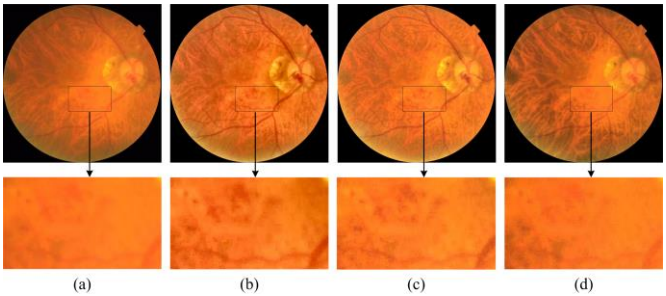

Fig. 6. (a) Original retinal image; luminosity and contrast enhanced images with contrast enhancement in the (b) L*a*b*, (c) HSI, and (d) HSV color space. The selected regions in the black rectangle are zoomed in in the bottom row.

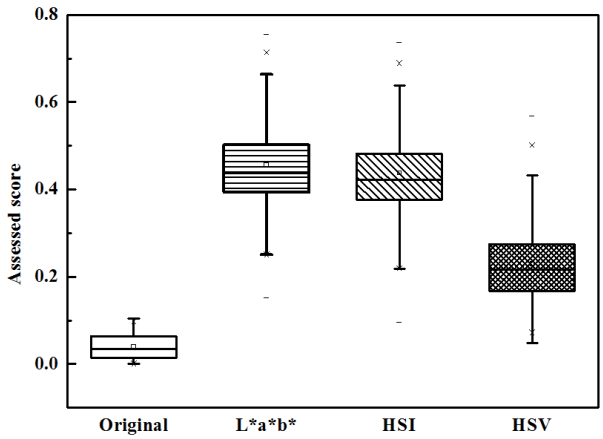

Fig. 7. Boxplot of the assessed scores of the original and luminosity and contrast enhanced 961 images with contrast enhancement in the L*a*b*, HSI, and HSV color space.

method for contrast enhancement by spreading the histogram of the processed image. The luminosity enhancement can improve the contrast to some extent. The dynamic range of the histograms in the R, G, and B channels of these processed images is further remarkably broadened by contrast enhancement, as indicated by the ROI histograms for the contrast enhanced images (Fig. 5c), which demonstrates better contrast compared to the luminosity enhanced images. The analysis result of histograms is consistent with our visual perception (Fig. 4).

The resulting retinal images enhanced by our proposed method display improved visualization of not only blood vessels but also other important anatomical structures of the retina (i.e., optical disc and macula), and improves the prominence of lesions. Moreover, our method preserves the naturalness of the retinal images while at the same time enhancing critical details, which can assist the ophthalmologists in better retinal image analysis.

To verify the effectiveness of contrast enhancement of the luminosity enhanced image in the L*a*b* color space, we carried out a comparison of our method with contrast enhancement of the I and V channels in the HSI and HSV color spaces respectively by the CLAHE approach. The contrast enhancement in the L*a*b color space demonstrates superior luminance and contrast compared to enhancements in the HSI and HSV color space (representative color retinal images shown in Fig. 6). Although the image enhanced in the HSI color

TABLE I
AVERAGE AND STANDARD DEVIATION OF ASSESSED SCORES OF THE ORIGINAL AND ENHANCED IMAGES IN THE L*A*B*, HSI, AND HSV COLOR SPACES.

	Original images	LAB	HSI	HSV
Average score	0.0404	0.4565	0.4372	0.2297
Standard deviation	0.0291	0.1000	0.0981	0.0907

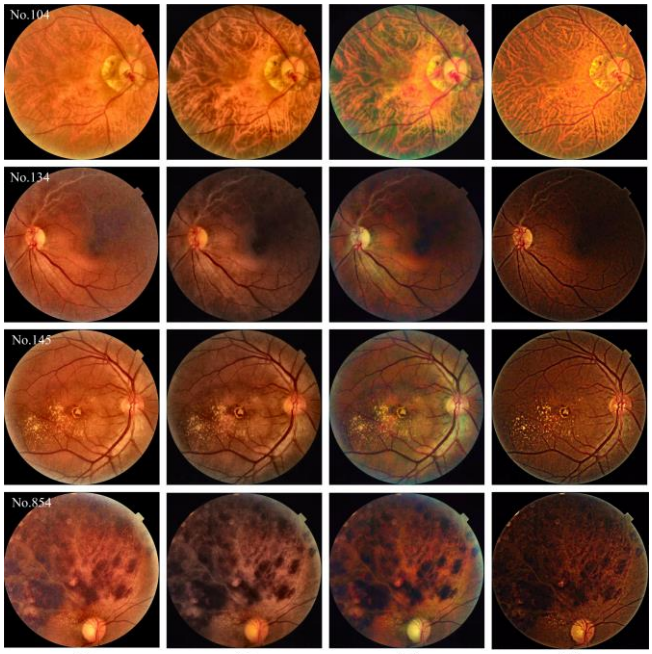

Fig. 8. Enhancement of poor quality color retinal images by different enhancement methods. Original images are found in Fig. 2. (a) Image enhancement was performed (a) by our proposed method based on luminosity and contrast enhancement, (b) by using CLAHE only in the L channel of CIE LAB color space, (c) using CLAHE in the R, G, and B channels, and (d) using the method based on guided image filtering.

space (Fig. 6c) has comparable luminance with the enhanced image in the L*a*b* color space (Fig. 6b), it also has increased noise and inferior contrast in visual perception compared to the image enhanced in the L*a*b* color space. Furthermore, comparison of selected regions demonstrates that blood vessels and other important details in the image enhanced in the L*a*b* color space have better visibility and clarity than in images enhanced in the HSI and HSV color spaces. To quantitatively compare the three color spaces, the original and enhanced images from our 961 image data subset were assessed by our proposed quality assessment method. This assessment indicated that the quality of images with contrast enhanced in the L*a*b* color space is superior to those enhanced in the HSV and HSI color space, as indicated by higher assessed scores for individual images and for the 961 image data subgroup as a whole (Fig. 7, Table I). This demonstrates that our proposed method is able to achieve the best overall assessed score for enhanced images, and indicates that the L*a*b* color space has an advantage over the HSV and HSI color spaces for improving image contrast and highlighting retinal vessel characteristics.

We further carried out a comparison with other related enhancement methods, including a method using CLAHE only

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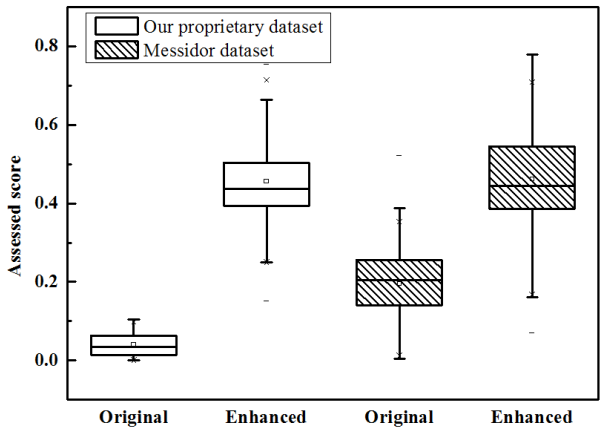

Fig. 9. Boxplot of assessed scores of the original and enhanced images in our proprietary dataset and the Messidor dataset respectively.

in the L channel of the L*a*b* color space, a method using CLAHE in the R, G, and B channels, and a method based on guided image filtering [25], in which the input image itself is used as a guidance image (Fig. 8). In contrast to our proposed enhancement method based on luminosity and contrast enhancement (Fig. 8a), the method using CLAHE in only L channel of the L*a*b* color space improves contrast for the retinal images with normal illuminance, but it is unable to balance luminosity for retinal images with low illuminance (Fig. 8b). The image enhancement using CLAHE in the R, G, and B channels results in severe color distortion, which may lead to a clinical misdiagnosis (Fig. 8c). Finally, although the enhancement method based on guided image filtering can effectively enhance the details of the whole image (Fig. 8d), this method results in unnatural looks due to the over enhancement of details and edges. And the two methods are also unable to improve luminosity. Therefore, luminosity enhancement in our method is necessary, especially for poor quality color retinal images, and contrast enhancement in our method is more effective.

Moreover, the retinal images in the Messidor dataset were processed by our enhancement method, and were also evaluated by the same assessment method (Fig. 9). The averages of assessed scores of the original and enhanced images are 0.1957 (standard deviation 0.0819) and 0.4610 (standard deviation 0.1152) respectively. The assessment result demonstrates that our method can improve the normal retinal images, too. When the retinal image is collected, it can be directly processed by the proposed method without prior assessment. By comparing the assessed scores of the two datasets, the average of the enhanced images in the Messidor dataset is slightly better in general, but the average of the original images is significantly higher. Despite the good quality achieved with enhanced images in both datasets, our method performs better on the poor quality retinal images in our proprietary dataset.

In summary, the above results demonstrate that our proposed method works well on both the poor and normal retinal images to improve their luminosity and contrast, and provides qualitatively and quantitatively superior enhancement compared to other image enhancement methods.

IV. Conclusions

Here we present an effective method for color retinal image enhancement based on luminosity and contrast adjustment. First, the luminosity of the color retinal image is enhanced by a luminance gain matrix based on gamma correction, and then image contrast is enhanced by CLAHE in the L*a*b* color space. The performance of our proposed method was validated on two large color retinal image datasets. The results show that, compared with contrast enhancement in other color spaces and other methods, our proposed method achieves superior improvement of color retinal images, especially for those with initially of poor quality. This method is not only able to enhance important anatomical structures of the retina, but it also preserves the naturalness of the images. This effective method of color retinal image enhancement will greatly assist ophthalmologists in disease diagnosis through retinal image analysis, and will be greatly beneficial to automated image analysis systems. The clinical evaluation of our method is currently in progress.

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