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Intensity exposure-based bi-histogram equalization for image enhancement

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Abstract: In this paper, we present a study of the usage of intensity exposure in histogram segmentation and its performance in histogram equalization. Two techniques are proposed: the mean-based bi-histogram equalization plateau limit (mean-BHEPL) or median-based BHEPL (median-BHEPL) and adaptive bi-histogram equalization algorithm (ABHE). Both techniques initially divide the input histogram into two subhistograms through a threshold value computed from the intensity exposure of the image. Histogram clipping for mean-BHEPL and median-BHEPL is then performed on these subhistograms using the mean and median values, respectively. Conventional histogram equalization is also implemented on each clipped subhistogram. The second proposed technique, ABHE, applies the modified version of the adaptive histogram equalization algorithm (AHEA) on both subhistograms. Results of extensive simulations reveal that mean-BHEPL and median-BHEPL perform comparably to the conventional BHEPL technique. ABHE exhibits excellent performance in image quality, naturalness, and mean brightness preservation. However, it is slightly inferior in image detail preservation to the conventional AHEA technique. In conclusion, segmenting the input histogram through the threshold value calculated based on the intensity exposure of the image yields good enhancement results.

Key words: Histogram equalization, gray-scale image, histogram segmentation, histogram clipping, image details

1. Introduction

Current trends show that the use of visual information has become increasingly essential in our daily lives. Consequently, good-quality images are important, and image enhancement has attracted increasing attention in image processing. Conventional histogram equalization (CHE) is well known in image contrast enhancement. It works by stretching the dynamic range of histogram through gray-level remapping based on the cumulative density function (CDF) of the image [1]. Despite the simplicity and effectiveness of this technique, CHE has several disadvantages. One of these disadvantages is its inability to preserve the original brightness of the image. In addition, gray levels with relatively high frequency are often prioritized and overenhanced. Meanwhile, gray levels with fewer pixels are neglected, thereby resulting in the loss of information. The excessive merging of image gray levels may result in false contours, which may introduce artifacts and unnatural enhancement [2]. Moreover, CHE may cause saturation problems in which some local areas become excessively bright, thereby further degrading the visual quality of the image [3].

The earliest idea on conserving the mean brightness of the enhanced image was proposed by Kim [4]. The proposed brightness-preserving bi-histogram equalization (BBHE) technique segments the input histogram into two subhistograms using the mean brightness of the image, and the experimental results showed that BBHE

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successfully conserved the mean brightness of the image while decreasing the saturation effect and preventing unnatural enhancement and unwanted artifacts [5]. Dualistic subimage histogram equalization (DSIHE), which uses the median value as the separating threshold, was later proposed [1]. Following BBHE, recursive mean-separate histogram equalization (RMSHE) was proposed, in which the input histograms are segmented more than once using the mean value [6]. The generalization scheme of DSIHE, namely recursive subimage histogram equalization (RSIHE), was then proposed by Sim et al. [7]. RSIHE segments the input histogram using the median values. The limitations of RMSHE and RSIHE include the difficulty of defining the best value of the scale r. In addition, the number of subhistograms is always a power of two. Moreover, no enhancement occurs as r becomes relatively large because the output image appears the same as the input image [8].

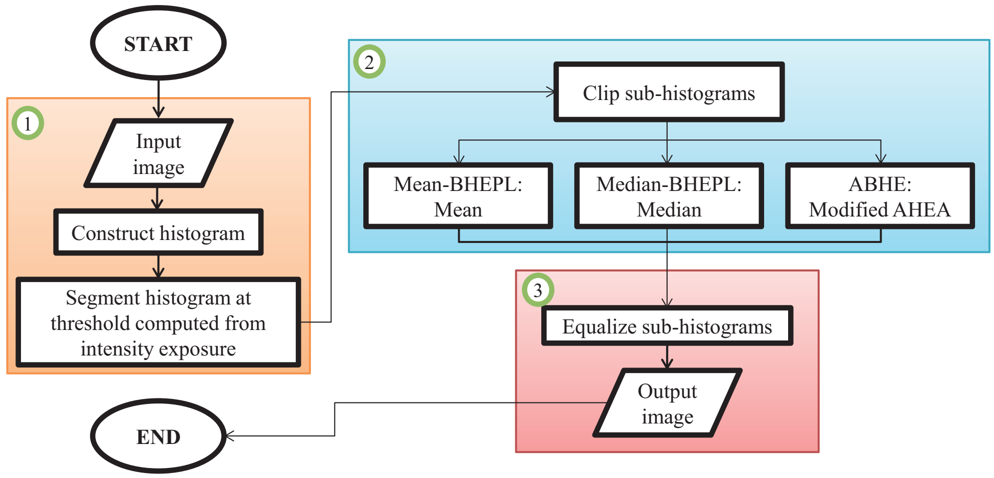
A number of works focused on overcoming the disadvantage of CHE in causing information loss. Entropy-based local histogram equalization for medical ultrasound image enhancement [9] implements the idea from local area histogram equalization [10], where modification is conducted with entropy as a control parameter. Abdullah proposed modified histogram equalization (MHE), which eliminates the domination of high-frequency histogram bins by changing the accumulations in the input histogram bins before applying CHE [11]. Zhu and Huang proposed adaptive histogram equalization algorithm (AHEA), which employs information entropy as target function [2].

Another approach used to improve CHE is histogram clipping. Because of the nature of CHE itself, which tends to emphasize high-frequency bins, it often leads to intensity saturation. The histogram stretching of high-frequency parts with squeezing of low-frequency parts occasionally pushes the intensities toward the lower or upper ends of the histogram. The concept of histogram clipping avoids this saturation effect by controlling the enhancement rate. Histogram bins are limited to the threshold value used. According to [5], the output image retains its mean brightness. Abdullah-Al-Wadud indirectly showed that histogram clipping also helps preserve the details in the image by eliminating the domination of high-frequency bins [11].

In our work, the first proposed technique is also based on histogram clipping and shares the idea applied in the bi-histogram equalization plateau limit (BHEPL) [5] and bi-histogram equalization median plateau limit (BHEPL-D) [12]. Both BHEPL and BHEPL-D combine the idea of BBHE with clipped histogram equalization. The difference between these two techniques is the plateau limits used (i.e. average number of intensity for BHEPL and the median of the occupied intensity for BHEPL-D). Ooi proved that segmenting the input histogram with the median value followed by clipping the subhistograms with the median value of the occupied intensity yields the best result, and this technique is referred to as brightness-preserving plateau limits histogram equalization (BPPLHE) [13].

This study investigates the effect of intensity exposure to determine the threshold value for histogram segmentation. All the proposed techniques segment the input histogram using the threshold value calculated from the intensity exposure of the input image. The first proposed technique, called the mean-BHEPL or median-BHEPL, uses the mean value for mean-BHEPL and the median value for median-BHEPL to clip the subhistograms. The second proposed technique is called the adaptive bi-histogram equalization algorithm (ABHE). First this technique separates the input histogram into two subhistograms, as in the case of the first proposed technique. A modified function of AHEA is then implemented to equalize the subhistograms.

The novelty of the proposed techniques is the replacement of the conventional techniques with intensity exposure to determine the threshold values (i.e. mean and median). The experimental results show that our proposed techniques have a comparable performance with the conventional techniques for both standard images and special cases (i.e. low-contrast and noisy images). The overall idea of the proposed techniques is shown in Figure 1.



* Note: 1=Histogram segmentation, 2=Histogram clipping, 3=Histogram equalization

Figure 1. Flowchart of the proposed techniques: mean-BHEPL, median-BHEPL, and ABHE techniques.

The rest of the paper is organized as follows: Section 2 presents the methodology of the first proposed techniques (i.e. mean-BHEPL and median-BHEPL). Section 3 then discusses the second proposed technique (i.e. ABHE) in detail. Section 4 presents results and discussions, and Section 5 concludes our work.

2. First proposed technique: mean-BHEPL or median-BHEPL

The first proposed techniques, called mean-BHEPL and median-BHEPL, apply the fundamental idea of BHEPL and BHEPL-D. Both the conventional BHEPL and BHEPL-D techniques use the average intensity to segment the input histogram. In general, not all images have good contrast, and their histograms usually do not occupy the entire dynamic range. For a relatively dark image, the gray levels are concentrated at the lower end of the histogram and vice versa. These extreme conditions of gray-level distribution in a histogram are more significant when the brightness of the image is uneven. Thus, the idea of intensity exposure was proposed in [14]. The threshold computed from the intensity exposure divides an image into underexposed and overexposed regions and hence provides information about applying a proper operator to separately enhance these regions. Motivated and inspired by the findings published in [15,16], we propose the mean-BHEPL and median-BHEPL techniques. Instead of using the input mean brightness to segment the histogram, as in the BHEPL and BHEPL-D techniques, the proposed techniques divide the input histogram using the threshold computed from the intensity exposure before histogram clipping and equalization are performed.

For a gray-level input image X, the probability density function (PDF) of the image, $p(k)$, is defined as:

$$p(k) = \frac{H(k)}{N}, \text{ for } k = 0, 1, \ldots, L-1 \tag{1}$$

where $H(k)$ is the histogram of the image for intensity k, L is the total number of gray levels, and N is the total number of pixels in the image. The summation of $p(k)$ is equal to 1.

The threshold value for histogram segmentation is then computed based on the intensity exposure of the input image. The intensity exposure of an image, E, is calculated based on the PDF, as defined in Eq. (2). The value of exposure is normalized in the range of [0, 1].

$$E = \frac{1}{L-1}\left[\sum_{i=0}^{L-1} p\left(i\right)\times i\right] \tag{2}$$

The intensity exposure is small for a dark image and large for a bright image because of the multiplication effect in Eq. (2). From this intensity exposure, the threshold value for histogram segmentation, Γ, can be defined as:

$$\Gamma = L\left(1-E\right) \tag{3}$$

As in Eq. (3), X-mirror projection indicates that the threshold and exposure values have an inverse correlation. A small exposure value means that the image generally appears dark. The threshold computed should therefore be large because it divides the large portion of the image into the dark region. In other words, given the inverse variation of the threshold value with the intensity exposure, a bright image with large intensity exposure value will have a small threshold value and vice versa. The threshold value divides the input image with a gray-level range [0, L-1] into two regions with gray levels [0, Γ-1] for the underexposed region and [Γ, L-1] for the overexposed region. Consequently, the input histogram is segmented into two subhistograms: the lower histogram $H_l(k)$ and the upper histogram $H_u(k)$. The PDF of each subhistogram is calculated using Eqs. (4) and (5):

$$p_l\left(k\right) = \frac{H_l\left(k\right)}{N_l},\ \text{for } k = 0,1,\ldots,\Gamma-1 \tag{4}$$

$$p_u\left(k\right) = \frac{H_u\left(k\right)}{N_u},\ \text{for } k = \Gamma,\Gamma+1,\ldots,L-1 \tag{5}$$

where N_l is the total number of pixels whose intensity is lower than or equal to the threshold value, and N_u is the total number of pixels whose intensity is greater than the threshold value. The summation of N_l and N_u gives the total number of pixels in the image, N.

Histogram clipping is then performed using the mean value for the mean-BHEPL and the median value for the median-BHEPL. The plateau limits for the mean-BHEPL are defined in Eqs. (6) and (7):

$$L_l = mean\left[p_l\left(k\right)\right],\ \text{for } k = 0,1,\ldots,\Gamma-1 \tag{6}$$

$$L_u = mean\left[p_u\left(k\right)\right],\ \text{for } k = \Gamma,\Gamma+1,\ldots,L-1 \tag{7}$$

For the median-BHEPL, the plateau limits are defined in Eqs. (8) and (9):

$$L_l = median\left[p_l\left(k\right)\right],\ \text{for } k = 0,1,\ldots,\Gamma-1 \tag{8}$$

$$L_u = median\left[p_u\left(k\right)\right],\ \text{for } k = \Gamma,\Gamma+1,\ldots,L-1 \tag{9}$$

With the plateau limits for each subhistogram, histogram clipping is then performed using Eqs. (10) and (11):

$$p_l = \begin{cases} p(k),\ \text{for } p(k) < L_l \\ L_l,\ \text{for } p(k) \geq L_l \end{cases} \tag{10}$$

$$p_u = \begin{cases} p(k), \text{ for } p(k) < L_u \\ L_u, \text{ for } p(k) \geq L_u \end{cases} \tag{11}$$

The CDF of the histogram, $c(k)$, is defined as:

$$c\left(k\right) = \sum_{i=0}^{k} p\left(i\right), \text{ for } k = 0, 1, \ldots, L-1 \tag{12}$$

The transfer function for CHE is then defined as:

$$f(k) = X_0 + (X_{L-1} - X_0) \cdot c(k) \tag{13}$$

where X_0 is the minimum gray level and X_{L-1} represents the maximum gray levels.

The same concept is applied for the clipped subhistograms in the proposed mean- and median-BHEPL techniques. After the clipping process, CHE is applied on the subhistograms using Eq. (14):

$$f(k) = \begin{cases} X_0 + (X_{\Gamma-1} - X_0) \cdot \sum_{i=0}^{k} p_l\left(i\right), & for \quad k = 0, 1, \ldots, \Gamma - 1 \\ X_\Gamma + (X_{L-1} - X_\Gamma) \cdot \sum_{i=\Gamma}^{k} p_u\left(i\right), & for \quad k = \Gamma, \Gamma + 1, \ldots, L-1 \end{cases} \tag{14}$$

The graphical illustration of the proposed mean- or median-BHEPL techniques is demonstrated in Figure 2, and the flowchart is shown in Figure 3.

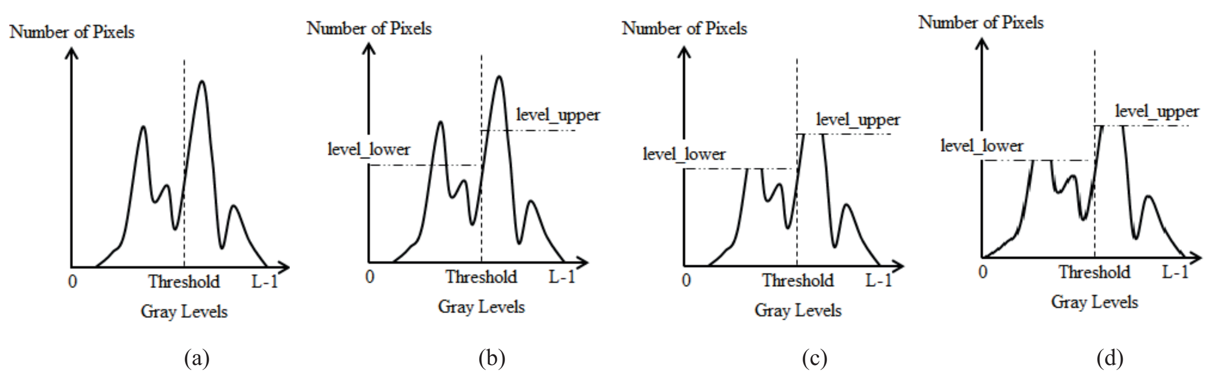


Figure 2. Implementation of the first proposed technique: (a) input histogram segmented with the threshold value calculated based on intensity exposure, (b) two plateau limits (i.e. mean value for mean-BHEPL and median value for median-BHEPL) for the lower and upper histograms, (c) subhistograms clipped with plateau limits, and (d) subhistograms equalized using CHE.

3. Second proposed technique: ABHE

The conventional AHEA does not implement histogram segmentation because it focuses on preserving image details. This technique has superior performance in its entropy measurement but it suffers from mean brightness shifting. Conventional AHEA may be improved through an additional step in ABHE, i.e. histogram segmentation. The effectiveness of histogram segmentation in preserving mean brightness is well demonstrated in the literature [1,5–7]. Thus, we propose the ABHE technique, which initially segments the input histogram into two subhistograms using the same method as the first proposed technique. A modified version of AHEA [2] is then used to equalize the subhistograms. Hence, the enhanced image is obtained. To obtain the threshold value for histogram separation, Eqs. (2) and (3) are employed so that the subhistograms are obtained based on the intensity exposure of the image. A modification is then performed for the conventional AHEA to ensure that it can be applied in our proposed algorithm.

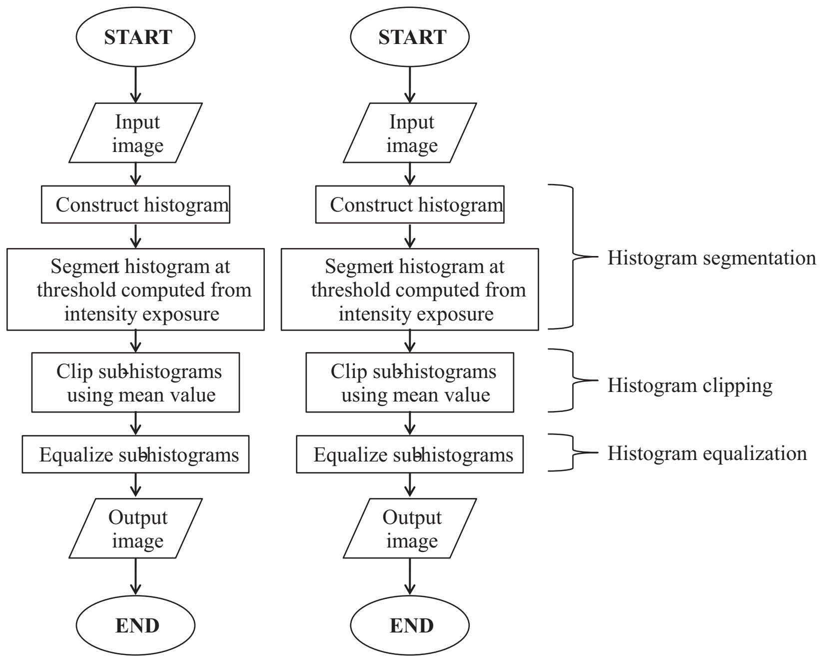


Figure 3. Flowchart of the proposed techniques: (a) mean-BHEPL and (b) median-BHEPL.

3.1. Conventional AHEA

In 2012, Zhu and Huang proposed conventional AHEA, which yields enhanced image with information entropy that remains the same [2]. Conventional AHEA introduces an adaptive parameter β, and the entropy of the image is used as the objective function to select the optimum value for β [17]. The implementation of histogram mapping is described below.

Despite using the conventional histogram, $H(k)$, as described in Eq. (1), the logarithmic mapping relationship of $H(k)$ is employed using Eq. (15) to enlarge the spacing between the two neighboring gray levels. With the logarithmic value of $H(k)$, the PDF is calculated and histogram mapping is performed using Eq. (16):

$$H\left(k\right)\_new = \log\left[H\left(k\right)+1\right] \tag{15}$$

$$j = (L-1)\left[\frac{\sum_{i=0}^{k-1} p(i)}{\sum_{i=0}^{k-1} p(i) + \beta \sum_{i=k+1}^{L-1} p(i)}\right], \beta \in (0, +\infty) \tag{16}$$

where j is the mapping value of gray-level k.

3.2. Modified AHEA

Conventional AHEA is modified to suit our proposed algorithm. Given that the threshold calculated based on intensity exposure divides the input image into underexposed and overexposed regions, the adaptive parameter β used in conventional AHEA is no longer suitable for implementation in our proposed algorithm. In ABHE, two adaptive parameters, β_1 and β_2, are required to equalize the lower histogram (i.e. the underexposed region) and the upper histogram (i.e. the overexposed region). From the experiments, the values of β_1 and β_2 are set to 0.75 and 1.50, respectively. These values are selected based on parameter testing and the details are demonstrated in the next section. The proposed ABHE technique first calculates the logarithmic mapping relationship of $H(k)$ using Eq. (15) and then performs the mapping for each subhistogram using Eq. (17).

$$j = \begin{cases} X_0 + [X_{\Gamma-1} - X_0] \times \left[\dfrac{\sum_{i=0}^{k-1} p(i)}{\sum_{i=0}^{k-1} p(i) + \beta_1 \sum_{i=k+1}^{\Gamma-1} p(i)} \right] & \text{for } k = 0, 1, \cdots, \Gamma - 1 \\ X_\Gamma + [X_{L-1} - X_\Gamma] \times \left[\dfrac{\sum_{i=\Gamma}^{k-1} p(i)}{\sum_{i=\Gamma}^{k-1} p(i) + \beta_2 \sum_{i=k+1}^{L-1} p(i)} \right] & \text{for } k = \Gamma, \Gamma + 1, \cdots, L - 1 \end{cases} \quad (17)$$

As such, the advantage of conventional AHEA is maintained by modification in ABHE. The initial idea of enhancing the image based on histogram distribution with a constant β is modified to enhance the image based on the intensity exposure of the image using β_1 and β_2 for the underexposed and overexposed regions, respectively.

3.3. Parameter testing for modified AHEA

As explained in [2], the adaptive parameter β for a relatively dark image should be less than 1 to improve the visual effect, whereas that for a relatively bright image, in which the gray levels are excessively grouped at the upper end of the histogram, should be greater than 1. Based on this concept, we varied the values of β_1 from 0.1 to 1.1 while fixing β_2 to 1.5 to obtain the suitable range for β_1, as presented in Figure 4a. Three evaluation functions, entropy, peak signal-to-noise ratio (PSNR), and absolute mean brightness error (AMBE), are employed to observe the effect of altering parameters β_1 and β_2. The details of these evaluation functions are shown in the following section.

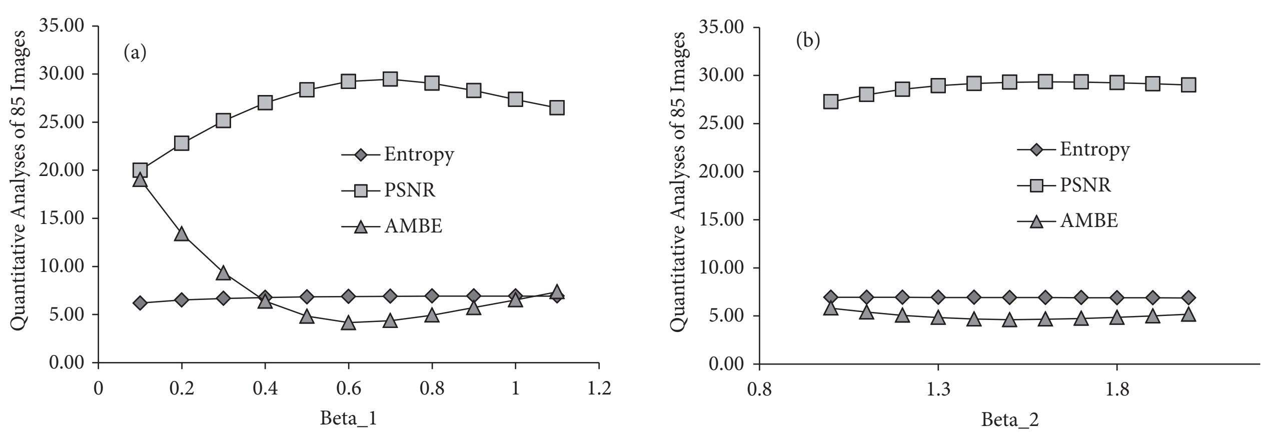


Figure 4. Quantitative analyses of 85 test images for various (a) β_1 and (b) β_2.

Varying the value of β_1 does not have a significant effect on the entropy values, although a slow rising trend is observed as β_1 increases, and the entropy value becomes stable as β_1 gets closer to 0.7. However, both PSNR and AMBE demonstrate a certain trend as β_1 increases. For PSNR, its value increases and reaches the maximum when β_1 approximates 0.7 and the value starts to decrease. By contrast, AMBE demonstrates a decreasing trend until it reaches its minimum value when β_1 is equal to 0.6. Therefore, the acceptable ranges for entropy, PSNR, and AMBE are [0.7, 1.0], [0.6, 0.8], and [0.5, 0.8], respectively. We can reasonably conclude that the suitable range to fulfill all three requirements is [0.7, 0.8]. To obtain the acceptable range for β_2, we fix β_1 at its optimum value, 0.75. In this study, the values of β_2 vary from 1 to 2, as shown in Figure 4b. The graphs show that the values for all three analyses performed demonstrate a stable trend at a common point where β_2 is equal to 1.5. Thus, the suitable range for β_2 must be greater than 1.5. Figure 5 demonstrates the flowchart of the proposed ABHE technique.

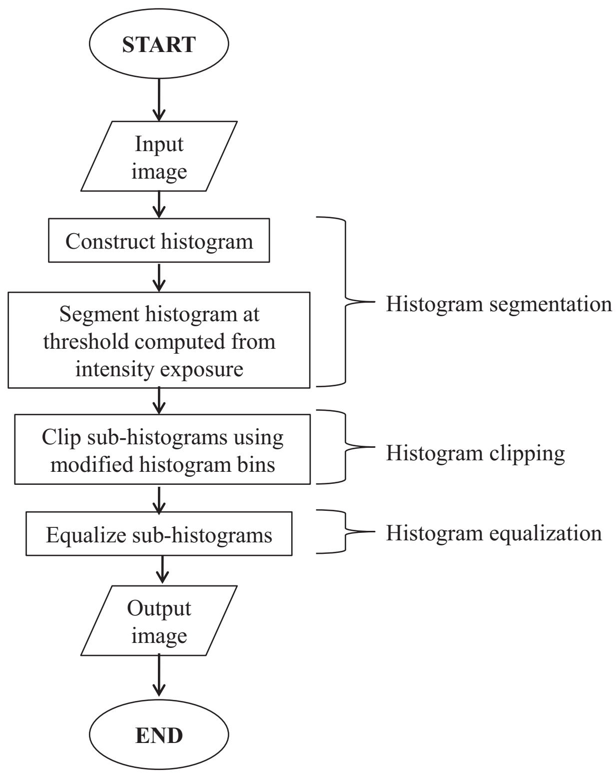


Figure 5. Flowchart of the proposed ABHE technique.

4. Results and discussion

The performances of the proposed mean- or median-BHEPL and ABHE techniques are tested with 85 images downloaded from a public image database, the CVG-UGR Image Database. Low-contrast images and noisy images are used to further investigate the performance of the proposed techniques. In addition to the proposed techniques, six other techniques are implemented for performance comparison. These techniques are RSIHE [7], MHE [11], AHEA [2], BHEPL [5], BHEPLD [12], and BPPLHE [13]. The scale r for RSIHE is set to 4. Three commonly used objective evaluation functions, entropy, PSNR, and AMBE, are employed to quantitatively investigate the performance of the proposed techniques.

The concept of entropy, introduced by Shannon [18], is widely used to evaluate the richness of the information contained in the image [12,19,20]. The higher the entropy value of an image, the greater the amount of information contained in the image. The entropy of a gray-level k is defined as:

$$e(k) = -p(k)\log_2 p(k) \tag{18}$$

Thus, the entropy of an image is the total of individual entropies at all gray levels, as defined in Eq. (19) [2]:

$$\text{Entropy } = \sum_{k=0}^{L-1} e(k) = -\sum_{k=0}^{L-1} p(k)\log_2 p(k) \tag{19}$$

The average percentage of entropy for the 85 test images is calculated using Eq. (20) for ease of comparison.

$$\text{Entropy\%} = \frac{\text{Entropy}_{\text{OutputImage}}}{\text{Entropy}_{\text{InputImage}}} \times 100 \tag{20}$$

One of the benchmark analyses, PSNR, is employed to evaluate the performance of the proposed mean- or median-BHEPL and ABHE techniques in terms of contrast enhancement and overall visual quality of the enhanced image .()[21].

The proposed techniques should generally be able to enhance the contrast of the resultant image while maintaining its natural look. The enhancement should neither amplify the noise level in the image nor create an undesired artifact in the output image. Apart from evaluating the degree of contrast enhancement in the image, PSNR is widely used to evaluate the quality gain between the input and output images [12,15,16,19,22–27]. A good quality image should possess a high PSNR value. The PSNR of an image is defined as:

$$PSNR = 10\log_{10}\left[\frac{(L-1)^2}{MSE}\right] \tag{21}$$

The mean square error (MSE) is the average square difference between the input and the output image as described in Eq. (22):

$$MSE = \frac{1}{N}\sum_{u}\sum_{v}\left|X(u,v) - Y(u,v)\right|^2 \tag{22}$$

where $X(u,v)$ is the intensity of the input image at position(u,v), and$Y(u,v)$ is the intensity of the output image at the same position.

In terms of mean brightness preservation, AMBE is used as the objective function because it directly measures the absolute difference between the output and input mean brightness. Many studies use AMBE to evaluate the ability of a technique in preserving brightness [5,8,12,19,21,27,28]. Given that it is a measurement of error, the desired value for the AMBE of a resultant image should be small and ideally zero. AMBE can be calculated using Eq. (23):

$$AMBE = \left|\overline{U} - \overline{V}\right| \tag{23}$$

where $\overline{U}$ and $\overline{V}$ are the mean intensity of the input and the output images, respectively.

Apart from these three objective evaluation functions, execution time is also calculated because it serves as a yardstick to investigate the complexity of the proposed algorithms. All the techniques are implemented on Intel Core i5 CPU 3.30 Ghz using MATLAB R2010a. The shorter the execution time required, the simpler the algorithms to be implemented.

4.1. Standard images

Three randomly selected images from the standard image database (*Bottle*, *Sailboat*, and *Fish*), as shown in Figures 6a–6c, are used for qualitative analysis. The resultant images enhanced with the proposed and other state-of-art techniques are shown in Figures 7–9. The first test image, *Bottle*, in Figure 7, obviously indicates that the proposed ABHE technique produces the result that appears to be the most similar to the input image. Their brightness levels do not differ widely, and this finding is supported by the minimum AMBE value obtained among all the other techniques. Although ABHE does not produce the largest entropy value, it successfully preserves details. This finding can be observed from the label on the bottle, which remains readable. Compared with the resultant image enhanced with other techniques, the image enhanced with ABHE indicates that the edge of the circle on the label can be clearly seen. No saturation effect occurs in the resultant image enhanced with ABHE. However, for the image enhanced with MHE, the edge of the circle becomes blurred. In addition, the petals of the sunflower in the image enhanced with ABHE, which is highlighted with boxes, demonstrate fine detail with relatively clear edges. The enhanced image of ABHE looks natural. This finding is significant when we observe the appearance of the sunflower and bottle. The image enhanced with ABHE is not overenhanced like the image enhanced with CHE, and these findings are proven by the highest PSNR value.

(a) Entropy = 7.46 (b) Entropy = 7.22 (c) Entropy = 6.02

Figure 6. Input test images: (a) *Bottle*, (b) *Sailboat*, and (c) *Fish*.

By contrast, the proposed mean-BHEPL and median-BHEPL perform similarly to the conventional BHEPL and BHEPL-D techniques. This finding shows that instead of using the mean or median value in histogram segmentation, using the threshold value calculated from intensity exposure is applicable because it gives comparable output results. In addition to comparable output results, both the mean-BHEPL and median-BHEPL techniques require similar execution time as the conventional BHEPL and BHEPL-D techniques to achieve the same output results. Thus, this finding indicates that the complexity of the proposed technique and that of the conventional techniques do not significantly differ.

For the second test image, *Sailboat*, the resultant image enhanced with the proposed ABHE technique outperforms all the images enhanced with other techniques in terms of detail preservation, except for AHEA, which is particularly designed for entropy preservation. All the numbers on the sail in the image enhanced with ABHE can be clearly read, as highlighted with boxes. Although the numbers in the images enhanced with other techniques are legible, they are not as clear as those in the image enhanced with ABHE. Moreover, the line on the sail highlighted with boxes can only be observed in the image enhanced with ABHE. This finding is due to the optimal degree of contrast enhancement introduced by ABHE. Furthermore, the resultant image enhanced with the ABHE technique is closest to the input image in terms of brightness. It has the lowest AMBE value.

In addition, ABHE yields the most natural-looking image. This finding can be observed in terms of the smoothness of the sky and the sail. The image enhanced with ABHE has relatively smooth regions. Nearly all the techniques are generally able to give enhanced images with good image contrast. However, the images are

(a) Entropy = 7.33; PSNR = 23.93; AMBE = 5.43; Exe. Time = 0.73 s

(b) Entropy = 7.21; PSNR = 12.99; AMBE = 48.40; Exe. Time = 0.52 s

(c) Entropy = 7.41; PSNR = 21.91; AMBE = 18.16; Exe. Time = 0.53 s

(d) Entropy = 7.38; PSNR = 24.36; AMBE = 5.85; Exe. Time = 0.55 s

(e) Entropy = 7.39; PSNR = 27.88; AMBE = 2.66; Exe. Time = 0.54 s

(f) Entropy = 7.40; PSNR = 26.66; AMBE = 3.68; Exe. Time = 0.57 s

(g) Entropy = 7.38; PSNR = 24.36; AMBE = 5.85; Exe. Time = 0.53 s

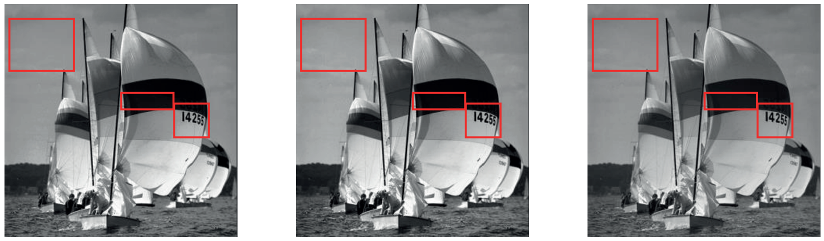
(h) Entropy = 7.39; PSNR = 27.88; AMBE = 2.66; Exe. Time = 0.56 s

(i) Entropy = 7.34; PSNR = 37.79; AMBE = 0.11; Exe. Time = 0.55 s

Figure 7. Test image (i.e. *Bottle*) enhanced with (a) RSIHE, (b) MHE, (c) AHEA, (d) BHEPL, (e) BHEPL-D, (f) BPPLHE, (g) proposed mean-BHEPL, (h) proposed median-BHEPL, and (i) proposed ABHE.

overenhanced until they lose their naturalness. The ability of ABHE in producing natural-looking images with sufficient contrast enhancement is strongly supported by its highest PSNR value, which is approximately 40 dB (i.e. a processed image with good quality delivers PSNR values within 30 dB and 40 dB [29]).

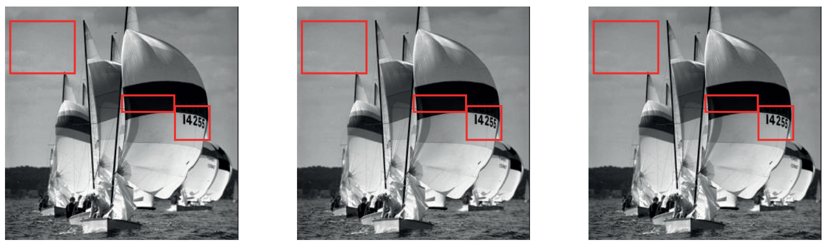
For *Sailboat*, the first proposed mean-BHEPL and median-BHEPL techniques yield results comparable with those of the conventional BHEPL and BHEPL-D techniques. Entropy, PSNR, and AMBE values with mean-BHEPL are equal to those of the conventional BHEPL technique, whereas the median-BHEPL technique retains as many details as BHEPL-D. Although median-BHEPL loses to BHEPL-D in terms of PSNR value,



(a) Entropy = 6.97; PSNR = 23.80; AMBE = 0.95; Exe. Time = 0.71 s

(b) Entropy = 7.00; PSNR = 16.95; AMBE = 8.74; Exe. Time = 0.51 s

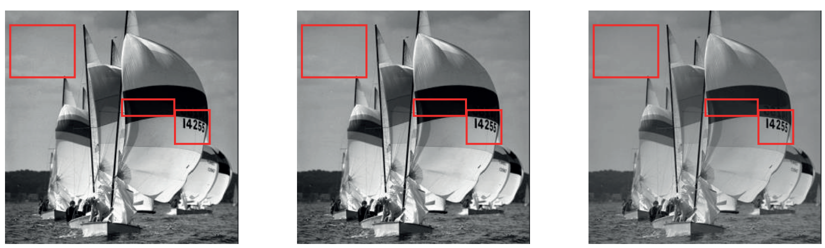
(c) Entropy = 7.21; PSNR = 27.16; AMBE = 7.51; Exe. Time = 0.51 s



(d) Entropy = 7.12; PSNR = 21.79; AMBE = 4.90; Exe. Time = 0.55 s

(e) Entropy = 7.15; PSNR = 23.14; AMBE = 2.15; Exe. Time = 0.54 s

(f) Entropy = 7.15; PSNR = 23.53; AMBE = 0.98; Exe. Time = 0.54 s



(g) Entropy = 7.12; PSNR = 21.79; AMBE = 4.90; Exe. Time = 0.53 s

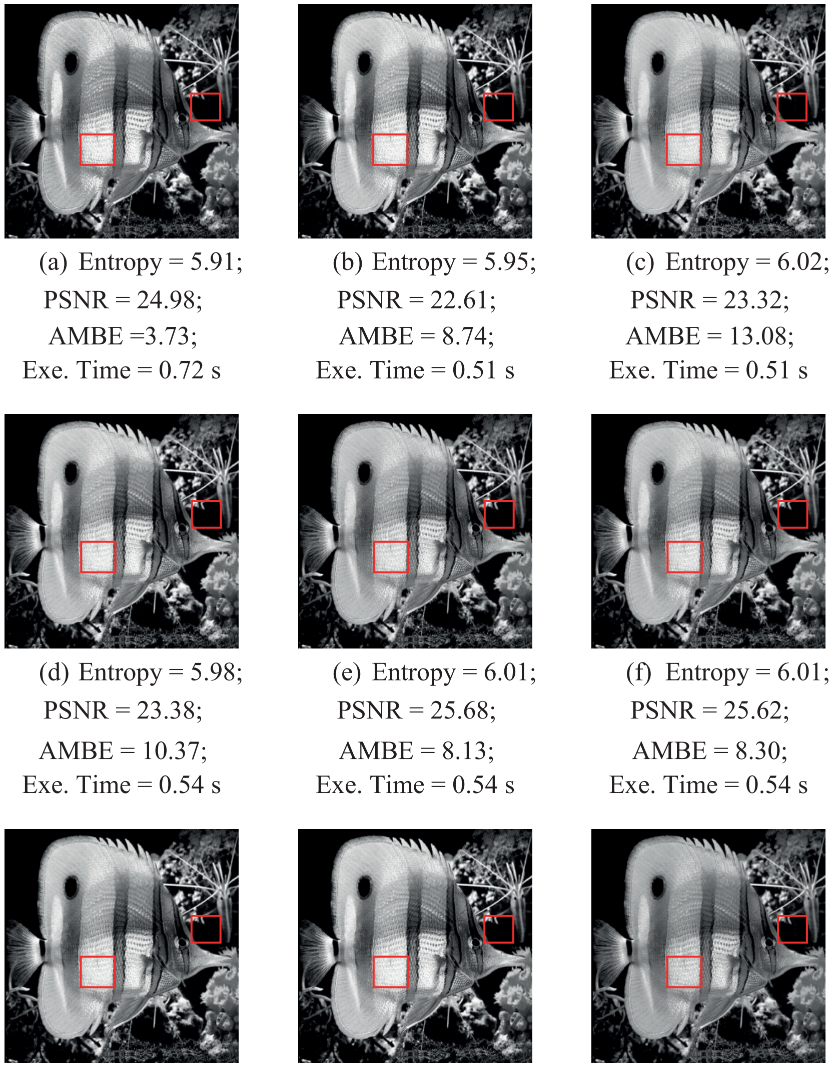
(h) Entropy = 7.15; PSNR = 23.06; AMBE = 1.99; Exe. Time = 0.55 s

(i) Entropy = 7.19; PSNR = 39.99; AMBE = 0.68; Exe. Time = 0.54 s

Figure 8. Test image (i.e. *Sailboat*) enhanced with (a) RSIHE, (b) MHE, (c) AHEA, (d) BHEPL, (e) BHEPL-D, (f) BPPLHE, (g) proposed mean-BHEPL, (h) proposed median-BHEPL, and (i) proposed ABHE.

the difference is extremely small. Thus, the noise level is not significantly amplified compared with BHEPL-D. Median-BHEPL is slightly better than conventional BHEPL-D in terms of mean brightness preservation. For this test image, their execution time is approximately the same. Thus, the findings prove that segmenting the input histogram using the threshold based on intensity exposure is workable, given that the resultant images are at least as good as those enhanced with the conventional techniques.

The third test image, *Fish*, in Figure 6c, is an example of an image with many details. The proposed ABHE technique successfully prevents the saturation effect. The saturation effect can be observed in all the resultant images except for the image enhanced with ABHE. In such images, the fish scale, as highlighted in



(a) Entropy = 5.91; PSNR = 24.98; AMBE =3.73; Exe. Time = 0.72 s

(b) Entropy = 5.95; PSNR = 22.61; AMBE = 8.74; Exe. Time = 0.51 s

(c) Entropy = 6.02; PSNR = 23.32; AMBE = 13.08; Exe. Time = 0.51 s

(d) Entropy = 5.98; PSNR = 23.38; AMBE = 10.37; Exe. Time = 0.54 s

(e) Entropy = 6.01; PSNR = 25.68; AMBE = 8.13; Exe. Time = 0.54 s

(f) Entropy = 6.01; PSNR = 25.62; AMBE = 8.30; Exe. Time = 0.54 s

(g) Entropy = 5.99; PSNR = 23.65; AMBE = 8.98; Exe. Time = 0.53 s

(h) Entropy = 5.97; PSNR = 22.87; AMBE = 10.07; Exe. Time = 0.59 s

(i) Entropy = 6.02; PSNR = 33.67; AMBE = 2.50; Exe. Time = 0.57 s

Figure 9. Test image (i.e. *Fish*) enhanced with (a) RSIHE, (b) MHE, (c) AHEA, (d) BHEPL, (e) BHEPL-D, (f) BPPLHE, (g) proposed mean-BHEPL, (h) proposed median-BHEPL, and (i) proposed ABHE.

boxes, is excessively bright until the whole region appears white in color. Moreover, in terms of mean brightness preservation, only the image enhanced with ABHE appears similar to the input image. Its brightness is not far from that of the input image (i.e. has high capability in mean brightness preservation), and this finding is proven by the lowest AMBE value. Compared with all the images enhanced with the other techniques, the image enhanced with ABHE looks the most natural because the contrast is not enhanced to the point that the image appears to be too artistic. The promising performance of ABHE in yielding natural-looking images without amplifying the noise in the images is supported by its highest PSNR value, which is in the range of a good-quality image (i.e. within 30 dB to 40 dB) [29].

The findings on the performance of the proposed techniques for the three test images, *Bottle*, *Sailboat*, and *Fish*, when compared with the findings on the performance of the other nine techniques are encouraging, particularly those of the second proposed technique, ABHE. Therefore, to further investigate the performance of the proposed mean- or median-BHEPL and ABHE techniques, all the techniques are tested with 85 test images from the CVG-UGR Image Database. The aforementioned objective evaluation functions are employed again, and their average values are presented in Table 1. The best value for each analysis is set in boldface.

Table 1. Average values of the objective evaluation analyses for 85 standard images.

Techniques	Entropy (bits)	Entropy (%)	PSNR (dB)	AMBE	Exe. time (s)
RSIHE	6.80	97.72	23.22	4.91	0.54
MHE	6.89	99.01	19.22	18.79	0.39
AHEA	**6.94**	**99.74**	21.04	18.71	0.39
BHEPL	6.90	99.15	21.80	8.20	0.41
BHEPL-D	6.49	92.45	21.42	14.47	0.41
BPPLHE	6.56	93.58	22.18	11.95	0.47
Mean-BHEPL	6.90	99.18	22.21	8.26	0.41
Median-BHEPL	6.90	99.25	22.82	7.95	0.43
ABHE	6.92	99.47	**29.29**	**4.61**	0.40

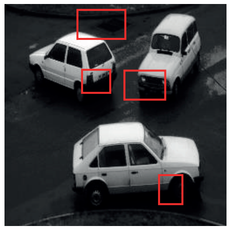
4.2. Special cases: low-contrast and noisy images

In addition to standard images, we tested the capability of our proposed techniques for several special cases to investigate their robustness in handling low-contrast and noisy images. Low-contrast images are created by restricting the input histogram to half of the intensity range, so that the distribution of the histogram is limited to either the first or second half of the entire intensity range. In other words, dark images are created by restricting the histogram distribution in the range of 0 to 128 (i.e. the first half of the intensity range), whereas bright images have a histogram distribution ranging from 128 to 255 (i.e. the second half of the intensity range). For both cases, the histograms of the images do not cover the entire intensity range. Thus, the contrast of the images is low. Apart from low-contrast images, we created noisy images by adding Gaussian noise of zero mean and 0.01 variance to the standard images. A test image is randomly selected for each of these three special cases, the dark image *Cars*, the bright image *Tank*, and the noisy image *Couple*, as shown in Figure 10. The enhanced images are shown in Figures 11–13.

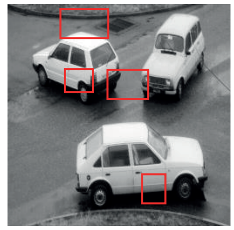
(a) Entropy = 5.99 (b) Entropy = 4.87 (c) Entropy = 7.62

Figure 10. Low-contrast and noisy test images: (a) dark image *Cars*, (b) bright image *Tank*, and (c) noisy image *Couple*.

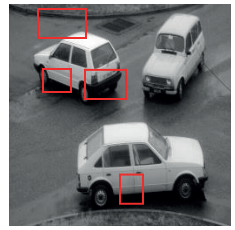
The test image in Figure 10a, *Cars*, demonstrates low contrast, given that the entire image appears dark. The effect of overenhancement is significant in images enhanced with the MHE and AHEA techniques because



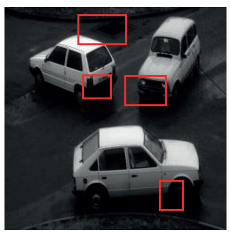
(a) Entropy = 5.82; PSNR = 15.36; AMBE = 17.75; Exe. Time = 0.21 s



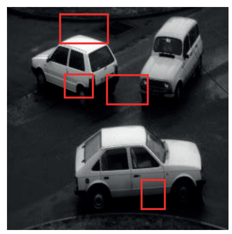
(b) Entropy = 5.97; PSNR = 9.14; AMBE = 81.33; Exe. Time = 0.13 s



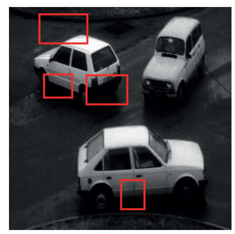
(c) Entropy = 5.99; PSNR = 11.10; AMBE = 64.89; Exe. Time = 0.15 s



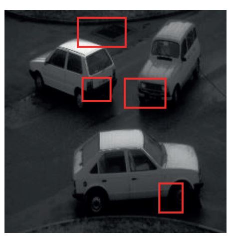
(d) Entropy = 5.94; PSNR = 17.50; AMBE = 12.00; Exe. Time = 0.15 s



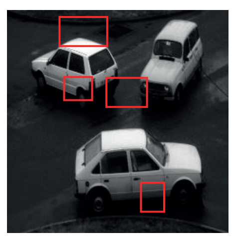
(e) Entropy = 5.95; PSNR = 16.95; AMBE = 14.40; Exe. Time = 0.33 s



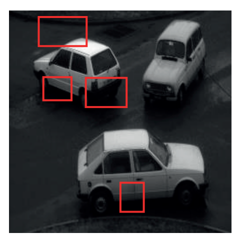
(f) Entropy = 5.96; PSNR = 16.88; AMBE = 14.61; Exe. Time = 0.26 s



(g) Entropy = 5.89; PSNR = 22.88; AMBE = 9.76; Exe. Time = 0.14 s



(h) Entropy = 5.96; PSNR = 17.09; AMBE = 13.15; Exe. Time = 0.28 s



(i) Entropy = 5.97; PSNR = 19.97; AMBE = 9.47; Exe. Time = 0.14 s

Figure 11. Test image (i.e. *Cars*) enhanced with (a) RSIHE, (b) MHE, (c) AHEA, (d) BHEPL, (e) BHEPL-D, (f) BPPLHE, (g) proposed mean-BHEPL, (h) proposed median-BHEPL, and (i) proposed ABHE.

their resultant images are significantly and excessively bright compared with the input image. This observation is supported by their large AMBE values. Saturation effects can be observed in most of the resultant images (i.e. images enhanced with BHEPL, BHEPL-D, and BPPLHE), except for the images enhanced with the proposed techniques. The highlighted boxes show the effect of saturation, which includes the tires and front parts of the cars. The edges of these objects cannot be seen clearly because of saturation effects. As shown by the low-contrast test image *Cars*, our proposed techniques yield natural-looking images with high PSNR values. The images enhanced with the proposed techniques demonstrate the least inhomogeneity compared with the images enhanced with the other techniques. In fact, the proposed ABHE technique generates a resultant image

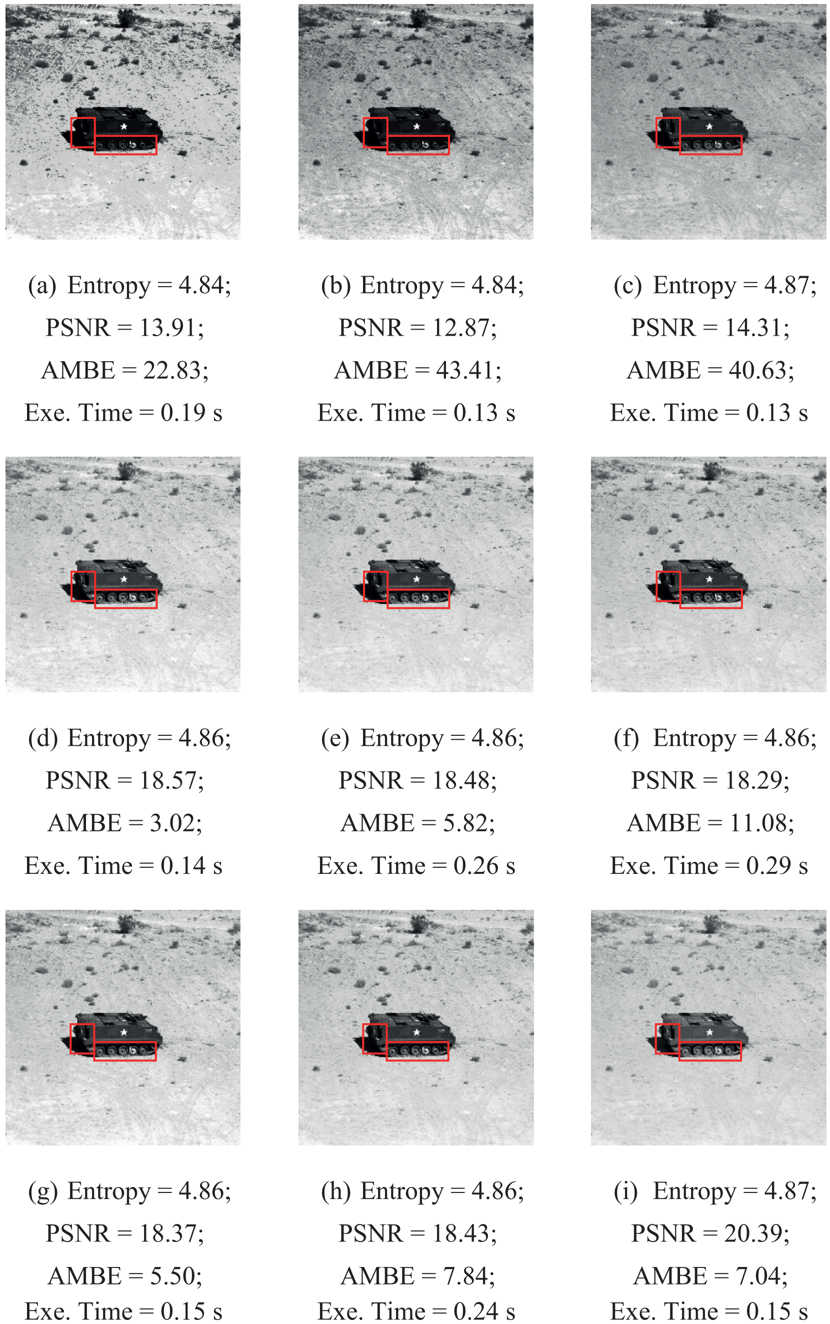
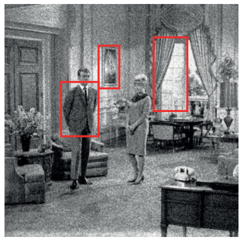


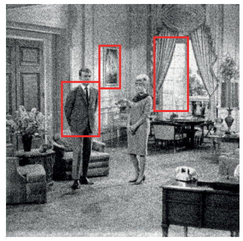
Figure 12. Test image *Tank* enhanced with (a) RSIHE, (b) MHE, (c) AHEA, (d) BHEPL, (e) BHEPL-D, (f) BPPLHE, (g) proposed mean-BHEPL, (h) proposed median-BHEPL, and (i) proposed ABHE.

with the highest PSNR value. In addition, the image enhanced with ABHE has the mean brightness nearest to that of the input image because it has the minimum AMBE value.

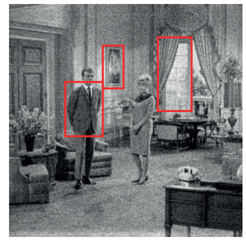
Figure 10b shows another example of a low-contrast image. Compared with the image in Figure 10a, the test image *Tank* in Figure 10b demonstrates low contrast as the image appears generally bright, which is contrary to the image in Figure 10a. Overenhancement leads to the loss of details in the image enhanced with RSIHE. The low entropy value compared with the entropy values of the other images and the findings



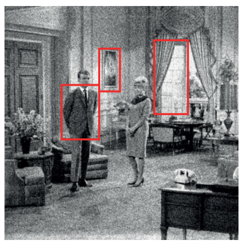
(a) Entropy = 7.45; PSNR = 25.56; AMBE = 2.16; Exe. Time = 0.72 s



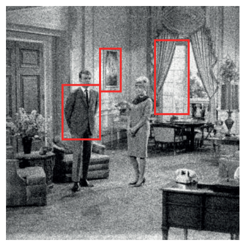
(b) Entropy = 7.50; PSNR = 22.86; AMBE = 8.02; Exe. Time = 0.52 s



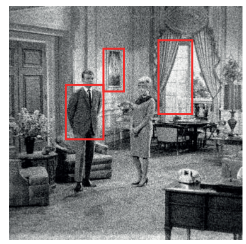
(c) Entropy = 7.59; PSNR = 33.53; AMBE = 1.83; Exe. Time = 0.51 s



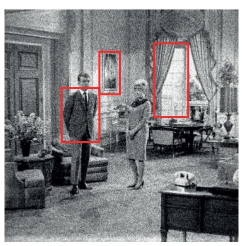
(d) Entropy = 7.50; PSNR = 23.45; AMBE = 3.80; Exe. Time = 0.54 s



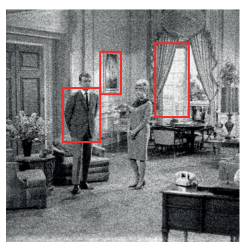
(e) Entropy = 7.52; PSNR = 24.80; AMBE = 3.65; Exe. Time = 1.03 s



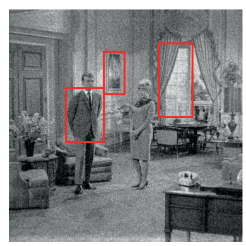
(f) Entropy = 7.52; PSNR = 25.09; AMBE = 2.43; Exe. Time = 1.05 s



(g) Entropy = 7.49; PSNR = 23.36; AMBE = 4.05; Exe. Time = 0.54s



(h) Entropy = 7.52; PSNR = 24.77; AMBE = 3.95; Exe. Time = 1.01 s



(i) Entropy = 7.49; PSNR = 39.80; AMBE = 0.06; Exe. Time = 0.58 s

Figure 13. Test image (i.e. *Couple*) enhanced with (a) RSIHE, (b) MHE, (c) AHEA, (d) BHEPL, (e) BHEPL-D, (f) BPPLHE, (g) proposed mean-BHEPL, (h) proposed median-BHEPL, and (i) proposed ABHE.

on the details of the image (i.e. tires of the tank) support our observation. The image enhanced with AHEA possesses the highest entropy value. However, this image demonstrates mean brightness, which is far from that of the input image. The resultant image is significantly darker than the input image. Our proposed techniques present comparable performance with the BHEPL, BHEPL-D, and BPPLHE techniques. The proposed mean- and median-BHEPL techniques have entropy and PSNR values that are approximately the same as those of these three techniques. The shadow of the tank, as highlighted in the boxes, reveals that saturation effects occur and lead to the loss of details. The proposed ABHE technique yields the resultant image with the highest entropy value, which is the same as that of the AHEA technique, which is particularly designed to preserve image entropy. It does not suffer from saturation effect. The highest PSNR of the image enhanced with ABHE proves that this technique amplifies the noise level in the image the least during enhancement. Based on the image background, the image enhanced with ABHE has the fewest nonhomogeneous regions among all the images enhanced with the other techniques.

For the last special case, the image *Couple* is corrupted by Gaussian noise, as shown in Figure 10c. The capability of noise removal of all the techniques appears to be similar. This observation may be attributed to the fact that these techniques are designed for contrast enhancement. Nevertheless, some differences exist among the resultant images. The proposed mean- and median-BHEPL techniques perform comparably with the BHEPL, BHEPL-D, and BPPLHE techniques. All the measurements (i.e. entropy, PSNR, and AMBE) are not far from one another. In terms of detail preservation, the highlighted boxes prove that the proposed techniques have the same capability as the conventional ones. This finding further proves the possibility of using the intensity threshold during histogram segmentation. Although the contrast enhancement of the resultant image enhanced with the proposed ABHE technique is slightly less than that of the other techniques, the proposed technique has increased robustness in handling noisy images. With the highest PSNR value, the ABHE technique produces an enhanced image with the least amplified noise when compared with the other techniques. The PSNR value of 39.80 dB proves that the resultant image has good quality because a processed image with good quality is known to deliver PSNR values within 30 dB to 40 dB. The nonhomogeneous regions are generally the least-enhanced regions with ABHE. Our proposed ABHE technique also yields the image whose mean brightness is closest to that of the input image, given that it has the lowest AMBE value.

The observations on both the qualitative and quantitative analyses of the three special cases show the robustness of the proposed techniques. For further justification, all techniques are tested with 85 corrupted images. Tables 2–4 show the average values of the 85 test images for low-contrast dark images, low-contrast bright images, and noisy images, respectively.

Table 2. Average values of the objective evaluation analyses for 85 low-contrast dark images.

Techniques	Entropy (bits)	Entropy (%)	PSNR (dB)	AMBE	Exe. time (s)
RSIHE	5.86	96.98	15.89	14.78	0.41
MHE	6.01	99.50	10.23	65.91	0.30
AHEA	**6.04**	**99.99**	10.27	70.46	0.30
BHEPL	5.98	99.00	15.25	21.90	0.32
BHEPL-D	5.99	99.21	14.78	24.32	0.57
BPPLHE	5.99	99.29	14.90	24.48	0.61
Mean-BHEPL	5.94	98.49	**23.93**	**7.06**	0.31
Med-BHEPL-D	5.99	99.19	14.81	24.12	0.57
ABHE	6.01	99.54	17.69	17.55	0.33

4.3. Overall discussion

Table 1 suggests that all the proposed techniques (i.e. the mean-BHEPL, median-BHEPL, and ABHE techniques) perform comparably to the other nine techniques. In terms of detail preservation, which can be observed from the entropy value, conventional AHEA outperforms all the other techniques because this technique particularly focuses on retaining the information entropy of the image. The proposed ABHE technique is ranked second, followed by the proposed median- and mean-BHEPL techniques in the third and fourth ranks. For overall image visual quality, the ABHE technique demonstrates the highest PSNR value, and this finding indicates that the images enhanced with ABHE have the least noise-amplifying effect, which leads to more natural-looking images. The mean- and median-BHEPL techniques produce good visual quality and preserve the high naturalness of the resultant images as these techniques ranked third and fourth in terms of PSNR values.

Table 3. Average values of the objective evaluation analyses for 85 low-contrast bright images.

Techniques	Entropy (bits)	Entropy (%)	PSNR (dB)	AMBE	Exe. time (s)
RSIHE	5.88	97.17	15.10	**18.55**	0.39
MHE	6.02	99.51	10.91	58.38	**0.29**
AHEA	**6.05**	**99.99**	9.96	74.58	0.30
BHEPL	6.01	99.29	15.01	21.42	0.31
BHEPL-D	6.02	99.43	14.40	24.70	0.55
BPPLHE	6.02	99.48	14.26	26.51	0.63
Mean-BHEPL	6.01	99.35	14.89	22.40	0.33
Med-BHEPL-D	6.02	99.43	14.29	25.65	0.54
ABHE	6.01	99.38	**16.61**	21.10	0.32

Table 4. Average values of the objective evaluation analyses for 85 noisy images.

Techniques	Entropy (bits)	Entropy (%)	PSNR (dB)	AMBE	Exe. time (s)
RSIHE	7.26	97.69	23.81	4.95	0.41
MHE	7.33	98.57	19.83	19.68	**0.28**
AHEA	**7.40**	**99.48**	24.80	14.21	0.29
BHEPL	7.33	98.57	22.91	6.27	0.29
BHEPL-D	7.34	98.76	24.53	4.68	0.53
BPPLHE	7.34	98.79	24.56	4.48	0.57
Mean-BHEPL	7.33	98.57	22.92	6.17	0.29
Med-BHEPL-D	7.34	98.76	24.54	4.60	0.54
ABHE	7.34	98.78	**36.58**	**1.74**	0.31

Moreover, the smallest AMBE value displayed by the proposed ABHE technique proves that the use of intensity exposure in histogram segmentation successfully retains the brightness of the input image. The AMBE values produced for the proposed mean- and median-BHEPL techniques are not the lowest ones (i.e. greater than that of RSIHE technique). However, the values are close to that of the conventional BHEPL technique and better than that of the conventional BHEPL-D technique. RSIHE focuses mainly on mean brightness preservation. This observation further supports the use of intensity exposure for histogram separation to maintain the mean brightness of the image. The excellent performance of ABHE compensates for its fourth rank in terms of execution time. The mean- and median-BHEPL techniques require an execution time similar to that of most of the other techniques. This observation shows that the use of intensity exposure to divide the input histogram does not greatly increase the complexity of the algorithm.

For low-contrast images, which include both dark and bright images, the quantitative analysis in Tables 2 and 3 reveals that our proposed techniques have comparable performance in detail preservation. Moreover, the proposed mean-BHEPL and ABHE techniques possess the highest PSNR values for dark and bright images, respectively. This finding indicates that our techniques do not significantly increase the noise level during the enhancement process, although the images appear to have low contrast. It also shows that the resultant images have a natural appearance with the fewest nonhomogeneous regions. In terms of mean brightness preservation, the mean-BHEPL technique outperforms all the other techniques in dark images with its lowest AMBE value. By contrast, our proposed ABHE technique is the second in preserving mean brightness. Although CHE is the fastest and easiest technique to implement, it has the worst performance in terms of detail preservation, mean brightness preservation, and image quality.

For noisy images, the performance in detail preservation of our proposed mean- and median-BHEPL techniques is similar to that of the conventional BHEPL and BHEPL-D techniques, as shown in Table 4. The proposed ABHE technique has the second highest entropy value, which shows that it is excellent in detail preservation. The ABHE technique also has the highest PSNR value, which is 32.2% higher than the second largest PSNR value. It is the only technique that produces a PSNR value greater than 30 dB (i.e. 36.58 dB). This finding shows that the quality of the image enhanced with ABHE is high, with the least amplified noise. Furthermore, the ABHE technique also yields images with the lowest AMBE value. Thus, the resultant images have the closest mean brightness to the input image.

4.4. Comparison between the proposed mean- or median-BHEPL technique and the conventional BHEPL and BHEPL-D techniques

The main difference between the proposed and conventional techniques is the threshold value used at the initial step, which is used to segment the input histogram. Histogram segmentation is performed to preserve the mean brightness of an image. A comprehensive study is conducted to observe the performance of the proposed techniques in using intensity exposure to determine the threshold value for histogram segmentation. Given that the mean- and median-BHEPL are modified versions of the BHEPL and BHEPL-D techniques, the comparison is focused on these techniques. From Table 1, mean-BHEPL performs similarly in terms of detail preservation, mean brightness preservation, overall image quality, and execution time. These observations indicate that segmenting the input histogram through the threshold calculated based on intensity exposure yields at least comparable output images. By contrast, median-BHEPL is better than the BHEPL-D technique in nearly all aspects. The entropy, PSNR, and AMBE values of median-BHEPL are better than those of the BHEPL-D technique, with slight compensation in execution time. The capability of the conventional BHEPL-D is improved in the proposed median-BHEPL technique.

4.5. Comparison between the proposed ABHE technique and the conventional AHEA technique

As discussed in Section 3, the resultant images enhanced with the conventional AHEA technique exhibit excellent performance in detail preservation. However, these images suffer from mean brightness shifting. The proposed ABHE technique preserves the capability of the conventional AHEA in retaining the details while improving its capabilities in other aspects. The performance of the proposed ABHE technique is compared with that of the AHEA technique. ABHE demonstrates superior performance in image visual quality and mean brightness preservation, with a slight compromise in detail preservation (i.e. entropy difference of 0.27%) and an improvement of 39.21% in PSNR and 75.36% in AMBE measurements for the standard test images. In addition to the standard test images, the images enhanced with the proposed ABHE technique outperform those enhanced with the conventional AHEA techniques for both low-contrast and noisy images. The additional step in ABHE leads to an additional 0.01 s in execution time for the standard test images. However, this step greatly contributes to mean brightness preservation. ABHE significantly outperforms the RSIHE technique, which is designed to maintain mean brightness.

5. Conclusion

In this work, we propose two techniques of bi-histogram equalization to investigate the use of intensity exposure as a preprocessing step before clipping and/or further equalizing the subhistograms. The findings suggest that the first proposed technique, mean- or median-BHEPL, generally demonstrates comparable performance with the conventional BHEPL and BHEPL-D techniques. The second proposed technique, ABHE, slightly compromises detail preservation when compared with the conventional AHEA technique. However, it shows an excellent performance in image visual quality, naturalness of image, and mean brightness preservation compared with all the other techniques. From these findings, we can conclude that the use of intensity exposure to calculate the threshold value for histogram segmentation is applicable for good enhancement results.

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