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An objective method to identify optimum clip-limit and histogram specification of contrast limited adaptive histogram equalization for MR images

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ABSTRACT

In contrast limited adaptive histogram equalization (CLAHE), the selection of tile size, clip-limit and the distribution which specify desired shape of the histogram of image tiles is paramount, as it critically influences the quality of the enhanced image. The optimal value of these parameters devolves on the generic of the image to be enhanced and usually they are selected empirically. In this paper, the degradation of intensity, textural and geometric features of the medical image with respect to the variation in clip-limit and specified histogram shape is analyzed. The statistical indices used to quantify the feature degradation are Absolute Mean Brightness Error (AMBE), Absolute Deviation in Entropy (ADE), Peak Signal to Noise Ratio (PSNR), Variance Ratio (VR), Structural Similarity Index Matrix (SSIM) and Saturation Evaluation Index (SEI). The images used for the analysis are axial plane MR images of magnetic resonance spectroscopy (MRS), under gradient recalled echo (GRE), diffusion weighted imaging (DWI) 1000b Array Spatial Sensitivity Encoding Technique (ASSET), T2 Fluid Attenuation Inversion Recovery (FLAIR) and T1 Fast Spin-Echo Contrast Enhanced (FS-ECE) series of pre-operative Glioblastoma-edema complex. The experimental analysis was performed using Matlab®. Results show that for MR images the exponential histogram specification with a clip-limit of 0.01 is found to be optimum. At optimum clip-limit, the mean of SSIM exhibited by the Rayleigh, uniform and exponential histogram specification were found to be 0.7477, 0.7946 and 0.8457, for ten sets of MR images and mean of variance ratio are 1.242, 2.0316 and 1.7711, respectively.

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1. Background

Contrast limited adaptive histogram equalization (CLAHE) [1] is an advanced version of adaptive histogram equalization (AHE) and it is meant to avoid over enhancement of noise. CLAHE divides the input image into non-overlapping blocks, called as tiles and enhances the blocks individually, rather than enhancing the image globally. It blends the merits of histogram equalization and histogram specification into a single transform so that the shape of the histogram of the enhanced tile closely resembles a user specified probability distribution. The individual tiles, after enhancement are clubbed together using bilinear interpolation to avoid the inter-tile edges, artificially induced during the transformation. In CLAHE, the level of contrast enhancement, especially in the homogeneous regions, is held constrained to avoid amplification of noise [2,3].

CLAHE has been proven to be a viable choice for medical image enhancement in many studies [3–10]. The type of images on which CLAHE has been proven feeble includes chest computer tomography (CT) [3], sclera blood vessel [4], myocardial perfusion images [5], diabetic retinopathy imagery [6,7] and intra-oral dental radiograph [8]. Etta et al. [9] appreciated that CLAHE is helpful for the detection of simulated speculations from dense monograms [9]. Yousefi et al. [10] suggested that CLAHE with Rayleigh histogram specification is adequate for optical micro-angiography. In spite, CLAHE has extensively been used, its performance and quality of the enhanced image highly depends on the selection of the tile size, clip-limit, number of histogram bins, intensity range of the enhanced image, specified distribution of the image tiles and the parameters of distribution itself.

Among these operational parameters of CLAHE, clip-limit and histogram specification of the contextual region exhibit comparatively dominating influence on the quality of the enhanced image [11]. The size of the non-overlapping blocks to which the image has to be divided (tile size), the desired shape of the probability density function to which the histogram of the block has to be approximated (distribution) and the factor which determines the threshold with respect to which the histogram of the block has to be clipped (clip-limit) depend on the category or kind of the input image and it can be ascertained only empirically via trial and error, by visually inspecting the enhanced image. 'clip-limit' is a factor which controls the degree of enhancement and there by the gray level saturation, particularly in homogenous regions. Homogenous regions are typified by tiles with large histogram peaks, as majority of the pixels in the tile fall in a confined range of gray levels. If the clip-limit is not properly selected, the enhanced image in some cases may be intolerably poor in contrast and overall quality, compared to the original image. Third parameter of CLAHE, 'Distribution' which specifies the probability distribution to which the histogram of the contextual region has to be approximated, act as the framework or kernel according to which the contrast transform is formulated. The distribution is a parameter which has to be carefully selected based on the type of the image to be enhanced. For instance, it was reported in literature [2] that the enhanced underwater imagery seems to be more natural for Rayleigh histogram specification.

The term, Medical Image covers numerous imaging modalities. Under a single modality like magnetic resonance imaging (MRI) itself there are numerous series and characteristics of these image classes are unique and diverse. Since, aim of CLAHE is only optimizing the contrast, there is no one to one correspondence between the original image and contrast enhanced one. Consequently, images enhanced with CLAHE are not suited for quantitative measurements that rely on physical meaning of the image intensity [12]. In fact, characterizing the lesions, grading and contouring them for radiotherapy planning and image guided surgical interventions are done purely based on the physical meaning of the intensity, in medical images. Still, CLAHE has been extensively in application because of the lack of an alternative. Hence, there is an urgent need to investigate the optimum operational parameters of CLAHE, suitable for each class of medical imaging. The efforts to track the optimum parameters of CLAHE are only few [11–14] and these studies are purely for panoramic images rather than medical images.

Min et al. [11] introduced a strategy to objectively manipulate the optimum clip-limit and tile size from the variations in the entropy of the enhanced image. This technique was based on the intuition that the entropy is correlated with the range of gray levels over which the histogram of the enhanced image is distributed or in other words the extent to which the histogram is stretched during enhancement. Through subjective evaluation of the enhanced image it was concluded that the optimum values of the clip-limit lies in the exponential region (maximum curvature) of the entropy versus clip-limit curve. Along with the entropy, Ravishankar and Mohan [13] added number of edge pixels in the enhanced image and the sum of intensities at these edge pixels also, as the objective functions to identify the optimum clip-limit. This was based on the expectation that the clip-limit can be optimal if the edge quality gets improved during the enhancement. In literature [14] particle swarm optimization (PSO) was employed to tune the operational parameters of CLAHE to its optimal. Except the clip-limit, the influence of other significant parameters as distribution on the quality of the enhanced image remains still un-investigated. While identifying the clip limit suitable for medical images all aspects of quality degradation happening during the contrast enhancement, like saturation, shift in mean intensity, deterioration of geometrical and intensity features, etc. also have to be taken into account rather than mere textural changes measured through entropy.

In this paper, the degradation of intensity, textural and geometric features of the medical image, in relation to the distribution, tile size and clip-limit of CLAHE is analyzed. The forthcoming discussion comprises mathematical formulation of CLAHE and the way of computing statistical indices for quantifying the degradation in intensity, textural and geometric features. Eventually, the variation of these indices with respect to the clip-limit, for Rayleigh, uniform and exponential distributions are analyzed, on ten sets of axial plane MR images.

2. Methods

The specimen images used in the experimental analysis are MR images of pre-operative and biopsy-proven GBM-edema complex, collected from Hind Labs, Govt. Medical College Kottayam, Kerala. The specimen images belong to the study, MRS, under T2 FLAIR, GRE, DWI, 1000b ASSET and T1 FS-ECE series. The specification of MR equipment is; Manufacturer: GE Medical Systems, Model Name: Signa HDxt, Acquisition Type: 2D and 1.5 T field strength. The experimental analysis is performed with Matlab®. The variation in AMBE, PSNR, SSIM, ADE, global variance of enhanced image (σ^2) and SEI with respect to the distribution and clip-limit of CLAHE are primarily analyzed, on various series of MRI. These indices offer quantitative information regarding degradation of geometric, textural and intensity features of the image during contrast enhancement.

Selecting the optimum value of clip-limit or choosing the right distribution, adequate for a MRI series would be possible only if their influence on degree of enhancement and degradation of the features is quantitatively known. Except the critical parameters, clip-limit and histogram specification of the contextual region, other CLAHE parameters are maintained constant in this experiment. The parameter setting is as; dynamic range of the enhanced image: 0–255, number of histogram bins equal to 256, tile size as 8 * 8 and distribution parameter as 0.4 (both for Rayleigh and uniform). For every specimen image from each MRI series, clip-limit is varied between zero and one, with a resolution 0.01 and corresponding deviation in statistical indices are noted. The step was repeated for Rayleigh, uniform and exponential distributions separately.

In histogram equalization (HE) the degree of contrast enhancement is determined by the slope of the mapping function, which transforms the original intensity into contrast enhanced intensity. Hence, the enhancement of pixel intensity transitions contributed by noise can be managed by manipulating the slope of the mapping function [1]. The contrast enhanced intensity 'S_k' is directly proportional to the cumulative probability density (CPD). The slope of the transformation at any gray level is proportional to the histogram height at that gray level, as apparent in (1). Hence, it is possible to restrict the slope of the mapping function by reducing the height of the histogram, by simply clipping it with respect to a threshold [1].

$$S_k = \frac{(L-1)}{MN}\sum_{j=0}^{k} n_j \quad k = 0, 1, 2, \ldots, L-1 \tag{1}$$

where '$L-1$' is the maximum possible intensity, say 255 in a UInteger8 image, $M*N$ is the total number of pixels and n_j is the number of occurrence of the jth intensity.

In CLAHE, the image is divided into non-overlapping contextual region or tiles and the local histogram of the tile is computed. Prior to the estimation of the cumulative probability density and the contrast enhanced intensity, histogram of each tile is clipped with respect to a user defined clip-limit. The clip-limit is a multiple of the average height of the histogram of the contextual region. Average height of the histogram is the ratio of total number of pixels present in the contextual region and the number of gray levels. In this respect, clip-limit is the product of the user-defined contrast factor, 'α' and average number of pixels falling in each histogram bin [12]. For a contextual region of size 'M' rows and 'N' columns and 'L' being the number of histogram bins, clip-limit is given by,

$$n_T = \begin{cases} 1 & \text{if } \dfrac{\alpha MN}{L} < 1 \\ \dfrac{\alpha MN}{L} & \text{else} \end{cases} \quad 0 < \alpha \leq 1 \tag{2}$$

Original height of the histogram of the contextual region 'n_k' is clipped with respect to the clip-limit 'n_T' such that,

$$h_k = \begin{cases} n_T & \text{if } n_k \geq n_T \\ n_k & \text{else} \end{cases} \quad k = 1, 2, \ldots, L-1 \tag{3}$$

n_k is the histogram of the contextual region given. Note that:

$$\sum_{k=0}^{L-1} n_k = MN \tag{4}$$

Total number of the clipped pixels,

$$n_c = MN - \sum_{k=0}^{L-1} h_k \tag{5}$$

To renormalize the histogram or to bring its area under the curve back to the original, the clipped pixels are distributed back to the histogram bins. This redistribution can be uniform or else the clipped pixels can be non-uniformly distributed into the bins with number of pixels below the clip-limit, in proportion to their content. Here, the clipped pixels are equally distributed to all the histogram bins such that none of the bin contents exceed clip-limit. The number of pixels to be distributed to each histogram bin,

$$n_\mu = \frac{n_c}{L} = \frac{MN - \sum_{L-1}^{k=0} h_k}{L} \tag{6}$$

In (6) h_k is the clipped histogram. Now the clipped histogram is renormalized as,

$$h_k = \begin{cases} n_T & \text{if } n_k + n_\mu \geq n_T \\ n_k + n_\mu & \text{otherwise} \end{cases} \tag{7}$$

The number of undistributed pixels are computed from (5) to (6) and the transformation (7) is repeated till all the clipped pixels get distributed uniformly to the histogram bins and the histogram grows back to the original area. The cumulative histogram of the contextual region is computed as,

$$C_k = \frac{1}{MN}\sum_{j=0}^{k} h_j \tag{8}$$

The shape of the histogram reflects the brightness characteristics and to a certain extent the visual quality of the image. In histogram matching, the pixel intensities in the image are transformed in such a way that the histogram of the contrast enhanced image matches with the specified histogram shape. So that, 'histogram matching' gives an opportunity to 'prefix' the brightness and visual quality of the enhanced image. The pixel intensities in the tile is transformed such that the shape of the histogram of the enhanced tile closely resembles a user specified probability distribution as uniform (flat), Rayleigh (bell-shaped) or exponential (curve shaped). The individual tiles, after enhancement are clubbed together using bilinear interpolation to avoid the inter-tile edges, artificially induced during the transformation, as mentioned earlier.

As any other contrast enhancement scheme, in CLAHE also the similarity of textural, intensity and geometrical features of the original and the contrast enhanced image diminishes with increasing contrast. A good selection of the clip-limit and distribution should offer optimum trade-off between the degree of contrast enhancement and feature preservation. The clip-limit and distribution, suitable for MR images can be identified only by objectively analyzing the degree of contrast enhancement and the feature degradation, for different values of clip-limit and specified distribution.

Six different statistical indices are used to quantify the degradation of image features and the increase in contrast. These statistical indices include AMBE, ADE, PSNR, SEI, SSIM and the ratio between global variance of original and enhanced images. Ratio between global variance of original and enhanced images provides an objective measure of increase in contrast. Even though not critical as in GHE, CLAHE also disturbs the mean illumination level of the image. Analyzing the change in mean brightness of the image with respect to the variation in clip-limit is necessary to identify the optimum clip-limit. AMBE accounts for the change in intensity features of the image. It is a measure of change in mean brightness of the image.

Entropy is a statistical index which objectively expresses richness of information in an image. It accounts for the texture of the image and randomness of the intensities which constitute the image. ADE is the difference in the entropy values of the original and enhanced images. It represents the change in texture of the image, induced during the enhancement with CLAHE. The SSIM quantifies the degradation of geometric features of the MR image during enhancement with CLAHE. The Structural Similarity Index Matrix [15] between the raw MR image 'X' and contrast enhanced image 'Y',

$$\mathrm{SSIM}(X,Y) = \frac{(2\mu_x\mu_y + C_1)(2\sigma_{xy} + C_2)}{(\mu_x^2 + \mu_y^2 + C_1)(\sigma_x^2 + \sigma_y^2 + C_2)} \tag{9}$$

where $C_1 = (K_1L)^2$ & $C_2 = (K_2L)^2$, $K_1, K_2 \ll 1$. K1 and K2 are two arbitrary constants with values 0.01 and 0.03, respectively. The terms μ_x, μ_y, σ_x^2, σ_y^2 and σ_{xy} are the mean brightness of original image, mean brightness of contrast enhanced image, global variance of original image, global variance of contrast enhanced image and covariance between original and contrast enhanced images, respectively.

PSNR is also a statistical measure of similarity between two images. The PSNR for images X and Y of size $M * N$ [16],

$$\mathrm{PSNR} = 20\log\left(\frac{\mathrm{Max}(X)}{\sqrt{\frac{1}{MN}\sum_M^{i=1}\sum_N^{j=1}[X(i,j) - Y(i,j)]^2}}\right) \tag{10}$$

The level of saturation for different values of clip-limit and specified distribution also has to be taken into account, while identifying the optimum clip-limit and distribution. SEI is an index used to quantify the level of saturation. Saturation Evaluation Index [17,18],

$$\mathrm{SEI} = \frac{n_s}{MN} \tag{11}$$

where n_s is the number of newly saturated pixels either 0 or 255, which were not saturated before contrast enhancement.

Absolute Mean Brightness Error [19],

$$\mathrm{AMBE} = |\mu_x - \mu_y| \tag{12}$$

Absolute Deviation in Entropy,

$$\mathrm{ADE} = \left|\left(\sum_{k=0}^{L-1} P_r(s_k)\log_2 P_r(s_k)\right) - \left(\sum_{k=0}^{L-1} P_r(r_k)\log_2 P_r(r_k)\right)\right| \tag{13}$$

where $k = \{0, 1, 2, \ldots, L-1\}$ and $P_r(r_k)$ and $P_r(S_k)$ are the normalized histogram of the original and the contrast enhanced images, respectively.

3. Results

The variation of SSIM, PSNR, AMBE, ADE, global variance [20] of the equalized image and SEI with respect to the variation in clip-limit for Rayleigh, uniform and exponential distributions for an MR image from propeller series is depicted in Figs. 1–6. The variation of these feature preservation indices with respect to the clip-limit is evaluated for ten sets of MR images from five different series. The nature of variation of these indices with respect to the clip limit remains identical for test images from all the series of MRI. This is a clear indication that the optimum clip-limit and distribution, identified objectively, would be suitable for the entire MRI images regardless of their series.

The variation of SSIM with respect to the variation in clip-limit for Rayleigh, uniform and exponential distributions is depicted in Fig. 1. The feature similarity or more specifically the structural similarity between the original and contrast enhanced image monotonically decreases with increase in the clip-limit. SSIM has a range between zero and one. SSIM value of unity represents perfect structural similarity of two images. In GHE the maximum possible SSIM between the original and

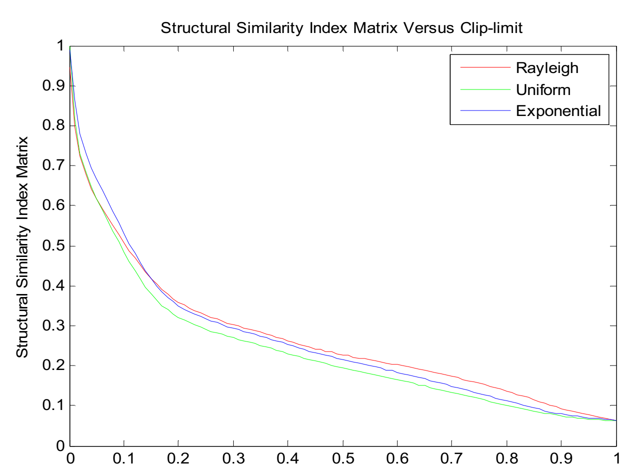

Fig. 1 – SSIM versus clip-limit for CLAHE with Rayleigh, uniform and exponential distributions.

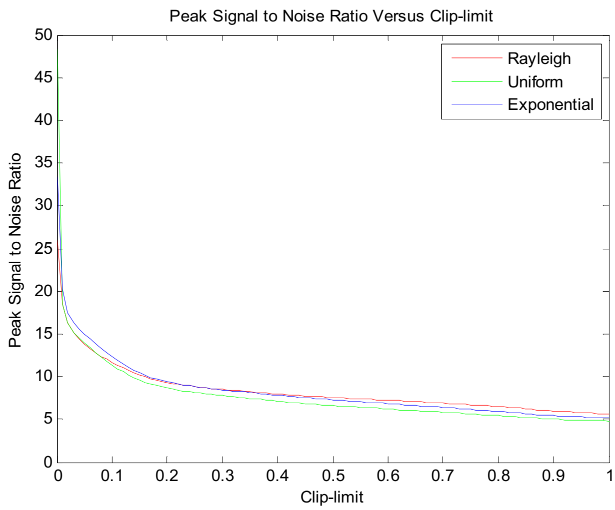

Fig. 2 – PSNR versus clip-limit for CLAHE with Rayleigh, uniform and exponential distributions.

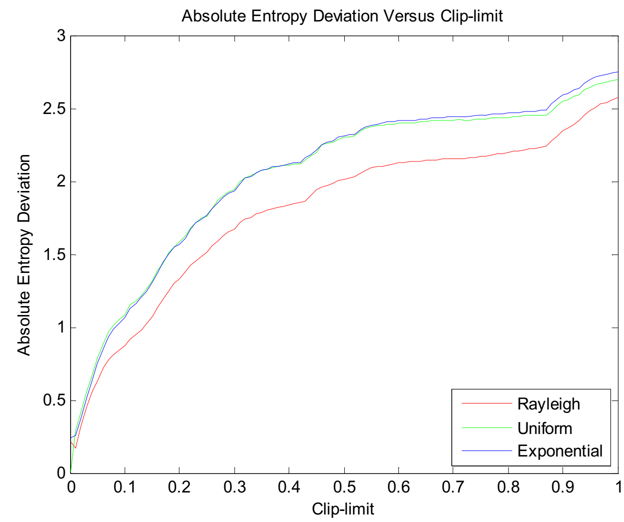

Fig. 4 – ADE versus clip-limit for CLAHE with Rayleigh, uniform and exponential distributions.

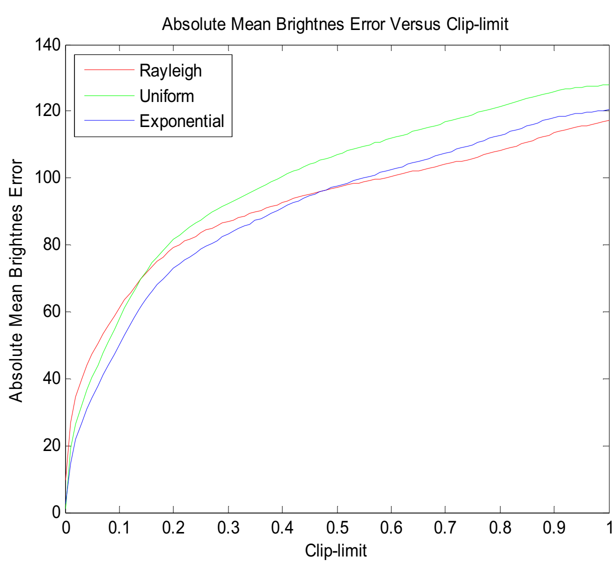

Fig. 3 – AMBE versus clip-limit for CLAHE with Rayleigh, uniform and exponential distributions.

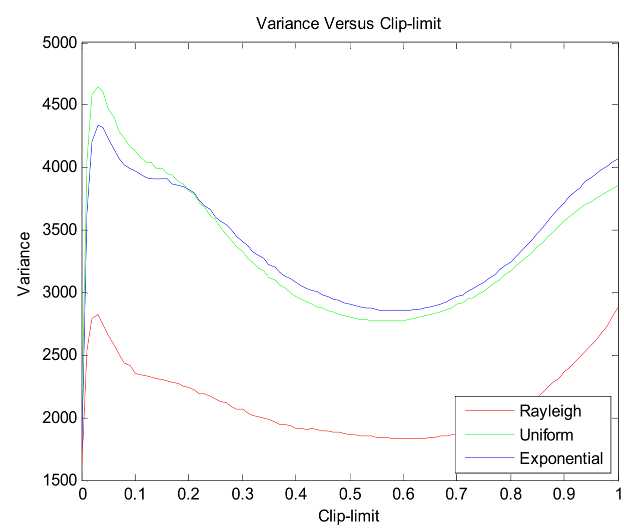

Fig. 5 – Global variance of enhanced image versus clip-limit for CLAHE with Rayleigh, uniform and exponential distributions.

enhanced image is mostly less than 0.3. But in CLAHE the SSIM falls below 0.5 only after a clip-limit of 0.1. Geometrical features are not degraded significantly when the clip-limit is below 0.1.

In the PSNR versus clip-limit curve in Fig. 2, PSNR falls sharply before a clip-limit of 0.02, itself. This implies, better preservation of the geometrical features is possible only when the clip-limit is less than 0.02. The PSNR variation with respect to the clip-limit refines the optimum range of clip-limit observed from the SSIM versus clip-limit curve. The variation of AMBE and ADE in Figs. 3 and 4 respectively, also confirm that the range of clip-limit with maximum preservation of intensity and textural features is below 0.02.

The global variance of the enhanced image versus clip-limit in Fig. 5 suggests that the degree of enhancement increases sharply for clip-limits till 0.01 and falls gradually beyond it. This observation implies that the best trade-off between the degree of contrast enhancement and feature preservation is at a clip-limit of 0.1, regardless of the specified distribution. The pattern of variation of the statistical indices with respect to the clip-limit is identical for all the three distributions. Hence, the distribution suitable for MR images can be identified only after observing the feature degradation and contrast enhancement offered by CLAHE with uniform, exponential and Rayleigh distributions, at the optimum clip-limit of 0.01. However, from Fig. 5, it can be concluded that CLAHE with Rayleigh distribution offers poor contrast enhancement, compared to CLAHE with uniform and exponential distributions. But these conclusions can be confirmed only after qualitative inspection of the MR images enhanced with CLAHE with these specified distributions. SEI versus clip-limit in Fig. 6 ensures that the problem of saturation is only when the clip-limit exceeds 0.35.

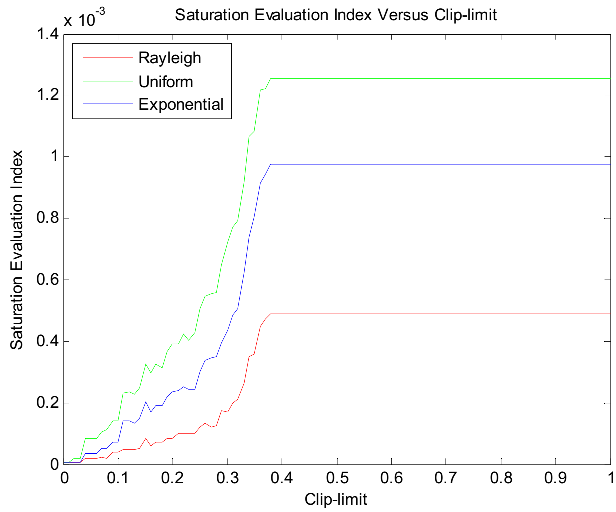

Fig. 6 – SEI versus clip-limit for CLAHE with Rayleigh, uniform and exponential distributions.

However, the percentage of saturated pixels is less than 0.12, beyond the clip-limit of 0.35.

The maximum curvature in the statistical indices versus clip-limit curve is observed for clip-limit values between 0.05 and 0.15. But, from the variation of SSIM and PSNR it is evident that for the clip-limit above 0.02, the geometrical features of the image are substantially degraded. Hence, the method of identifying the optimum value of the clip-limit from the region of maximum curvature on the entropy versus clip-limit curve, proposed in [11] is seen to be unreliable. The ratio of the global variance of the equalized image to the global variance of the original image and SSIM for different histogram specifications at a clip-limit of 0.01, on MR images from different series are shown in Table 1. Variance ratio and SSIM are two contradictory feature evaluation indices; the former is an indirect measure of contrast enhancement and the latter is a measure of capability to preserve the geometrical features during enhancement. Variance ratio is the ratio of global variances of the contrast enhanced and the original images.

From Table 1 it is apparent that CLAHE, with uniform histogram specification offers maximum degree of contrast enhancement and exponential distribution offers maximum preservation of geometrical features, on ten sets of MR images from five different series. At the optimum clip-limit, the mean of SSIM exhibited by the Rayleigh, uniform and exponential histogram specification are 0.7477, 0.7946 and 0.8457, for ten sets of MR images and mean of variance ratio are 1.242, 2.0316 and 1.7711, respectively.

The numerical values of the feature degradation indices for different histogram specifications on an MR image of propeller series, at the optimum clip-limit of 0.01 are showed in Table 2.

Table 1 – Variance ratio and SSIM for different histogram specifications of CLAHE for various series of MRI at optimum clip-limit 0.01.

MRI series	Image no	Distribution	Variance ratio	SSIM
T2 FLAIR	Z14	Rayleigh	1.1684	0.7360
		Uniform	2.1238	0.7678
		Exponential	1.8984	0.8253
	Z16	Rayleigh	1.3828	0.6815
		Uniform	2.5272	0.7035
		Exponential	2.2114	0.7706
T2 Propeller	Z02	Rayleigh	1.1882	0.7973
		Uniform	1.8981	0.8158
		Exponential	1.6997	0.8643
	Z03	Rayleigh	1.2239	0.7309
		Uniform	1.9388	0.7733
		Exponential	1.7190	0.8296
GRE	Z19	Rayleigh	0.7629	0.8369
		Uniform	1.2276	0.8996
		Exponential	1.1041	0.9263
	Z21	Rayleigh	0.8017	0.8245
		Uniform	1.2881	0.8892
		Exponential	1.1576	0.9194
DWI	Z23	Rayleigh	1.1291	0.7700
		Uniform	1.7470	0.8536
		Exponential	1.5161	0.8968
	Z24	Rayleigh	0.9776	0.7985
		Uniform	1.5240	0.8838
		Exponential	1.3386	0.9182
SEFS + C	Z07	Rayleigh	2.2857	0.5784
		Uniform	3.5718	0.6156
		Exponential	2.9462	0.6975
	Z16	Rayleigh	1.5000	0.7231
		Uniform	2.4699	0.7442
		Exponential	2.1195	0.8085

Table 2 – Value of feature degradation indices at optimum clip-limit 0.01 for different histogram specifications.

Statistical indices	Probability distribution		
	Rayleigh	Uniform	Exponential
AMBE	26.7297	19.0691	14.4903
Variance	2539.8	4057.4	3633.2
ADE	0.1749	0.2918	0.2561
PSNR	18.5279	18.5362	20.1943
SEI	0.0000	0.0000	0.0000
SSIM	0.7973	0.8158	0.8643

It has been observed that the percentage of pixels getting saturated at the optimum clip-limit is approximately zero for three of the histogram specifications. At a clip-limit of 0.02, 0.01% of pixels get saturated for uniform distribution and other two distribution exhibits fairly negligible saturation, the percentage of pixels saturated being approximately zero. At a clip-limit of 0.03, both uniform and exponential distributions have a percentage saturation of 0.02%. For all the three distributions, CLAHE is perfectly immune to saturation for clip-limits between 0 and 1, as evident in Fig. 6.

On the entire set of test MR images the exponential histogram specification exhibits the highest PSNR values. The maximum preservation of textural features is seen in exponential distribution as the minimum value of ADE is observed for CLAHE with exponential specification. The capability to preserve the textural features, during enhancement is higher in CLAHE with exponential histogram specification than uniform.

Similarly, the intensity features are preserved in CLAHE with exponential histogram specification better than uniform distribution as it produces minimum value of AMBE. For Rayleigh distribution, The AMBE is comparatively higher, the preservation of intensity feature is poor and the image gets blurred during enhancement.

The original MR image of propeller series and the images after CLAHE with Rayleigh, uniform and exponential histogram specifications are illustrated in Fig. 7. From the qualitative inspection of images, it is clear that the Rayleigh distribution blurs the image beyond tolerable limits. Emphasizing the observation from Table 1, the qualitative inspection of the equalized MR images in Fig. 7 reveals that exponential histogram specification preserve textural, geometrical and intensity features better than uniform specification and offer a degree of enhancement almost close to the enhancement possible with uniform distribution.

As majority of the pixel intensities in the MR images lie in the lower gray scale, mostly their histograms are positively skewed or right tailed. The shape of the histograms has more resemblance to the exponential histogram than Rayleigh and uniform histograms. Hence, exponential histogram specification can preserve the brightness characteristics and features of the MR images better than Rayleigh and uniform distributions.

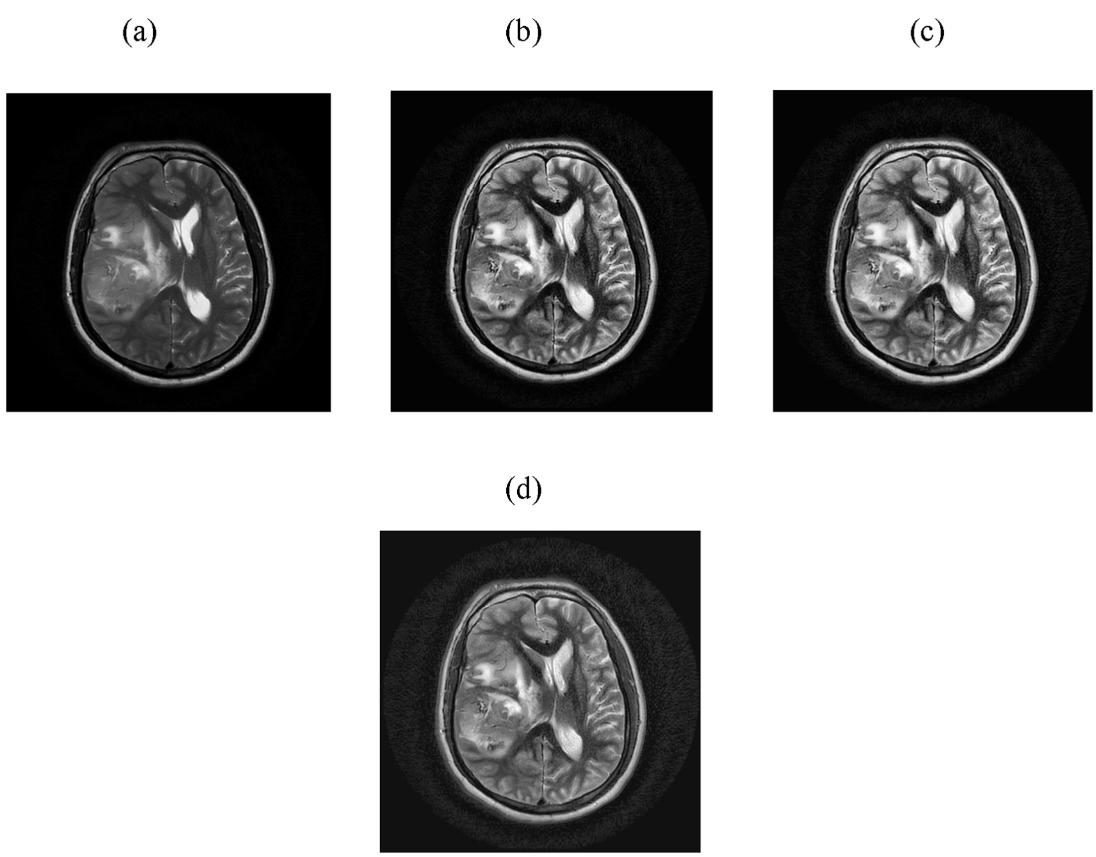

Fig. 7 – (a) Original MR image; (b) Image enhanced by CLAHE with exponential histogram specification; (c) Image enhanced by CLAHE with uniform histogram specification; (d) Image enhanced by CLAHE with Rayleigh histogram specification.

4. Discussion

More and Brizuela [19] has been the most recent attempt to identify the optimum values of clip-limit and tile size, suitable for specific class of images. This attempt was based on the expectation that at the optimum values of clip-limit and tile size, information content in the enhanced image is maximized, while distortion is minimized. Entropy and SSIM respectively were used to measure the information content and distortion in the enhanced image. The values of clip-limit and tile size for which entropy is maximum and SSIM is minimum, were identified with the help of PSO. In fact, SSIM is not a metric of distortion; instead it is an image quality index which expresses the similarity between two images. PSO had been used by Mohan and Mahesh [14] also to identify the optimum values of the operational parameters of CLAHE. It has been proven in our experiment that even for MR images, from different series, a consistent value of clip-limit equal to 0.01 is optimal. Hence, employing the PSO to identify the optimum value of operational parameters of CLAHE causes unnecessary computational burden.

Except the trials for investigating optimum values of operational parameters of CLAHE, suitable for panoramic images [11–14] and [19], attempts to derive them for medical images is not known to be available. This article specifically suggests clip-limit and distribution, exclusively suitable for MRI. It has been demonstrated experimentally in this article that exponential distribution is suitable for MRI, regardless of their series to which the images belong. The techniques available in literature have made use of either the slope of variation of entropy with respect to clip-limit [11] or maximum entropy [14] as the objective function to identify the optimum clip-limit and tile size. But, a finite relation between the image entropy and the range of pixel intensities over which the histogram is distributed is not known to be established. For the values of the clip-limit and tile size which maximize the entropy, the degradation in intensity and geometric features of the image may be beyond tolerable limits. Generally, these features have considerable clinical significance in medical images.

Instead of just entropy, all dimensions of feature degradation were objectively analyzed with the help of dedicated statistical indices in this article, for defining the optimum value of the operational parameters of CLAHE. All probable aspects of quality degradation which may happen during the contrast enhancement of medical images, like saturation, shift in mean intensity, deterioration of geometrical and intensity features etc. also have to be taken into account rather than mere textural changes measured through entropy. Number of edge pixels in the enhanced image and the sum of intensities at the edge locations cannot be considered as objective functions to derive optimum clip-limit, as done by Ravishankar and Mohan [13], because these values would be at their maximum when the image is over enhanced or saturated.

5. Conclusion

While enhancing the contrast of medical images, the textural, intensity and geometrical features of the image should be preserved to the maximum possible extent. Further clinical decisions like grading of the lesions may be done purely based on these features. The values of the operational parameters of the contrast enhancement schemes should be fixed such that the parameters selected ensure optimum trade-off between the contrast enhancement and the feature preservation. The optimum selection of the operational parameters of CLAHE suitable for MR images has been investigated. Six statistical indices, which can quantify the degree of feature degradation and contrast enhancement have been employed to objectively identify the optimum parameter setting of CLAHE for MR images.

The variation of AMBE, global variance of the contrast enhanced image, SEI, ADE, PSNR and SSIM with respect to the variation in clip-limit has been analyzed for CLAHE with uniform, Rayleigh and exponential histogram specifications on ten sets of spectroscopic MR images from five different series, T2 FLAIR, GRE, DWI, 1000b ASSET and T1 FS-ECE. Regardless of the series, CLAHE with exponential histogram specification is suitable for MRI than CLAHE with Rayleigh and uniform specifications. The variation of global variance of the enhanced image with respect to clip-limit suggests that the degree of enhancement increases sharply for clip-limits till 0.01 and falls gradually beyond it. Similarly, from the variation of AMBE, ADE, PSNR and SSIM with respect to clip-limit it is evident that intensity, textural and geometric features of MRI is preserved only if the clip-limit is less than 0.02 during enhancement with CLAHE, for all the series of MRI. CLAHE with exponential and uniform histogram specifications offer similar degree of enhancement. But, better feature preservation is observed in CLAHE with exponential specification than uniform. Though Rayleigh is reported to be the most suitable for under-water images, CLAHE with Rayleigh distribution blurs the MR image and cause a washed-out effect and textural, intensity and geometric features are degraded than in CLAHE with uniform and exponential histogram specifications.

At optimum clip-limit, the mean of SSIM exhibited by the Rayleigh, uniform and exponential histogram specifications are 0.7477, 0.7946 and 0.8457, for ten sets of MR images and mean of variance ratio are 1.242, 2.0316 and 1.7711, respectively. CLAHE is immune to saturation and the level of saturation is tolerable for clip-limits less than unity for all the three histogram specifications. In summary, while using CLAHE for contrast enhancement of MR images, the optimum clip-limit is 0.01 and the optimum histogram specification for the contextual region is exponential.

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