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X-Ray Image Contrast Enhancement Algorithms

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ABSTRACT

In medicine, X-ray images are widely used for early detection and reliable diagnosis of many diseases in patients. In this case, the quality of the X-ray image is required to be high for the diagnosis to be effective. For example, the lack of sufficient contrast in the X-ray image makes it difficult for experts in the field to distinguish between the structures of the patient's internal organs. This problem can be overcome by applying contrast enhancement algorithms to the image. Today, many algorithms designed to enhance image contrast have been developed, but not all of them are equally effective for existing types of X-ray images. It depends on the specific requirements of the choice of algorithm. In this case, it is very important to evaluate the effectiveness of different contrast enhancement algorithms in a set of X-ray images and compare their results with the original images. This article analyses contrast enhancement algorithms for improving the quality of X-ray images and compares them using image quality evaluation criteria. The research work aims to determine the optimal pair of image quality evaluation criteria and contrast enhancement algorithms to ensure accurate and fast diagnosis. In the computational experiment, histogram equalization, Contrasted-limited adaptive histogram equalization (CLAHE), contrast stretching and morphological contrast enhancement algorithms were applied to 3615 human knee X-ray images and evaluated based on Peak signal noise to ratio (PSNR), Mean square error (MSE) and structure similarity index measure (SSIM) evaluation criteria. As a result, the pair formed based on the MSE criterion and the CLAHE algorithm from the contrast enhancement algorithms was determined as the most optimal pair.

1. Introduction

X-ray is one of the main and important tools of medicine, it has been widely used in the diagnosis of various diseases for more than a century and has not lost its relevance in medicine even today [1]. Because doctors cannot see the patient's internal structures with the naked eye, they take an X-ray

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of the patient and make a diagnosis based on the X-ray image. X-rays use electromagnetic radiation to image the inside of the body. This allows doctors to see the structure of bones and other organs.

X-ray image is an image of an object created as a result of exposure to X-rays [2]. X-rays are used in the diagnosis of many diseases, such as broken bones, tumours, lung and dental diseases. X-rays were discovered by V. K. Rentgen in 1895 and the radiation in it is electromagnetic. The X-ray image is formed as a result of the impact of fast-moving electrons on the anode of the X-ray tube, that is, it consists of an X-ray emitter (tube) - a study object - an image receiver (X-ray film, screen). Through it, uneven absorption of X-ray radiation by various anatomical structures organs and tissues of the object is determined. The intensity of X-ray absorption depends on the atomic composition, density and thickness of the studied object. The heavier the chemical elements entering the tissue, the greater the density and thickness of the layer and the more intensively X-rays are absorbed. In other words, X-rays are absorbed to a large extent by bones and a small extent by soft tissues. The non-uniform absorption of X-rays in the tissues of the studied area leads to the formation of changed or non-uniform X-rays (output dose) in the space behind the object. Thus, an X-ray image is created from invisible X-rays [3].

X-ray imaging equipment usually consists of a tube that emits X-rays and a detector that receives the rays that pass through the human body. X-ray images can be in different formats, including digital or analogue. In a conventional X-ray machine, images are reflected on X-ray film and in this case, the X-ray images can be viewed in a lightbox. An analogue X-ray image requires a darkroom and it is time-consuming. A skilled specialist in analogue image capture and processing is needed. In addition, X-ray images cannot be easily manipulated and the process of storing and digitizing them is extremely complex. Digital X-ray imaging is also gaining popularity because of its high quality and ease of management and maintenance. A digital X-ray machine uses sensors to capture X-rays, which are then converted into digital images that can be viewed on a computer screen [4]. Currently, similar digital X-ray devices, especially Chinese Perlove PLD-type X-ray devices, are widely used in Uzbekistan.

X-ray equipment is one of the most widely used medical imaging tools and it allows images of internal body structures to be captured. In some cases, there is a need to improve the quality of medical images obtained from X-ray equipment. In digital radiography, it may also require an increase in radiation dose. Therefore, the goal of medical imaging is not to achieve perfection, but to obtain an image that is adequate for the diagnosis of a given medical problem and causes minimal harm to the patient. In this process, various complications can arise in obtaining high-quality images. For example, if the contrast of the image is not sufficient, its assessment will not be performed qualitatively. This article also discusses some approaches to improve the quality of images obtained by X-ray equipment, by implementing which medical professionals can obtain more accurate and useful images, which will lead to improved patient health.

Several algorithms designed to enhance the contrast of X-ray images can be found in the literature [5-7]. They are mainly aimed at increasing the difference between the intensity values of different tissues in the image, making it easier for radiologists to identify and analyse them. Existing algorithms for all types of X-ray images do not provide the same level of efficiency. In this case, the algorithm is selected or developed according to the essence of the problem to be solved. Therefore, it is very important to evaluate the effectiveness of contrast enhancement algorithms in X-ray image databases and to choose the optimal algorithm by comparing the results with the original images. In this study, four algorithms widely used in increasing the contrast of X-ray images were evaluated according to the criteria of Peak signal noise ratio (PSNR), Mean square error (MSE) and structure similarity index measure (SSIM), which evaluate image quality and the pair {criterion, algorithm} was determined.

1.1 Evaluation of X-Ray Image Contrast

Below is a 5-step process for ensuring X-ray image quality.

i. The first step is to provide standards for the photo lab process. If the standards are not met, then it is impossible to assess the degree of inconsistency between the parameters of the given beam and the assessment of other parameters of the x-ray image is useless.
ii. The second step is image optical density analysis. Visually, the density is evaluated as the degree of expression of black gradients in the area of the studied object. This indicator directly depends on exposure parameters and the amount of radiation energy.
iii. The third step is to evaluate the X-ray contrast. Photolab light conditions and secondary X-ray loss are important to ensure image contrast.
iv. The fourth stage is the structural analysis of the X-ray image. With sufficient darkening and optimal contrast, anatomical components and pathological changes of the research object can be seen.
v. The fifth stage is to clarify the details of the image.

In this study, the contrast assessment stage of the above-mentioned 5-step process is considered in more detail. One of the main problems in X-ray images is the limited contrast between different tissues in the body. This can make it difficult for radiologists to interpret images and accurately diagnose the condition of human internal structures and cause a variety of similar problems. On the other hand, when performing image recognition, image processing step algorithms are used [8-22] and the most important of these steps is image pre-processing. To improve the quality of the image, it is necessary to increase the contrast of the image.

Contrast is defined as the difference in brightness between the lightest and darkest areas of an image. One of the most important factors of X-ray imaging is the image contrast, that is, the ability to distinguish different tissues or structures in the image. Currently, many methods and algorithms for X-ray image contrast evaluation have been developed and there are widely used evaluation methods. A brief description of them is given below.

Visual assessment - the simplest and most common method of image contrast assessment is visual assessment by radiologists. Radiologists evaluate contrast based on their experience and knowledge by viewing X-ray images. They detect differences in brightness and contrast between different textures or structures. However, this method can also be subjective and different radiologists have different opinions and they will have differences among themselves.

Image histogram analysis is a quantitative method of image contrast assessment. It involves analysing the distribution of pixel values in an image. A histogram represents the number of pixels at each brightness level in an image and a wider distribution of pixel values indicates higher contrast. Histogram analysis can be performed automatically by software tools, which allows for a reduction of the subjectivity of the assessment [23].

Detailed analysis of contrast - an X-ray image is a quantitative method of evaluating the ability to distinguish small details. This involves using a test pattern consisting of small objects of different sizes and contrasts. The ability to distinguish objects is used to evaluate the contrast detail performance of the X-ray system.

The above methods are not considered optimal for evaluating and comparing image contrast in numerical values. Therefore, it is advisable to use other popular methods of calculating image contrast in digital values.

Weber contrast. This method of contrast assessment is usually used in situations where there are small details on the background of large objects that are almost indistinguishable in colour parameters. One of its main disadvantages is the strong dependence of the estimate on the background contrast and it is especially evident when processing bright images, in which case the contrast values are underestimated.

Michelson contrast. It is based on the comparison of dark and light areas and evaluates the contrast of the image using the minimum and maximum brightness values in the area that needs to be analysed. However, this method does not provide the expected results for X-ray images. Because the minimum and maximum brightness values in an X-ray image usually take the values 0 and 255. Therefore, it is not possible to accurately estimate the image contrast with this method.

Root mean square (RMS) is the most widely used method for evaluating the contrast of almost any image as in Eq. (1).

$$RMS = \sqrt{\frac{1}{l}\sum_{j=1}^{l}\left(T_j - \bar{T}\right)^2}, \quad \bar{T} = \frac{1}{l}T_j \tag{1}$$

Where, $T_j - j$ -pixel brightness [24].

X-ray image contrast is one of the important factors of medical reporting and several methods of its evaluation have been presented. Visual evaluation, histogram analysis and contrast detail analysis are useful methods for evaluating the X-ray image contrast. However, in this work, the RMS method is used to estimate the X-ray image contrast in numerical values. Because with this method, it is convenient and easy to calculate the contrast of any image in digital values.

1.2 Image Quality Evaluation Parameters

To evaluate the quality of the image in digital values, it is recommended to use the following three criteria, which depend on the relationship between the contrast-enhanced and the original image, that is, PSNR, MSE and SSIM. To evaluate the effectiveness of improving the quality of X-ray images, the contrast-enhanced image can be compared with the original image using the above criteria [25].

The evaluation criteria obtained in the study were defined as SSIM, PSNR, MSE and their mathematical expressions are presented in the Table 1 below.

The SSIM criterion is a measure of similarity between two images and the closer its value is to 1, the more similar the images are [26].

The criteria listed above are commonly used to evaluate the quality of images and provide a quantitative measure of the performance of various algorithms. However, it should be noted that these criteria may not always reflect the subjective quality of images received by radiologists. Therefore, it is necessary to perform a comprehensive evaluation of algorithms, including both objective and subjective quality indicators. Common image contrast enhancement algorithms are described below.

Table 1
Mathematical expression of evaluation criteria

Criteria name	Calculation formula	Criterion parameters	Best result
SSIM	$k_1 = \frac{1}{K}\sum_{x,y} ssim(x,y),$ $ssim(x,y) = \frac{(2\mu_x\mu_y + c_1)(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + c_1)(\sigma_x^2 + \sigma_y^2 + c_2)}$	μ_x, μ_y – average values in x and y windows; σ_x^2, σ_y^2 – variance of values in x and y; σ_{xy} – covariance in x and y; $c_1 = (k_1 L)^2$ and $c_2 = (k_2 L)^2$ are constants, $L = 255$, $k_1 = 0.01, k_2 = 0.03$, K – is the number of windows	$k_1 \to \max$
PSNR	$k_2 = 10\log_{10}\frac{(2^n - 1)^2}{\sqrt{MSE}}$	n – image bit depth	$k_2 \to \max$
MSE	$k_3 = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}(I_0(i,j) - I_1(i,j))^2$	$M \times N$ – image size, $I_0(i,j)$ and $I_1(i,j)$ reference and luminance at the location (i,j) of the distorted image	$k_3 \to \min$

2. Methodology
2.1 Histogram Equalization Algorithm

This algorithm is considered one of the most widely used contrast enhancement algorithms in digital X-ray imaging and performs image histogram transformation to enhance contrast. The histogram equalization algorithm is a simple algorithm that works by redistributing the image pixel values to obtain a uniform histogram [27]. The algorithm is easy to implement and can also be used to enhance the contrast of X-ray images. However, this may cause some artifacts in the image, such as noise enhancement. The algorithm is implemented based on the scheme presented in the Figure 1 below.

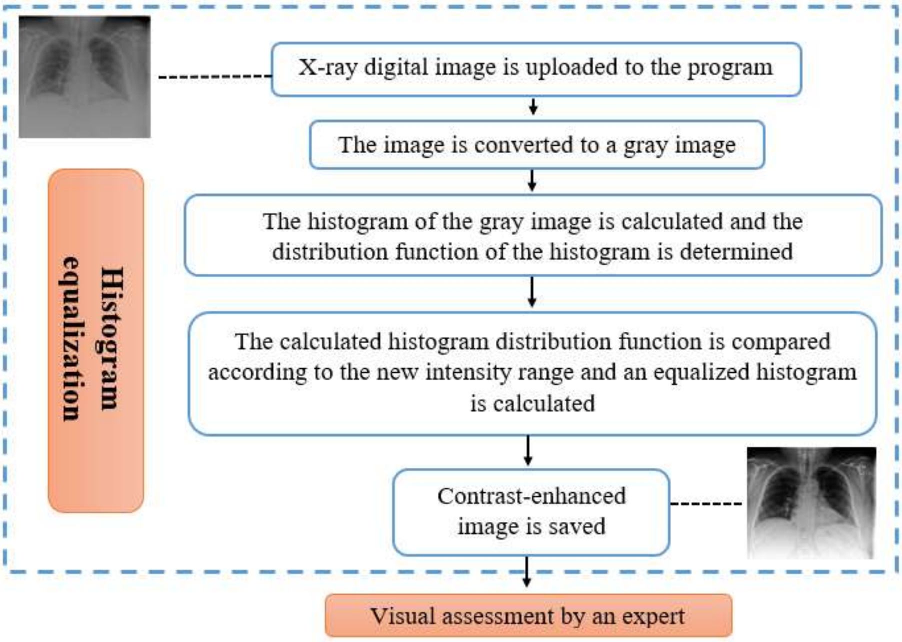

Fig. 1. Histogram equalization algorithm

2.2 Contrasted-Limited Adaptive Histogram Equalization (CLAHE) Algorithm

This algorithm is another advanced algorithm of contrast enhancement in X-ray digital images and it is an improved variant of the histogram equalization algorithm. CLAHE adapts the amount of contrast enhancement to local image features. The algorithm is effective in enhancing the contrast of X-ray images with nonuniform illumination, but may not be effective for images with high-frequency content. This algorithm works by dividing the image into small regions and applying a separate histogram smoothing to each region [28] and it is implemented based on the scheme presented in the Figure 2 below.

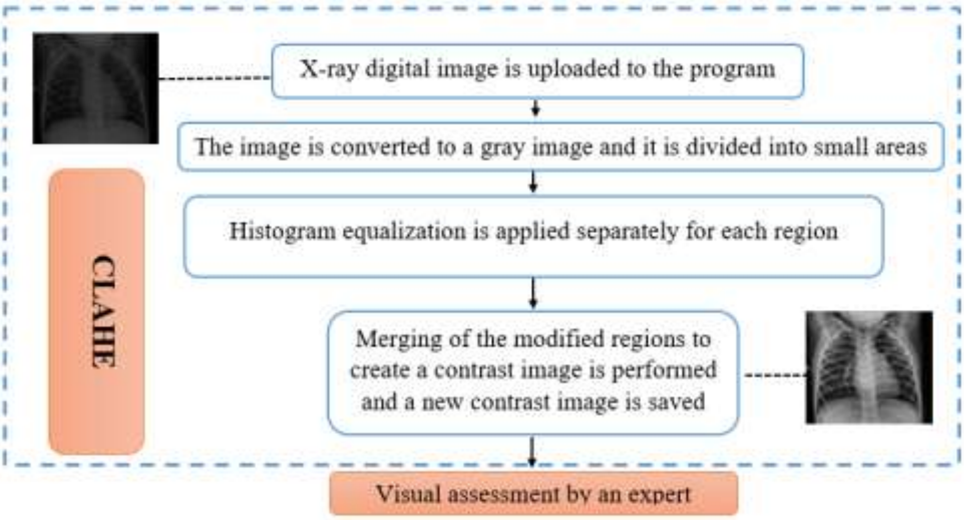

Fig. 2. CLAHE algorithm

2.3 Contrast Stretching Algorithm

Since this algorithm is very easy to implement, it is the simplest algorithm compared to the four algorithms presented above. By calculating the image mean and standard deviation and then expanding the intensity range based on the calculated values, the algorithm works well in contrast enhancement on low-contrast X-ray images, but may not be effective on high-contrast images [29]. The algorithm is implemented based on the scheme presented in the Figure 3 below.

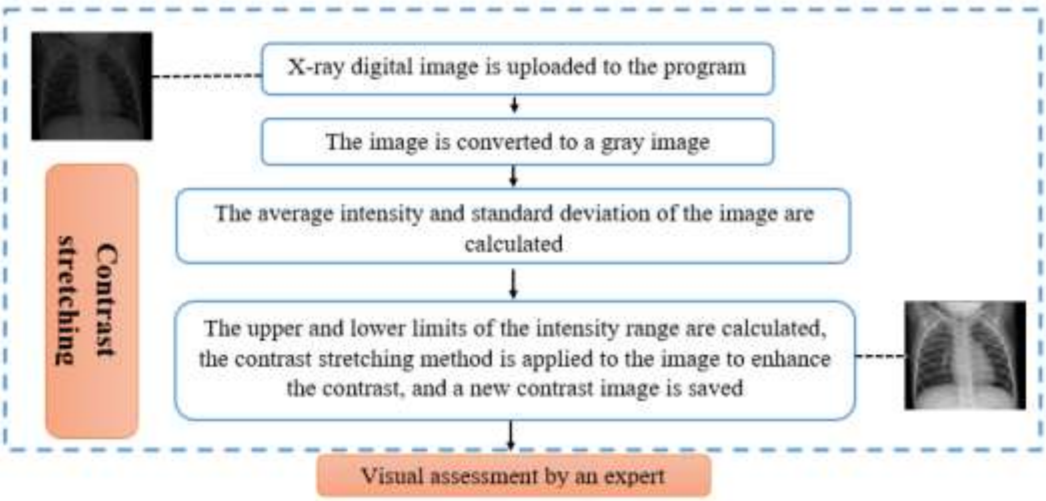

Fig. 3. Contrast stretching algorithm

2.4 Morphological Contrast Enhancement Algorithm

This algorithm uses morphological filters to change the shape and size of objects in the image while preserving the overall structure and it is implemented based on the scheme shown in the Figure 4 below.

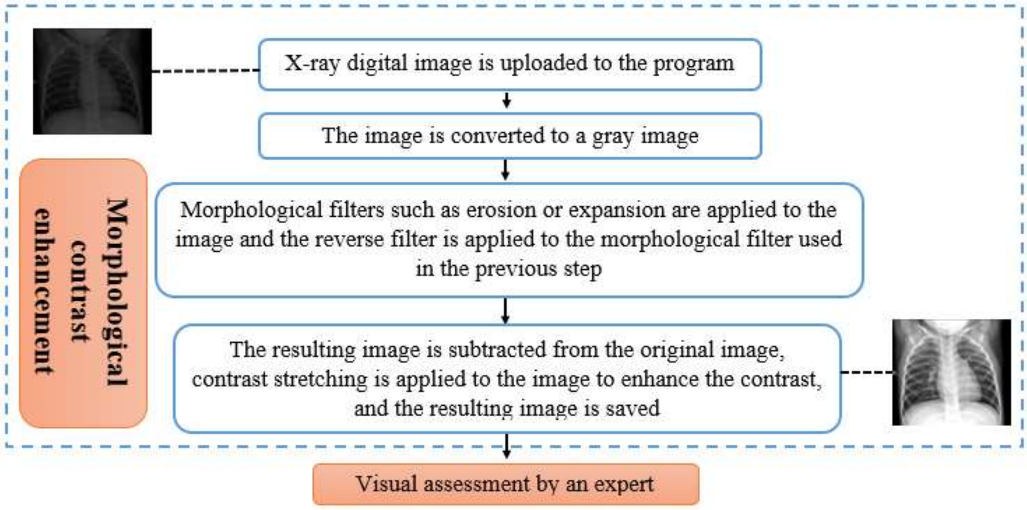

Fig. 4. Morphological contrast enhancement algorithm

The morphological contrast enhancement algorithm is based on morphological operations that change the shape of objects in the image, it helps to improve the edges and boundaries between structures and is effective in enhancing the contrast in low and high-contrast images. However, it can also cause increased noise in the image. Therefore, it is necessary to optimize the parameters of the morphological filters used in this algorithm to achieve the desired level of contrast enhancement while minimizing the noise gain.

3. Results

The analysis was carried out by conducting computational experiments based on the algorithms mentioned above to evaluate the quality of the image by enhancing the contrast in the X-ray image. 3615 X-ray images of human knees from the database Osteoarthritis-prediction [30] were used. 660 out of 3615 images have good contrast, 1779 images have average contrast and 1176 images have low contrast using the RMS contrast estimation method.

For images based on osteoarthritis-prediction M_1 - histogram equalization, M_2 – CLAHE, M_3 – Contrast Stretching, M_4 – Morphological Contrast Enhancement algorithms, the results in Table 2 to Table 4 were obtained according to criteria k_1, k_2 and k_3 when evaluating the quality of images.

Out of 3615 images according to k_1 criterion values, 683 images in algorithm M_1, 1078 in algorithm M_2, 1603 in algorithm M_3 and 251 in algorithm M_4 gave the best results. From the obtained results, algorithm M3, this is contrast stretching algorithm, is the best algorithm according to k_1, followed by the CLAHE algorithm, which provides good results.

Table 2
Contrast enhancement algorithm values in k_1

Algorithm values in k_1 criterion				k_1 value is the highest algorithm
M_1	M_2	M_3	M_4	
0,8064	0,8667	0,7221	0,7546	2
0,8308	0,8398	0,7371	0,7353	2
0,5763	0,7673	0,8908	0,4858	3
0,5945	0,7775	0,8554	0,4699	3
0,6444	0,8512	0,8562	0,6881	3
0,7536	0,8512	0,7791	0,6787	2
0,6208	0,8188	0,8898	0,7014	3
0,7061	0,8219	0,8358	0,6722	3
0,8568	0,8455	0,6927	0,7580	1
0,8245	0,7911	0,7093	0,7085	1
0,6469	0,7663	0,7611	0,7388	2
0,6562	0,7762	0,7367	0,6915	2
0,4946	0,8973	0,9254	0,7950	3
0,5609	0,8742	0,8891	0,7650	3
…….	…….	…….	…….	…….

Table 3
Contrast enhancement algorithm values in k_2

Algorithm values in k_2 criterion				k_2 value is the highest algorithm
M_1	M_2	M_3	M_4	
27,4432	27,8504	26,9957	30,2318	4
23,4753	23,4089	23,0592	22,4551	1
22,9363	23,3828	23,0914	22,4076	2
27,6279	28,3874	27,4671	26,9181	2
27,0857	28,4441	27,1485	27,1392	2
27,4861	28,1326	26,8828	26,8938	2
26,5180	28,0070	27,3457	26,9027	2
26,7633	27,7501	26,6698	27,7941	4
26,1565	27,1314	26,2288	28,3427	4
27,0786	27,9882	27,1343	26,7185	2
27,2625	28,0316	26,9558	26,3780	2
28,9017	29,2355	28,4994	31,7820	4
28,7141	28,5170	27,7710	27,6705	1
27,4432	27,8504	26,9957	30,2318	4
23,4753	23,4089	23,0592	22,4551	1
…….	…….	…….	…….	…….

The following results were obtained for the k_2 criterion values: out of 3615 images, the k_2 criterion gave the best results in 187 images in the M_1 algorithm, 1686 in the M_2 algorithm, 110 in the M_3 algorithm and 1632 in the M_4 algorithm. From the obtained results, it can be recognized that the M_2 algorithm, that is, CLAHE algorithm, is the best algorithm according to the PSNR criterion.

According to the k_3 criterion values, the following results were obtained: out of 3615 images, 97 in the M_1 algorithm, 2522 in the M_2 algorithm, 259 in the M_3 algorithm and 737 in the M_4 algorithm showed good results according to the k_3 criterion. From this, the M_2 algorithm, that is, the CLAHE algorithm, can be recognized as the best algorithm according to the MSE criterion.

Table 4
Contrast enhancement algorithms values in k_3

Algorithm values in k_3 criterion				k_3 value is the highest algorithm
M_1	M_2	M_3	M_4	
0,0363	0,0059	0,0385	0,0082	2
0,0288	0,0066	0,0505	0,0117	2
0,1372	0,0749	0,1224	0,0337	4
0,1388	0,0792	0,0871	0,0347	4
0,1125	0,0080	0,0214	0,0231	2
0,0530	0,0091	0,0387	0,0121	2
0,1105	0,0067	0,0306	0,0202	2
0,0677	0,0090	0,0425	0,0158	2
0,0160	0,0077	0,0434	0,0091	2
0,0196	0,0103	0,0463	0,0143	2
0,0641	0,0154	0,0433	0,0153	4
0,0571	0,0212	0,0450	0,0125	4
0,1918	0,0026	0,0122	0,0200	2
0,1512	0,0042	0,0211	0,0231	2
0,0363	0,0059	0,0385	0,0082	2
....	....	....	....	....

To compare the obtained results, Figure 5 shows the criterion results of SSIM, PSNR and MSE for images obtained by applying histogram equalization, CLAHE, contrast stretching and morphological contrast enhancement algorithm to the images.

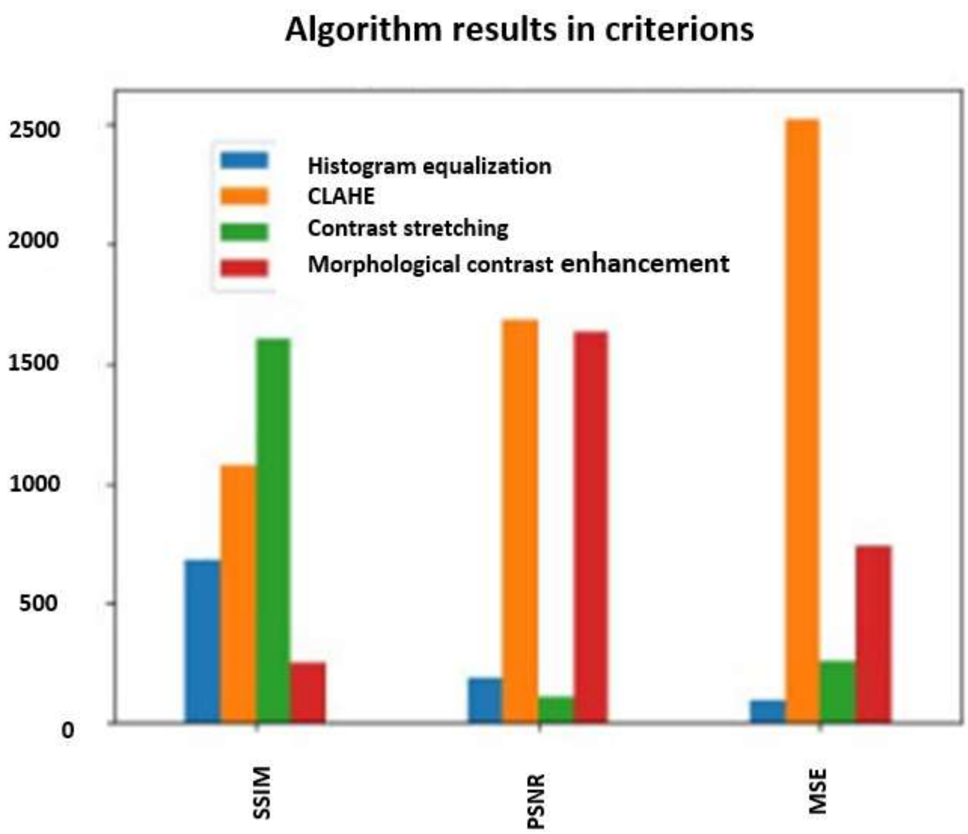

Fig. 5. SSIM, PSNR and MSE criterion results

4. Discussion

One of the main issues that arise in the discussion of the results of this research is the choice of the optimal criterion for image quality assessment. SSIM, PSNR and MSE, which are standard criteria for image quality assessment, each have their own merits and demerits [4]. For example, SSIM takes into account the structural features of the image and is more sensitive to distortions caused by image compression [31]. PSNR is a classic criterion for image quality assessment that measures the ratio of maximum signal power to noise power [32]. MSE is an evaluation criterion based on the standard deviation between the original and the processed image [28]. The choice of a particular criterion may depend on the specific task and requirements of the study.

This article discussed histogram equalization, CLAHE, contrast stretching and morphological contrast enhancement algorithms for image contrast enhancement. Each of these algorithms has its advantages and limitations and their effectiveness may depend on the image type and task characteristics. Because, in many literatures, it is emphasized that different algorithms of contrast enhancement are suitable for different types of images [33-38]. In experimental studies, contrast enhancement algorithms were evaluated by SSIM, PSNR and MSE criteria and as a result, the algorithm with the largest SSIM value and a value close to 1 is determined as the most optimal algorithm according to this criterion. The algorithm that gives the largest PSNR value and the smallest MSE value is recognized as the optimal algorithm corresponding to them. As a result, an approach to the selection of the contrast enhancement algorithm is formed in relation to the evaluation criterion. In turn, which algorithm result is closest to the original image?, allows to answer the question according to the criterion.

5. Conclusions

Radiologists need high-quality X-ray images to make a correct medical diagnosis. Evaluation of image quality by contrast enhancement is an important step in the interpretation of X-ray images. Because the X-ray image must have enough contrast. By applying image contrast enhancement algorithms, it can help doctors diagnose and treat various medical conditions.

In this article, using a set of X-ray images of human knee bones in PNG format, the quality of images generated by changing their contrast with four different algorithms was evaluated by SSIM, PSNR and MSE criteria. The following conclusions can be drawn from the results of the above calculation experiments:

i. Among the mentioned popular algorithms of contrast enhancement, the CLAHE algorithm was found to be the most optimal in improving the quality of X-ray images;
ii. The pair formed based on the MSE criterion and the CLAHE algorithm from the contrast enhancement algorithms was recognized as the most optimal pair.

The determined optimal pair helps not only to improve image quality but also to make accurate and fast diagnoses, which is extremely important in medical practice. Because every minute is important in medicine. The speed and accuracy of diagnosis directly affect the success of the treatment of patients. Therefore, it is not only relevant but also important to determine the optimal pair criteria and algorithms for enhancing the contrast of X-ray images.

One of the main advantages of the optimal pair is the ability to standardize the diagnostic process. That is, the optimal pairing helps medical professionals reduce variability in image evaluation. In addition, the optimal pair also serves to optimize the image processing process. By choosing the most effective algorithm based on a specific criterion, medical institutions can increase efficiency and speed up the diagnosis process. This saves the time of medical professionals and patients and reduces the burden on medical systems.

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