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EFFICIENCY OF WAVELET ANALYSIS FOR RESTORATION OF X-RAY IMAGES: A COMPARATIVE STUDY

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Abstract:

The article examines the application of various wavelet transforms for X-ray image processing aimed at improving the quality of medical diagnostics. A comparative analysis using the MSE, PSNR, and SSIM metrics was performed to assess the quality of image restoration. The obtained results demonstrate the effectiveness of specific wavelet families in enhancing image visualization and increasing the accuracy of anomaly detection. The presented research contributes to the advancement of medical image processing methods intended for the optimization of diagnostic procedures.

Keywords: Wavelet analysis, X-ray images, medical visualization, image quality, MSE (Mean Squared Error), PSNR (Peak Signal-to-Noise Ratio), SSIM (Structural Similarity Index), image processing, medical diagnostics, comparative analysis.

INTRODUCTION

In recent years, methods for processing X-ray images have gained significant importance in medical diagnostics, as they enable early detection of pathologies and improve the effectiveness of therapeutic interventions. One of the major challenges is the selection of appropriate algorithms capable of providing high-quality data processing with minimal computational cost [3, 7, 8].

Among the numerous methods used for image analysis, wavelets attract particular attention due to their ability to analyze data at different scales [5]. Wavelet analysis is successfully applied to image enhancement, noise reduction, contrast improvement, and anomaly detection. For example, study [1] demonstrated that image quality metrics such as PSNR and SSIM allow objective evaluation of image restoration after wavelet processing.

Nevertheless, the problem of selecting the optimal wavelet type for specific medical imaging tasks, including X-ray image processing, remains unresolved [4]. In this study, a comparative analysis of different wavelets (e.g., Haar, Daubechies, and Coiflet) was performed using benchmark metrics such as MSE, PSNR, and SSIM. The main objective of the study is to identify the most effective approach for medical image restoration, thereby contributing to improved diagnostic accuracy.

METHODS

For the analysis and processing of X-ray images, wavelet analysis was applied as a powerful tool for signal decomposition and extraction of significant features at different scales. This study investigates the performance of several wavelet families (Haar, Daubechies, Coiflet, and Bior), which are widely used in medical image processing tasks [2, 9].

Modern literature describes a large number of objective image quality metrics, which can be divided into three categories [1]:

- *Full-reference (FR) metrics* — assume the availability of an original reference image considered noise-free and of ideal quality.

- *No-reference (NR) metrics* — evaluate image quality without requiring a reference image. Such metrics are the most difficult to implement and are often designed for specific types of distortions.

- *Reduced-reference (RR) metrics* — assume that partial information about the reference image is available together with the distorted image, while the amount of this information is significantly smaller than that required for full-reference methods.

In this study, the class of full-reference metrics was selected for the following reasons:

- the quality assessment values of these metrics are closest to expert visual evaluation;
- they are widely used in image compression and restoration tasks;
- the majority of image quality assessment methods described in the literature belong to this category.

The following metrics were used to evaluate restoration quality.

Mean Squared Error (MSE) is a metric used to measure the average error between the original and reconstructed (or compressed) image. The metric calculates the mean squared difference between the pixel intensities of two images [6, 11].

The MSE between two images *I* and *K* of size *m x n*) is defined as:

$$MSE(I,K) = \frac{1}{mn}\sum_{i=1}^{m}\sum_{j=1}^{n}[I(i,j) - K(i,j)]^2$$

where:

- m and n are the image dimensions;

- $I(i, j)$ and $K(i, j)$ are the pixel values at position (i, j).

For example, if $m=n=256$ and the average pixel intensity difference $I(i, j)-K(i, j)$ equals 5, then $MSE=25$.

A lower MSE value indicates fewer differences between the original and restored image. However, MSE does not always correlate with human visual perception [4, 5]. For instance, large errors in bright image regions may be perceived as less significant than small errors in dark regions.

Peak Signal-to-Noise Ratio (PSNR) is used to evaluate the visual quality of images. Higher PSNR values indicate lower image distortion.

$$PSNR = 10 \cdot log_{10}\left(\frac{M^2}{MSE}\right)$$

where:

- M is the maximum possible pixel value (e.g., 255 for 8-bit images);

- MSE is the mean squared error.

A higher PSNR value corresponds to better image quality and lower distortion. PSNR is commonly used when comparing an original image with its reconstructed version after compression or restoration.

Structural Similarity Index (SSIM) is an image quality assessment metric based on three criteria: luminance, contrast, and structure. The metric ranges from 0 to 1, where higher values indicate lower distortion and better image quality.

Compared to PSNR, SSIM requires more computational resources. However, SSIM is considered one of the first successful metrics that closely corresponds to human visual perception, as confirmed by numerous studies [10, 11]. Therefore, SSIM is widely used in evaluating perceived image quality in applications such as medical imaging and broadcasting systems.

The SSIM formula is expressed as:

$$SSIM(x,y) = \frac{(2\mu_x\mu_y + c_1)(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + c_1)(\sigma_x^2 + \sigma_y^2 + c_2)}$$

where:

- x and y are the compared images;
- μ_x and μ_y are the mean values of images x and y;
- σ_x^2 and σ_y^2 are the variances;
- σ_{xy} is the covariance;
- c_1 and c_2 are constants introduced to stabilize the division.

Processing Stages

1. Data preparation. X-ray images were converted into digital format with predefined resolution parameters.
2. Wavelet application. Each image was decomposed using the selected wavelet.
3. Quality evaluation. MSE, PSNR, and SSIM metrics were applied to evaluate processing results.
4. Comparison and interpretation. The obtained results were analyzed to identify the most effective method.

Conceptual Processing Scheme

A conceptual scheme representing the stages of image processing was developed, starting from data acquisition and ending with result analysis.

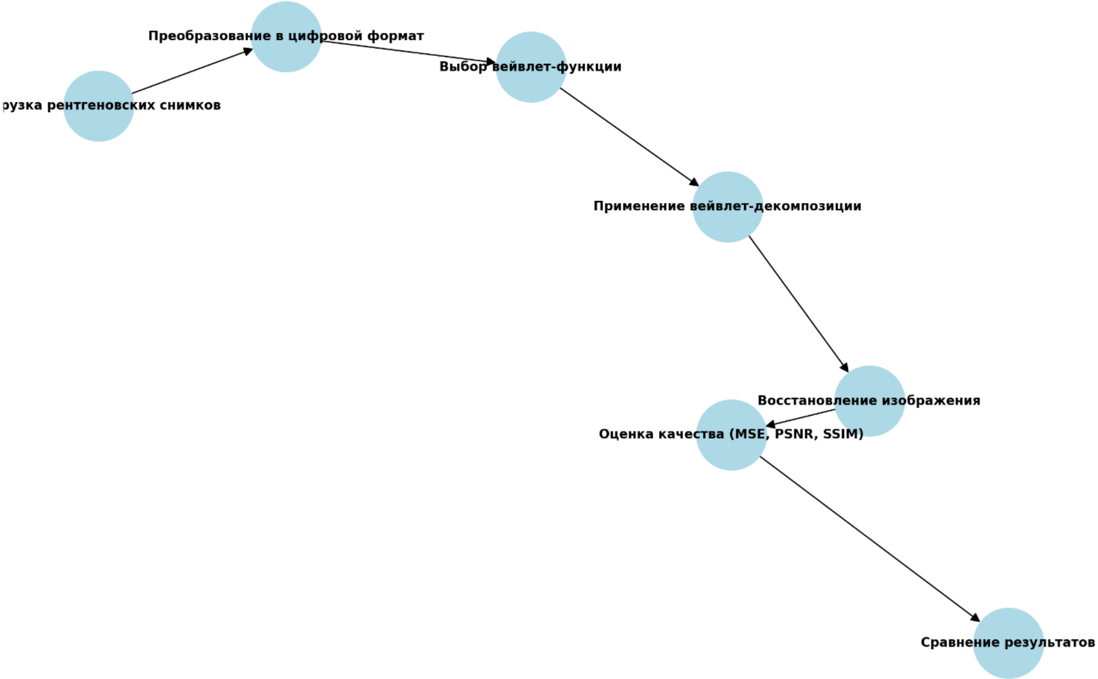

Fig. 1. Processing scheme of X-ray images

RESULTS AND DISCUSSION

In this study, a comparative analysis of different wavelet types (Haar, Daubechies, Coiflet, and Bior) for X-ray image processing was performed. The quality of reconstructed images was evaluated using the metrics MSE, PSNR, and SSIM. The results are presented in the form of graphs illustrating the efficiency of each method.

- MSE (Mean Squared Error). The minimum MSE value was obtained for Db10 (0.000050), indicating the lowest reconstruction error.

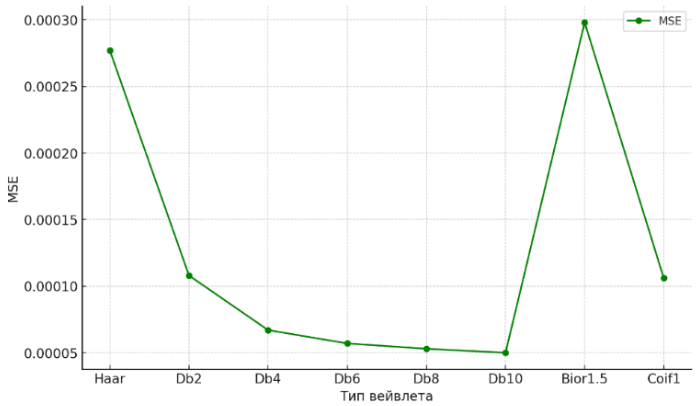

Fig. 2. Comparison of MSE for different wavelets

- PSNR (Peak Signal-to-Noise Ratio). The highest PSNR values were achieved by Daubechies (Db10) and Coiflet wavelets (42.97 dB and 42.72 dB, respectively), indicating minimal distortion after processing.

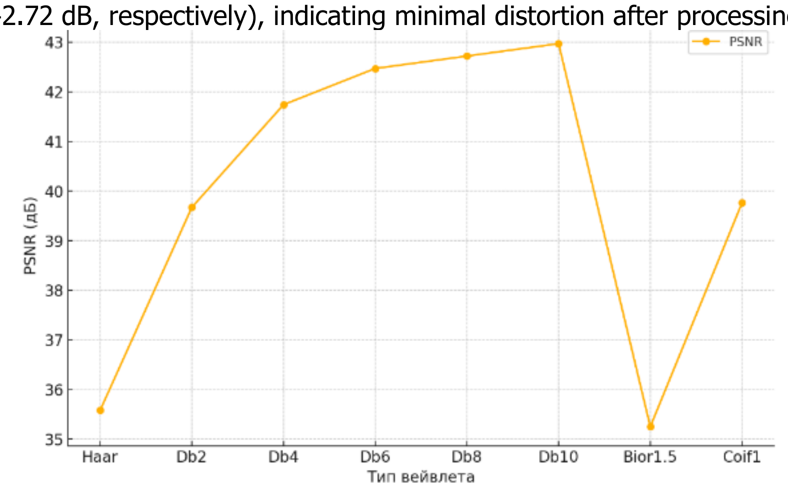

Fig. 3. Comparison of PSNR for different wavelets

- SSIM (Structural Similarity Index). SSIM values higher than 0.98 were also achieved using Db10 and Coiflet wavelets, demonstrating a high degree of structural similarity between the original and reconstructed images.

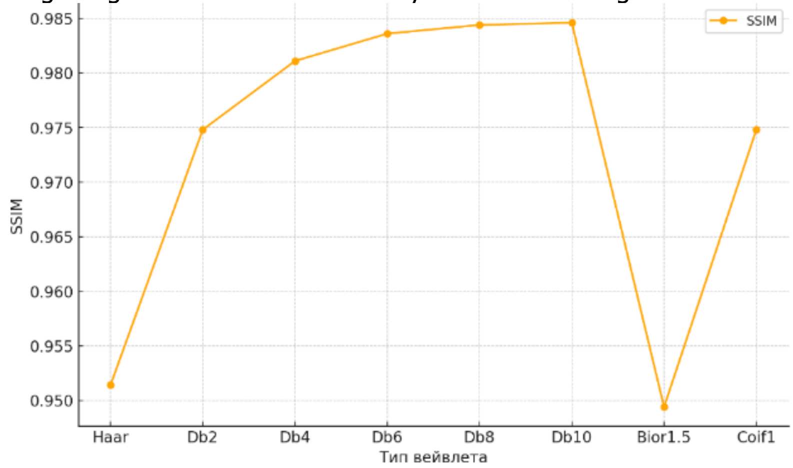

Fig. 4. Comparison of SSIM for different wavelets

The obtained results indicate that the choice of wavelet significantly influences the quality of X-ray image restoration.

The Daubechies (Db10) wavelet demonstrated high efficiency due to its superior PSNR and SSIM values combined with a low MSE value. Therefore, it can be considered the preferred choice for applications requiring minimal distortion.

The Coiflet wavelet showed results close to Db10 and may be recommended as an alternative approach when high restoration accuracy is required.

Although the Haar wavelet is simple and computationally efficient, its restoration quality was lower compared to more complex wavelet families.

The presented graphs demonstrate a general tendency toward improved image restoration quality with increasing wavelet complexity. However, the computational complexity of advanced wavelets should also be considered, especially in environments with limited computational resources

CONCLUSION

This study presented a comparative analysis of different wavelets for X-ray image processing. The application of MSE, PSNR, and SSIM metrics enabled objective evaluation of image restoration quality and identification of the advantages of each approach.

The Daubechies (Db10) wavelet demonstrated the best performance in terms of PSNR, SSIM, and MSE, making it the most suitable choice for medical image visualization tasks. Coiflet and Db8 wavelets also showed high performance and may be applied in tasks with less stringent computational efficiency requirements. Despite its implementation simplicity, the Haar wavelet demonstrated lower restoration quality.

The obtained results confirm that optimization of wavelet selection plays a significant role in improving the quality of medical imaging. This is particularly important for accurate diagnostics and enhancement of clinical decision-making processes.

The proposed approaches can be integrated into computer-aided medical image analysis systems to improve diagnostic accuracy. Furthermore, the results of this study may be useful for the development of algorithms for automated analysis of X-ray images.

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