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Digital Signal Processing 14 (2004) 158–170
Digital Signal Processing
www.elsevier.com/locate/dsp

A simple and effective histogram equalization approach to image enhancement

H.D. Cheng * and X.J. Shi

Department of Computer Science, Utah State University, Logan, UT 84322-4205, USA

Abstract

Image enhancement is one of the most important issues in low-level image processing. Mainly, enhancement methods can be classified into two classes: global and local methods. In this paper, the multi-peak generalized histogram equalization (multi-peak GHE) is proposed. In this method, the global histogram equalization is improved by using multi-peak histogram equalization combined with local information. In our experiments, different local information is employed. Experimental results demonstrate that the proposed method can enhance the images effectively.

Keywords: Histogram equalization; Generalized histogram equalization (GHE); Image enhancement; Edge detection; Multi-peak GHE; Mammogram enhancement

1. Introduction

Image enhancement is one of the most important issues in low-level image processing. Its purpose is to improve the quality of low contrast images, i.e., to enlarge the intensity difference among objects and background. A lot of methods have been developed and they can mainly be divided into two classes: local and global methods.

Local methods employ feature-based approach and the local features can be gained by using edge operators or by computing local statistics such as local mean, standard deviation, etc. They conduct contrast enhancement by modifying the features [3,4,7–9,13–15, 17,20,22–25]. The common feature-based method is to define the contrast first and enhance image contrast by increasing the contrast ratio. Another method uses local histogram modification to enhance image contrast in a local area [1,2,6,11,16,19,21,26], such as: (1) local

* Corresponding author.
E-mail address: cheng@hengda.cs.usu.edu (H.D. Cheng).

1051-2004/$ – see front matter
doi:10.1016/j.dsp.2003.07.002

histogram equalization; (2) local histogram stretching; and (3) nonlinear mapping methods (square, exponential, and logarithmic function). The main idea is to define a local function for each pixel (x_0, y_0) based on the neighboring pixels within a small window centered at this pixel:

$$I_0(x_0, y_0) = f\big(I(x, y)\big).$$

They are quite effective in local texture enhancement. However, they may distort original images since the transformation is not a monotonic mapping and the order of gray levels of the original image may be changed greatly.

Global methods are mainly implemented by using histogram modification approaches. One of the most commonly used methods is histogram equalization (HE). The main idea of HE-based methods is to re-assign the intensity values of pixels to make the intensity distribution uniform to utmost extent [5,10,12,18]. Suppose that the original image is normalized and the range of its intensities is $[0, 1]$, and $p(x)$ is the density function of intensity distribution of the original image, where x denotes the intensity value of the normalized image. The desired density function of intensity distribution of the output image is equal to 1 after equalization, i.e., HE formula is

$$y = \int_0^x p(u)\,du, \tag{1}$$

where y is the intensity of the output image, x the intensity of the input image, and u is a dummy variable. Both x and y are in $[0, 1]$.

HE is simple and effective in enhancing the low contrast image only if (a) it contains single object or (b) no apparent contrast change between object and background. Since the above conditions cannot be always met, the global methods have both over-enhancement and under-enhancement problems. To overcome the above drawbacks, various modifications have been developed [10,12,18]. Suppose that the range of gray levels is $[x_0, x_L]$, one or more mid-nodes x_i $(i = 1, 2, \ldots, L-1)$ was determined by the values of mean, median or the number of peaks in the image histogram. The original histogram is partitioned into segments between $[x_i, x_{i+1}]$, and they will be equalized piecewise and independently. This method is called multi-peak HE [12] that can only slightly improve HE method, and still has the drawbacks of HE.

The proposed multi-peak GHE method is very effective not only in enhancing the entire image but also in enhancing the textural details. It also makes the change of the order of gray levels of the original image completely controllable. Therefore, it can enhance images more effectively.

2. Mathematical description

Equation (1) is for continuous cases. For digital image $\mathcal{A}$ with size of $M \times N$, we have

$$p(x) = \frac{\sum_{i=1}^{M \times N} \delta(x, x_i)}{M \times N}, \tag{2}$$

where

$$\delta(x,y)=\begin{cases}1, & x=y,\\ 0, & x\neq y,\end{cases} \quad \text{and} \quad x\in[x_0,x_L],$$

x representing the intensity.

In multi-peak GHE approach, the function will be generalized. It depends not only on intensities $u(x,y)$, but also on the local information $v(x,y)$ of each pixel (x,y). It is described as

$$g(x,y)=f\big(u(x,y),\ v(x,y)\big). \tag{3}$$

$p(g(x,y))$ is the density function, and it can be described in short

$$p(g)=h\big(f(u,v)\big). \tag{4}$$

The principle of multi-peak GHE technique is to modify the multi-peak HE method by performing multi-peak histogram equalization based on the newly defined density function $p(g(x,y))$. The block diagram of multi-peak GHE method is shown in Fig. 1.

The local information could be an edge value obtained by the edge operators such as Laplacian operator, Sobel operator, etc., or could be any local statistic value associated with the distribution of the gray levels in a small window. To make the change of the order of the gray levels of the original image completely controllable, the range of the value $v(x,y)$ is normalized and shifted to the range $[-0.5, 0.5]$, then Eq. (3) can be re-written as

$$p(x,y)=u(x,y)+w(x,y)\times v(x,y), \tag{5}$$

where $w(x,y)$ is the weight of the edge values. By adjusting the value $w(x,y)$, the change of the order of the gray levels will be completely under the control.

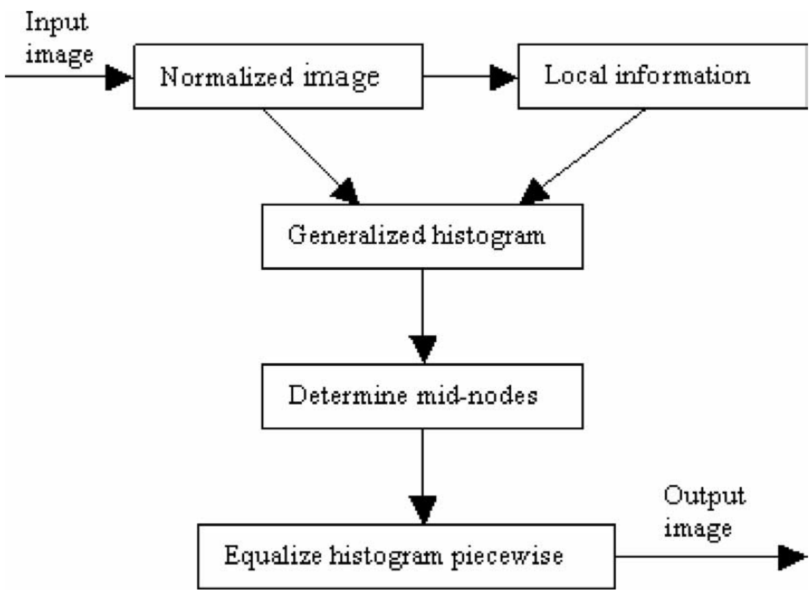


Fig. 1. The block diagram of the proposed approach.

3. Implementation of the proposed algorithm

To implement Eq. (5), the function $v(x, y)$ and its weight $w(x, y)$ should be determined first. Suppose that $I(x, y)$ is the intensity value of the point (x, y) in the original image, and the Laplacian operator calculates the edge value:

$$V(x, y) = \frac{\partial^2 I(x, y)}{\partial x^2} + \frac{\partial^2 I(x, y)}{\partial y^2}. \tag{6}$$

Commonly used discrete formula approximating to Eq. (6) is

$$V(x, y) = I(x, y) \times 9 - \sum_{i=-1}^{1} \sum_{j=-1}^{1} I(x+i,\ y+j). \tag{7}$$

Local mean of a window with size $(2m+1) \times (2m+1)$ is used to enhance mammogram (Fig. 4), Eq. (7) will be

$$V(x, y) = \frac{1}{m \times m} \sum_{i=-m}^{m} \sum_{j=-m}^{m} I(x+i,\ y+j). \tag{7$'$}$$

The weight $w(x, y)$ is

$$w(x, y) = \frac{\alpha}{I_{\max} - I_{\min}}, \tag{8}$$

where $I_{\max} = \max\{I(x, y) \mid (x, y) \in \mathcal{A}\}$ and $I_{\min} = \min\{I(x, y) \mid (x, y) \in \mathcal{A}\}$, α is a constant, and $\alpha > 0$. It is the distortion factor to control the change of the order of the gray levels.

3.1. Multi-peak GHE algorithm

Suppose the range of the gray-level values of the image $\mathcal{A}_{\text{out}}$ is $[G_{\min}, G_{\max}]$. The multi-peak GHE algorithm consists of the following steps:

1. Calculate the edge values $V(x, y)$ using Eq. (7).
2. Get the values of $u(x, y)$ and $v(x, y)$ by normalizing $I(x, y)$ and $V(x, y)$ as

$$u(x, y) = \frac{I(x, y) - I_{\min}}{I_{\max} - I_{\min}}, \tag{9}$$

$$v(x, y) = \begin{cases} -\frac{1}{2}\left(\frac{V(x, y)}{V_{\min}}\right)^{\beta}, & V(x, y) < 0, \\ \frac{1}{2}\left(\frac{V(x, y)}{V_{\max}}\right)^{\beta}, & V(x, y) \geqslant 0, \end{cases} \tag{10}$$

where $V_{\max} = \max\{V(x, y) \mid (x, y) \in \mathcal{A}\}$ and $V_{\min} = \min\{V(x, y) \mid (x, y) \in \mathcal{A}\}$, and β is the enhancement factor, $0 \leqslant \beta \leqslant 1$. If $\beta > 1$, it will be de-enhanced.
If using local mean, Eq. (10) will become

$$v(x, y) = \left(\frac{V(x, y) - V_{\min}}{V_{\max} - V_{\min}}\right)^{\beta}. \tag{10$'$}$$

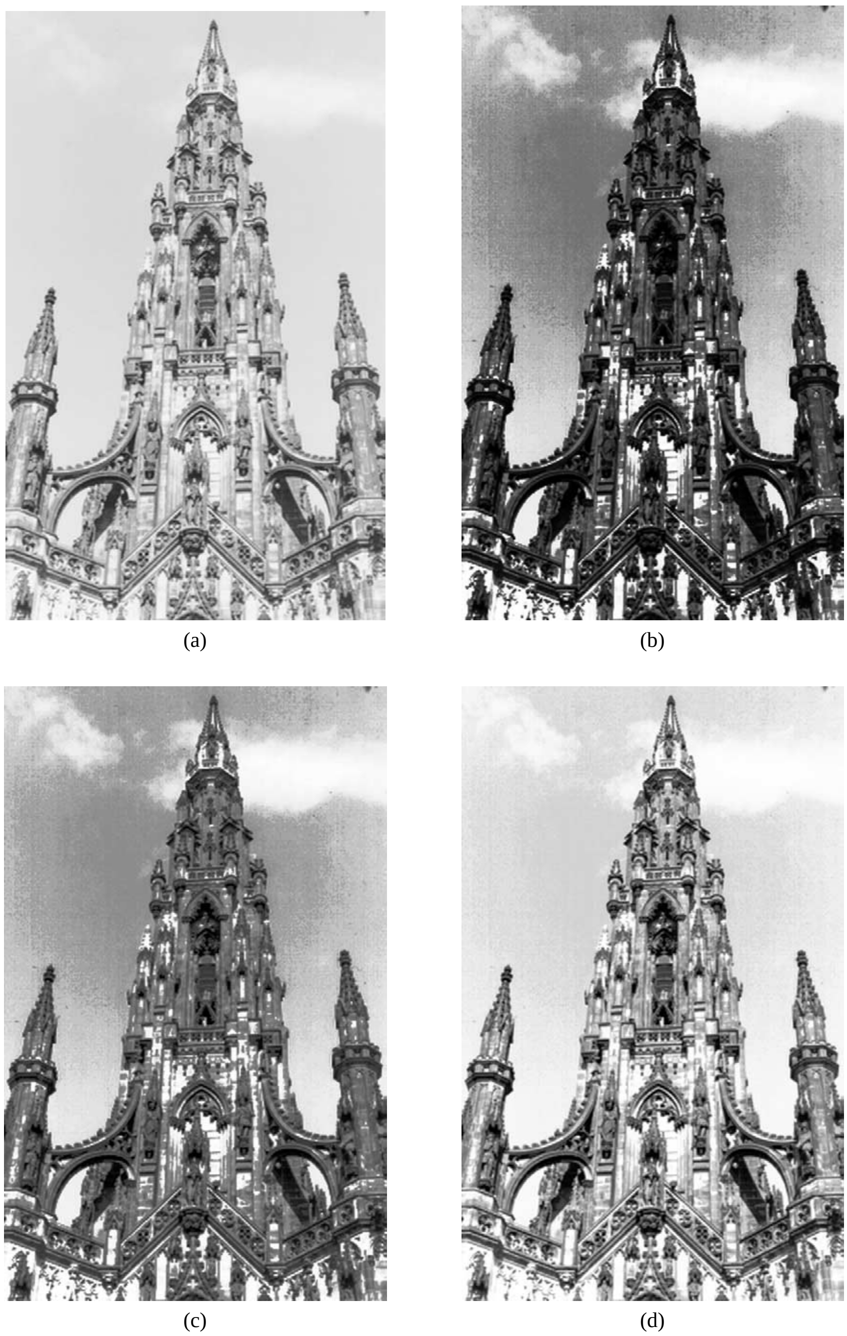


Fig. 2. The comparison of enhancement using different approaches. (a) Original image, (b) HE, (c) multi-peak HE, (d) multi-peak GHE ($\alpha = 30$, $\beta = 0.1$), (e) original image, (f) HE, (g) multi-peak HE, and (h) multi-peak GHE.

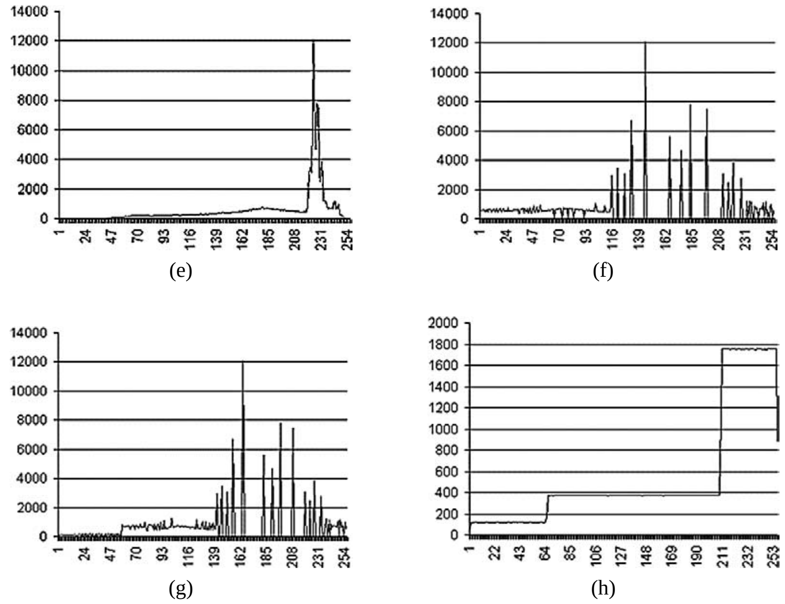


Fig. 2. (Continued.)

3. Calculate the values $p(x, y)$ using Eqs. (5), (8), (9), and (10) for every pixel.
4. Map the range of $p(x, y)$ into $[G_{\min}, G_{\max}]$,

$$G(x, y) = G_{\min} + \big(p(x, y) - p_{\min}\big)\frac{G_{\max} - G_{\min}}{p_{\max} - p_{\min}}, \tag{11}$$

   where $p_{\max} = \max\{p(x, y) \mid (x, y) \in \mathcal{A}\}$ and $p_{\min} = \min\{p(x, y) \mid (x, y) \in \mathcal{A}\}$.
5. Calculate the histogram $H(p)$ based on the values $G(x, y)$.
6. Since the histogram $H(p)$ is very noisy, we need to remove the noise, and we use the method in [27] to smooth the histogram.
7. Computing the local minimums, $\{p_i,\ i = 1, \ldots, m-1\}$, and let $p_0 = G_{\min}$, $p_m = G_{\max}$.
8. Equalize the histogram $H(p)$ piecewise and independently according to the segments between p_i and p_{i+1} $\{i = 0, 1, \ldots, m-1\}$. Finally, output the enhanced image.

4. Determine the parameters

The order of gray levels of the original image is completely controlled by the value of distortion factor α. For two pixels with original gray levels g_1 and g_2, respectively, the difference between these two pixels in step 4 of multi-peak GHE algorithm, can be derived from Eqs. (5), (8), (9), (10), and (11), that is

$$\begin{aligned} G_2 - G_1 &= (p_2 - p_1) \times \text{Const} \\ &= \left((u_2 - u_1) + \frac{\alpha}{I_{\max} - I_{\min}}(v_2 - v_1)\right) \times \text{Const} \end{aligned}$$

Fig. 3. The comparison of enhancement using different approaches. (a) Original image, (b) HE, (c) multi-peak HE, (d) multi-peak GHE ($\alpha = 50$, $\beta = 0.01$), (e) original image, (f) HE, (g) multi-peak HE, and (h) multi-peak GHE.

$$= \big((I_2 - I_1) + \alpha(v_2 - v_1)\big) \times \text{Const1}, \tag{12}$$

where

$$\text{Const} = \frac{G_{\max} - G_{\min}}{p_{\max} - p_{\min}} \quad \text{and} \quad \text{Const1} = \frac{\text{Const}}{I_{\max} - I_{\min}}.$$

First, suppose that $I_2 > I_1$, we will have

$$I_2 - I_1 \geqslant 1. \tag{13}$$

Second, v_1 and v_2 are in $[-0.5, 0.5]$, therefore

$$|v_2 - v_1| \leqslant 1. \tag{14}$$

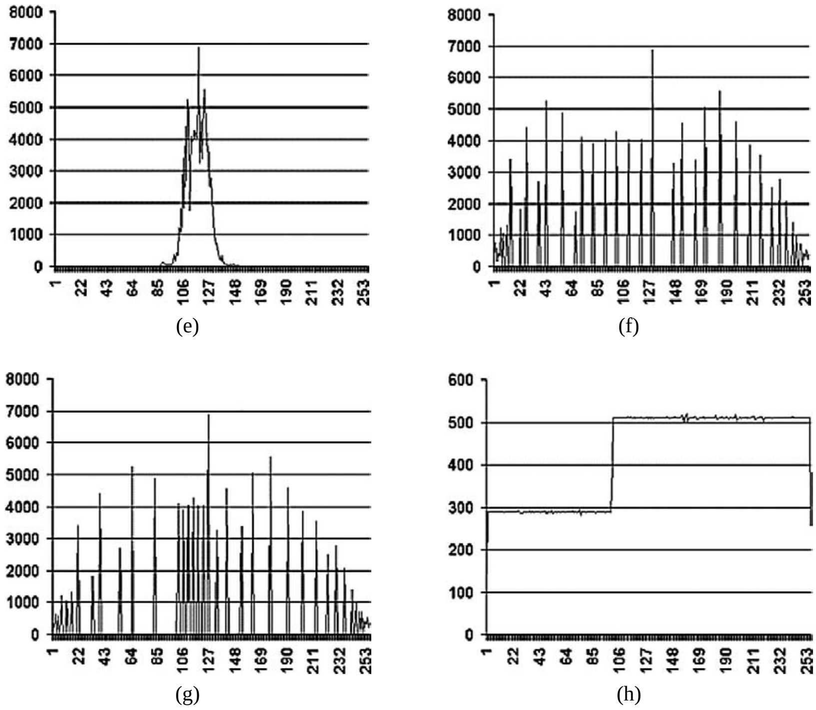


Fig. 3. (Continued.)

Finally, the multi-peak GHE method could change the order of the gray levels of the original image if Const1 > 0 in Eq. (12).

Therefore, the following cases can be discussed:

(1) $\alpha = 0$. The local information has no contribution to texture enhancement. The algorithm becomes multi-peak HE in [11,12,19]. Especially, if step 6 of multi-peak GHE algorithm is skipped, it becomes the standard HE.
(2) $\alpha \leqslant 1$. The order of the gray levels of the original image will be preserved. When $\alpha = 1$, image texture can be enhanced to the utmost extent without change the original order.
(3) $\alpha > 1$. The greater the value α is, the stronger the enhancement. However, if α is too big, the order of gray levels of the original image could be changed considerably (i.e., $G_2 < G_1$). The output image could be distorted apparently and over-enhanced heavily.

Another parameter is the factor β in Eqs. (10) and (10′). It is a power-law transformation to enhance/de-enhance the image. It will enhance the image when $\beta < 1$. The smaller the factor β, the greater the enhancement. It will de-enhance or blur the image when $\beta > 1$.

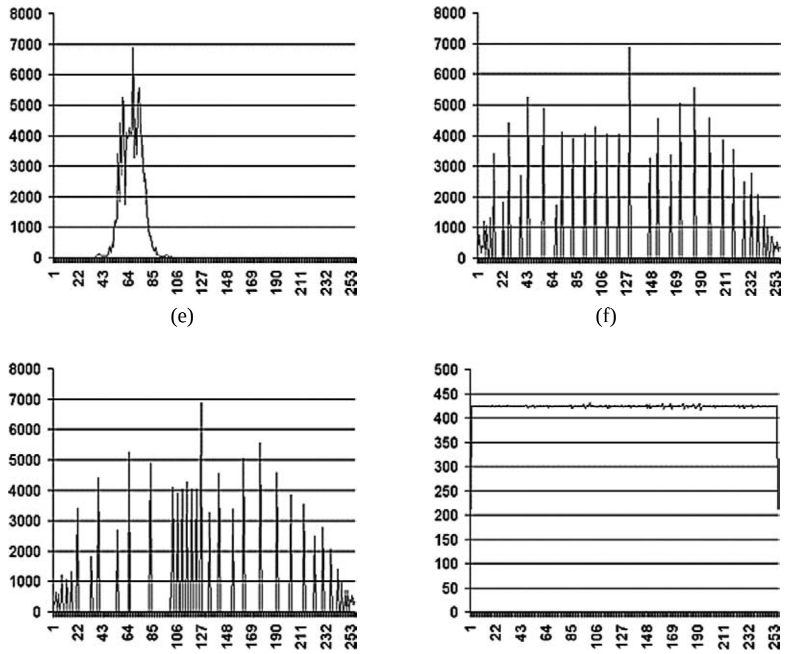
Generally, in order to obtain the desired result quickly, we will use a fixed value of $\beta (= 0.5)$ first. Then the value α is adjusted to get a better enhanced image. Finally, with the obtained value α, the value β will be finely turned to improve the performance.

(a) (b) (c) (d)

Fig. 4. The comparison of enhancement using different approaches for a dark image. (a) Original image, (b) HE, (c) multi-peak HE, (d) multi-peak GHE ($\alpha = 50$, $\beta = 0.01$), (e) original image, (f) HE, (g) multi-peak HE, and (h) multi-peak GHE.

5. Experimental results and discussion

In our experiments, the range of the gray-level values of the images is $[0, 255]$. A lot of images have been enhanced by the proposed approach. The results demonstrate that the proposed approach can enhance images effectively. It is especially effective for the images with narrow intensity distributions, i.e., their histograms have very narrow peaks. In Figs. 2–5, (a) is the original image, (b) the result of standard HE, (c) the result of the multi-peak HE, and (d) the result of the multi-peak GHE, respectively. With standard HE, the image may be over-enhanced as shown in Fig. 2b, or under-enhanced shown as Fig. 3b. By using the multi-peak HE, the output images are slightly improved. However, due to the fact that the local information is not used in this method, the image texture is not enhanced as nicely as those in (d).



(e) (f) (g) (h)

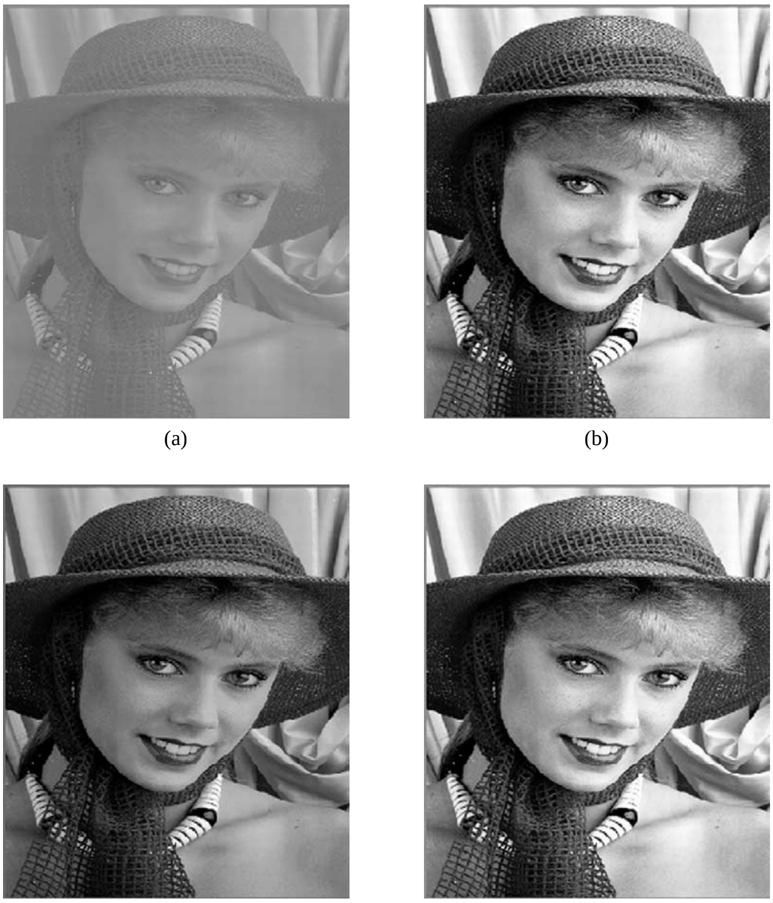
Fig. 4. (Continued.)

The castle in Fig. 2a is over-bright and blurry. The cloud is over-enhanced and some regions become too dark in (b) and (c). The statuaries on the castle in (b) and (c) are even more blurry than that in the original image (a). However, the cloud in Fig. 2d is more clear than that in (a) with no over- or under-enhancement such as in (b) or (c). It also makes statuaries more clear.

In order to confirm the observation that the proposed approach works well for the image with a histogram having a narrow peak no matter the image is dark or bright, we generate dark or bright images Fig. 3a and Fig. 4a from the original image Fig. 3a.

For the images in Figs. 3–5, with the standard HE, the left part of the hat is too dark as shown in (b). With the multi-peak HE, the texture on the left part of hat is improved, but the hair in (c) is a little blur. By using the proposed method, we can overcome those problems and produce better images as shown in (d).

The histograms of all the above original images are very alike, i.e., intensity distributions are very narrow. While using the standard HE or multi-peak HE to enhance this kind of images, all the pixels with the same intensity value will have the same intensity in the resulting image. On the other hand, using multi-peak GHE, the pixels with the same intensity may have different values G (refer Eq. (11)) if they have different local information, and it will make the distribution more uniform. The histograms of standard HE or multi-peak HE are shown in (f) and (g). The number of gray levels in use could be less than that in the original image since two or more consecutive gray level values might be mapped into the same gray level value. In the histograms (h), all gray levels are in use. The intensity dis-



(a) (b) (c) (d)

Fig. 5. The comparison of enhancement using different approaches for a bright image. (a) Original image, (b) HE, (c) multi-peak HE, (d) multi-peak GHE ($\alpha = 50$, $\beta = 0.01$), (e) original image, (f) HE, (g) multi-peak HE, and (h) multi-peak GHE.

tribution is more uniform piecewise. Hence, much clear texture can be obtained by using the proposed method, especially when the images have very narrow intensity distribution. The proposed algorithm is very fast as well. For instance, it took 0.15 s for enhancing the gray level image with the size 512×512 by using Dell Dimension 8200 with Pentium III (2.2 GHz).

6. Conclusions

Image enhancement is one of the most important issues in low-level image processing. All the methods are based either on local information or on global information. A novel approach using both local and global information to enhance image is studied in this pa-

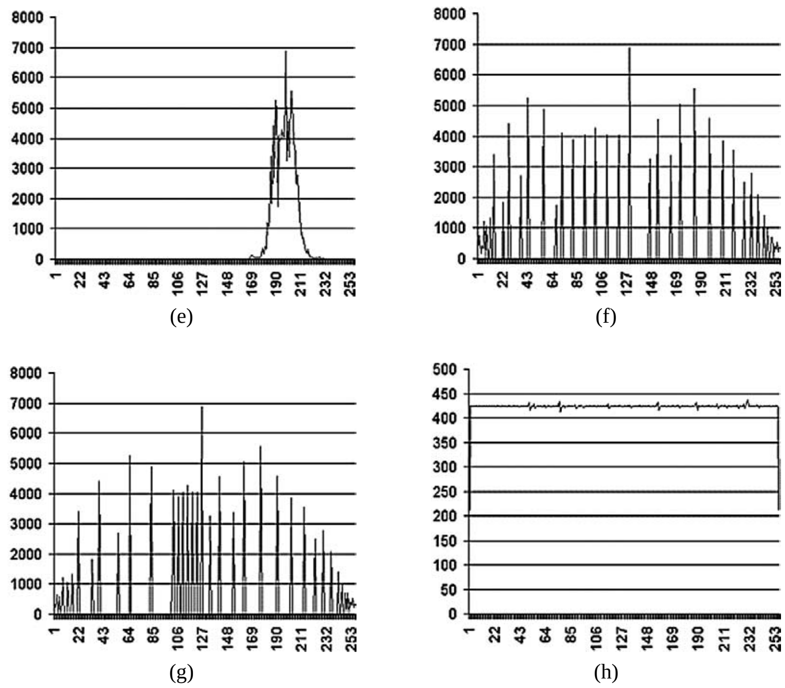


Fig. 5. (Continued.)

per. This method adopts the traits of existing methods. It also makes the degree of the enhancement completely controllable. Experimental results show that it is very effective in enhancing images with low contrast, regardless of their brightness. Multi-peak GHE technique is very effective to enhance various kinds of images when the proper features (local information) can be extracted.

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