Retinal image enhancement via a multiscale morphological approach with OCCO filter

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Abstract. Retinal images are widely used for diagnosis and eye disease detection. However, due to the acquisition process, retinal images often have problems such as low contrast, blurry details or artifacts. These problems may severely affect the diagnosis. Therefore, it is very important to enhance the visual quality of such images. Contrast enhancement is a pre-processing applied to images to improve their visual quality. This technique betters the identification of retinal structures in degraded retinal images. In this work, a novel algorithm based on multi-scale mathematical morphology is presented. First, the original image is blurred using the Open-Close Close-Open (OCCO) filter to reduce any artifacts in the image. Next, multiple bright and dark features are extracted from the filtered image by the Top-Hat transform. Finally, the maximum bright values are added to the original image and the maximum dark values are subtracted from the original image, previously adjusted by a weight. The algorithm was tested on 397 retinal images from the public STARE database. The proposed algorithm was compared with state of the art algorithms and results show that the proposal is more efficient in improving contrast, maintaining similarity with the original image and introducing less distortion than the other algorithms. According to ophthalmologists, the algorithm, by improving retinal images, provides greater clarity in the blood vessels of the retina and would facilitate the identification of pathologies.

Keywords: Retinal images · Contrast enhancement · Mathematical morphology · OCCO · Top-Hat transform.

1 Introduction

Eye diseases are detected from an eye fundus study. This test is very important to detect pathologies such as choroid melanoma, diabetic retinopathy, glaucoma, age-related macular degeneration, toxoplasmosis or other diseases. An image with a high visual quality is very important for ophthalmologists, because it guarantees a more precise diagnosis. However, image quality can be affected for different reasons at the time of acquisition. Some of the common problems that images often suffer at the time of acquisition are low contrast, poor detail, insufficient lighting or artifact generation. To solve these problems, digital image processing techniques are used to enhance the visual quality of the images [6].

Digital image processing has different techniques that are used to improve the visual quality of the images [1, 3–5, 7, 11–17, 20, 21, 23]. Among these are algorithms based on histograms and algorithms based on mathematical morphology. Also, some of these techniques have been used to enhance the visual quality of retinal images. For example, in [20] the Contrast Limited Adaptive Histogram Equalization (CLAHE) algorithm was used; in [11] the multiscale top-hat transform with the contrast stretch was used sequentially; and in [14] the multiscale top-hat transform by reconstruction was used. Although these algorithms improve the contrast of retinal images, new alternatives continue to be sought to better highlight the anatomical structures of the retina. This will help ophthalmologists to better diagnosis and follow up the eye disease that the patient.

This paper presents a novel retinal image contrast enhancement algorithm. The proposal is based on mathematical morphology operations. The morphological operation to reduce noise in images is called Open-Close Close-Open (OCCO) [2]. The morphological operation called Top-Hat transform is used in the contrast enhancement technique [19]. This technique improves the contrast of the images, but it also enhances the noises that may be present in the images. First, the OCCO filter is used to remove the noise present in the images. Second, multiple bright and dark features are extracted from the filtered image by the Top-Hat transform. Finally, the original image is enhanced by adding the bright areas and subtracting the dark areas previously adjusted by a weight.

The article is organized in 4 sections. Section 2 presents the morphological operations and the proposed algorithm for retinal image enhancement. Section 3 presents the visual and numerical results and Section 4 presents the conclusions of the work.

2 Proposed algorithm for retinal image enhancement

In this section some concepts of mathematical morphology are presented. The details of the algorithm are given below.

2.1 Basic concepts

Top-Hat transform is defined from morphological operations of dilation, erosion, opening and closing. Such operations are defined as follows:

i *Dilation and Erosion*: These are the basic operations of mathematical morphology [18]. They are defined as:

$$\delta_B(I)(u,v) = \max_{(x,y)\in B}(I(u-x, v-y)), \tag{1}$$

$$\varepsilon_B(I)(u,v) = \min_{(x,y)\in B}(I(u+x, v+y)), \tag{2}$$

where I is the original image, B is the flat structuring element and (u,v), (x,y) are the spatial coordinates of I and B.

ii *Opening*: To make the opening, first the image is eroded and secondly it is dilated using the same structuring element [19]. Morphological opening is defined as:

$$\gamma_B(I) = \delta_{\check{B}}(\varepsilon_B(I)), \tag{3}$$

where $\check{B}$ is the reflection of B.

iii *Closing*: To make the closing, first the image is dilated and then it is eroded using the same structuring element [19]. Morphological closing is defined as:

$$\phi_B(I) = \varepsilon_{\check{B}}(\delta_B(I)). \tag{4}$$

A structuring element is symmetrical if it is equal to its reflection, i.e. $B = \check{B}$.

Based on previous definition two Top-Hat operations can be defined:

i *White Top-Hat* (WTH): This is used to obtain the bright regions lost in the morphological opening [19]. WTH is defined as:

$$WTH_B(I) = I - \gamma_B(I), \tag{5}$$

where I is the original image, B is the structuring element and $\gamma_B(I)$ is the morphological opening.

ii Black Top-Hat (BTH): This is used to obtain the dark regions lost in the morphological closing [19]. BTH is defined as:

$$BTH_B(I) = \phi_B(I) - I, \tag{6}$$

where I is the original image, B is the structuring element and $\phi_B(I)$ is the morphological closing.

Finally, the Open-Close Close-Open[2] (OCCO) is introduced. It is applied intro an image to reduce noise. It is defined as:

$$OCCO_B(I) = \frac{1}{2}\gamma_B(\phi_B(I)) + \frac{1}{2}\phi_B(\gamma_B(I)). \tag{7}$$

2.2 Proposed algorithm

The proposal, which is based on mathematical morphology operations, strategically combines OCCO with multiscale Top-Hat. Such combination allows to perform image enhancement without introducing artifacts into the process. The pseudocode is shown in Algorithm 1. As it can be seen, it first applies OCCO filter to the original image. OCCO is used with a small structuring element to reduce noise. Then, features are extracted from the image by applying Top-Hat iteratively. Finally, the weighted maximum values of the bright scales are added to the original image and the weighted maximum values of the dark scales are subtracted from the original image. In this way, image enhancement is performed.

Algorithm 1 Open-Close Close-Open - Multi-scale Top-Hat for retinal image enhancement (OCCO-MTH)

Input: I: Original image, B: Structuring element B, G: Structuring element G, n: Number of iterations, ω: Contrast adjustment weight.
Output: I_E *(Enhanced image)*
Initialisation : B, G, n, ω
1: *Noise removal with OCCO filter* (Equation 7)
$OCCO = OCCO_B(I)$
2: **for** $i = 1$ to n **do**
3: *Multi-scale Top-Hat transform*
$TH_i = WTH_{G_i}(OCCO)$,
$BH_i = BTH_{G_i}(OCCO)$,
4: **end for**
5: *Calculation of the maximum areas of brightness and darkness.*
$MTH = \max_{1 \le i \le n}\{TH_i\}$,
$MBH = \max_{1 \le i \le n}\{BH_i\}$.
6: *Image enhancement calculation.*
$I_E = I + \omega \times MTH - \omega \times MBH$,
7: **return** I_E

3 Results

In this work, two different evaluation approaches are considered. The first one is a visual evaluation performed by two ophthalmologists. The other one is based on some performance metrics that allow to assess the quality of the processed images. In order to quantify the performance of the proposed algorithm, 397 color images from the public STructured Analysis of the Retina (STARE) [8] database were used. In the Fig. 1 it can be seen some retinal images from the STARE database.

OCCO-MTH was compared with the Histogram Equalization (HE), Contrast-limited adaptive histogram equalization (CLAHE) [23] and Multi-scale Top-Hat transform (MTH) [4] algorithms.

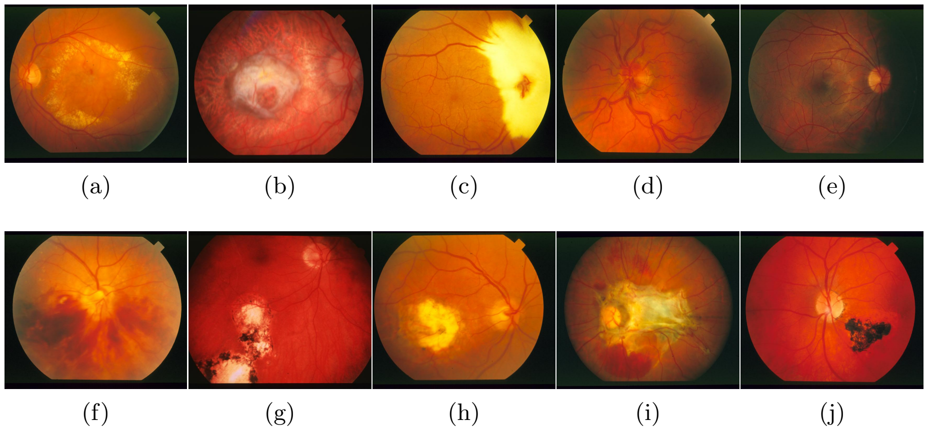


Fig. 1: STARE database retinographies.

The received and configurable parameters of the algorithms are: NumTiles: Number of rectangular contextual regions, clipLimit: Contrast enhancement limit, I: Original image, B: Radius r of the disk structuring element B, G: Radius r of the disk structuring element G, n: Number of iterations, ω: Contrast adjustment weight.

The settings of the different algorithms are presented in Table 1. The initial parameters of MTH and OCCO-MTH are: the original image I, the structuring element B disk with radius $r = 1$, the initial structuring element G disk with radius $r = 1$ which increases in a range of $i = \{1, ..., n\}$, the number of iterations $n = 10$ and $\omega = 1.5$ is the contrast adjustment weight. All the algorithms were implemented in MATLAB R2014a. HE does not use parameters and CLAHE uses a default configuration. The RGB images are first converted to the HSV color space, then the algorithms are applied in the V channel, and finally the enhanced image is converted back to RGB.

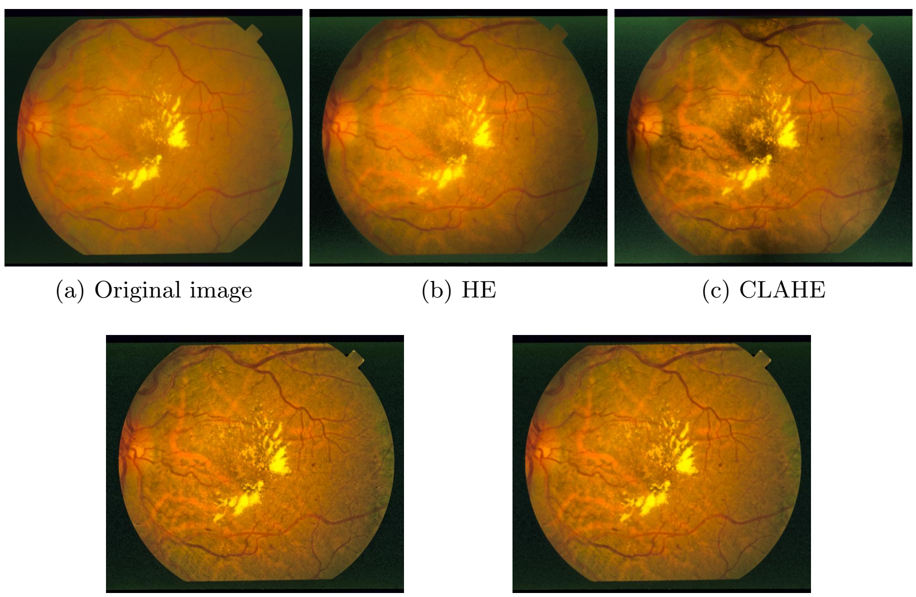
Table 1: Initial parameters of the algorithms HE, CLAHE, MTH and OCCO-MTH.

Algorithms	NumTiles	clipLimit	B	G	n	ω
HE	-	-	-	-	-	-
CLAHE	$[8, 8]$	0.01	-	-	-	-
MTH	-	-	1	1	10	1.5
OCCO-MTH	-	-	1	1	10	1.5

3.1 Visual analysis

The visual analysis was performed by two ophthalmologists who evaluated the images processed. Despite the subjectivity of this approach, it is the most common method nowadays.

In the Fig. 2 it can be seen images of diabetic retinopathy improved with the algorithms HE, CLAHE, MTH and OCCO-MTH. When the improvement is made, the choroidal vessels can be seen to be more enhanced. At the level of the retina, intraretinal hemorrhages, and microaneurysms can be seen more clearly, since they become darker, which facilitates the staging of the pathology. Also, the details of the retinal arterial and venous vascular wall can be better observed. The lipid exudates at the macular level are slightly more opaque in relation to the original image. However, in comparison with the other algorithms OCCO-MTH better preserves the original structure of the retinal image and distorts less in the enhancement process.

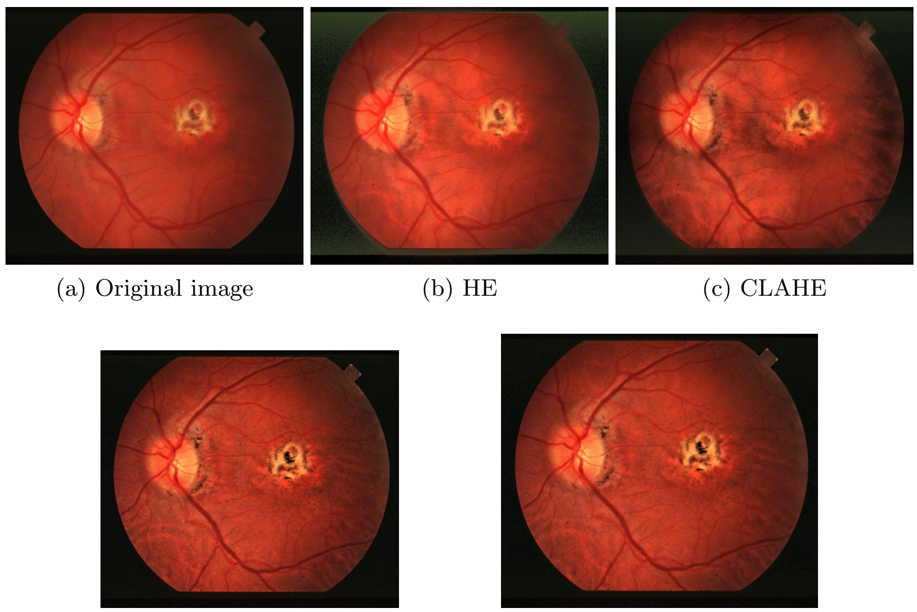


(a) Original image (b) HE (c) CLAHE

(d) MTH (e) OCCO-MTH

Fig. 2: Images with severe diabetic nonproliferative retinopathy.

In the Fig. 3 it can be seen macular scar retinographies improved with the HE, CLAHE, MTH and OCCO-MTH algorithms. By enhancing the image, greater contrast of the choroidal vessels can be observed; the pigment in the macular scar of chorioretinitis due to toxoplasmosis can be seen more defined and with clear limits at the edges of the lesion. Also, the pigment is enhanced at the central level of the scar and at the temporal edges of the optical papilla. The upper and lower temporal vascular arches are seen more clearly than in the original image. However, HE and CLAHE enhance the brightness in areas not seen in the original retinal image, MTH and OCCO-MTH improve retinal images, although the proposal introduces less distortions.



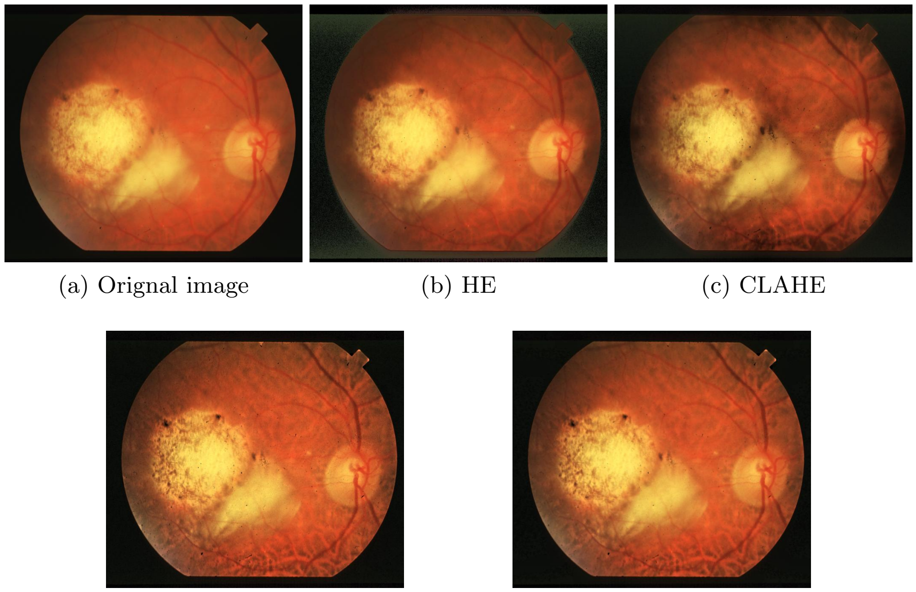
(a) Original image (b) HE (c) CLAHE

(d) MTH (e) OCCO-MTH

Fig. 3: Images of the macular scar of chorioretinitis by toxoplasmosis.

In the Fig. 4 it can be seen age-related macular degeneration retinographies, improved with the HE, CLAHE, MTH and OCCO-MTH algorithms. By improving the image, the contrast of the choroidal background and the enhancement of the vascular walls can be better appreciated. The macular lesion presents greater definition of the faint pigment at the edges of the lesion, as well as the retinal vessels. However, for this case the CLAHE introduces dark colors around the lesion.

In the Fig. 5 it can be seen age-related macular degeneration images improved with the HE, CLAHE, MTH and OCCO-MTH algorithms. By enhancing the image, the choroidal vessels are more clearly visible. At the level of the retinal vasculature, the vascular walls have greater clarity. The lipid exudates take on a dark color and at the end of the lower temporal arch there is an area of scar atrophy and fibrosis at the central level of the lesion. The target-like intraretinal bleeding located in the lower temporal arch has a darker coloration. However,



(a) Orignal image (b) HE (c) CLAHE

(d) MTH (e) OCCO-MTH

Fig. 4: Age-related macular degeneration.

OCCO-MTH preserves the structures of the image and visually it is appreciated a more smoothed image.

3.2 Numerical results

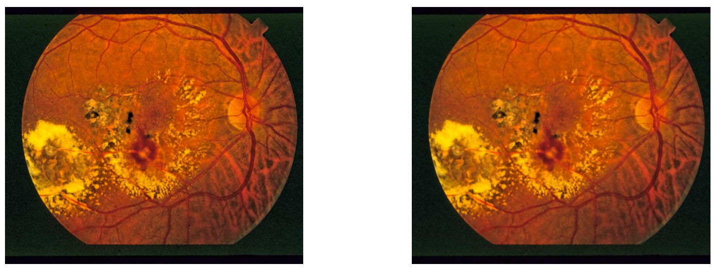
The image quality metrics used to evaluate the results are:

- Entropy (E): This metric is used to quantify the amount of information contained in the image [15, 10].
- Peak Signal-to-Noise Ratio (PSNR): This metric is used to quantify the amount of distortion introduced to the image in the enhancement process [9, 3].
- Structural Similarity Index (SSIM): This metric is used to quantify the similarity between the processed image and the original image [22, 16].

The metrics were applied to the V channel of the image obtained by the HE, CLAHE, MTH and OCCO-MTH algorithms.

As it can be seen in Table 2, OCCO-MTH presents better average results in PSNR and SSIM. However, CLAHE obtains better results in E. The best average results are highlighted in bold. This means that the algorithm improves the contrast without distorting the original image too much.

(a) Original image (b) HE (c) CLAHE



(d) MTH (e) OCCO-MTH

Fig. 5: Age-related macular degeneration images.

Table 2: Average results of the 397 retinal images processed with the HE, CLAHE, MTH and OCCO-MTH algorithms.

Algorithms	E	PSNR	SSIM
HE	5.821	17.128	0.777
CLAHE	**7.705**	18.175	0.820
MTH	7.259	29.552	0.771
OCCO-MTH	7.175	**32.115**	**0.895**

4 Conclusions

In this work, a novel retinal image enhancement algorithm was proposed. Through this algorithm, the image is improved by increasing the differentiation between the lesions, such as intra- and sub-retinal hemorrhages, and the choroidal background. This is due to the enhancement of the red-yellow spectrum of the image. The proposed algorithm enhances the color of the pigment in the retinographies, which facilitates the staging of lesions such as chorioretinitis scars, subretinal Drusen's accumulations, lipid or cottony intraretinal exudates, and provides greater clarity in the blood vessels of the retina and evaluation of their parietal profile.

OCCO-MTH was compared to algorithms used in improving retinal images. The numerical and visual results show contrast enhanced retinographies, similarity to the original image and low distortion with respect to the compared algorithms.

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