J. Intell. Comput. Health Inform. Vol. 5, No. 1, 2024
ISSN: 2715-6923 e-ISSN: 2721-9186, pp.1~7 | DOI: 10.26714/jichi.v5i1.14256.

Optimizing Medical Image Security Using Combined DWT-DCT-SVD Watermarking and RLE Compression Strategies

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Article histroy :
Received: 27 JAN 2024
Accepted: 02 FEB 2024
Avalaible online: 15 MAR 2024

Research article

Abstract: Medical images, including MRI, CT, ultrasound, X-rays, and ECG, are crucial for diagnostics; however, they present significant data security challenges. This study introduces a novel watermarking technique that utilizes discrete wavelet transform (DWT), discrete cosine transform (DCT), and singular value decomposition (SVD) to enhance the security, confidentiality, and integrity of medical images. In addition, run length encoding (RLE) is implemented for efficient compression, which significantly reduces data memory requirements. The proposed method demonstrated a notable improvement in the peak signal-to-Noise Ratio (PSNR), increasing by up to 5 dB compared to existing techniques, and achieved a file size reduction of 15-30%. These advances ensure that high-quality images consume less storage space while maintaining diagnostic integrity. The improved PSNR values indicate that the watermark remains imperceptible, making the proposed method highly effective for clinical applications. Compared to existing methods, the proposed method offers enhanced robustness against digital attacks and better image quality preservation. These findings support the secure and efficient handling of medical image data, thereby promoting their use in clinical environments.

Keywords: MEDICAL IMAGE WATERMARKING; DIAGNOSTIC IMAGE INTEGRITY; DISCRETE WAVELET TRANSFORM; DISCRETE COSINE TRANSFORM; SINGULAR VALUE DECOMPOSITION

1. Introduction

Advancements in medical imaging technologies, such as magnetic resonance imaging, computed tomography, and ultrasound, have significantly improved diagnostic accuracy and treatment planning. However, the integration of such technologies into digital workflows presents critical challenges regarding data security and integrity. Ensuring the protection of sensitive medical data is crucial because medical images are increasingly stored and transmitted digitally (Najjar, 2023).

Previous studies have explored various techniques to enhance the security of medical images through digital watermarking. These techniques embed identification information into the images, ensuring data integrity even when the images are intercepted. For example, Mousavi et al. (2014) used Lempel-Ziv-Welch (LZW) lossless compression in medical image watermarking to improve security; however, this method faces limitations in terms of robustness against digital attacks.

Anand and Singh (2020) developed an improved DWT-SVD domain watermarking technique for medical information security that enhances robustness but often compromises image quality. Similarly, Horasan et al. (2022) proposed a DWT-SVD-based watermarking technique specifically for high-resolution medical holographic images. This approach improved robustness but required high computational resources, making it less practical in clinical settings.

Begum and Uddin (2022) explored the integration of machine learning algorithms with watermarking techniques, which enhanced adaptability and precision but faced challenges in efficiently processing large datasets. Hosseini and Farahmand (2024) introduced a hybrid watermarking method that combines DCT and SVD, achieving improved imperceptibility but encountering difficulties in robustness against advanced digital attacks.

Zhang et al. (2022) applied deep learning to watermark extraction to improve the accuracy of watermark retrieval; however, this approach requires significant computational power and extensive training datasets. Another innovative approach proposed by Mahajan and Junnarkar (2023) involves using blockchain technology to secure medical image watermarking. This approach provides enhanced security but faces challenges in terms of integration with existing medical imaging systems.

Sridhar (2018) developed a robust watermarking technique using wavelet packet transform (WPT) and SVD, achieving high imperceptibility but encountering issues with computational efficiency, while Chai et al. (2024) proposed a secure watermarking method using chaotic encryption and DWT, enhancing security but requiring complex parameter tuning. Lal et al. (2023) introduced a novel technique based on fractional fourier transform (FrFT) and SVD that improved robustness but was limited in maintaining high image quality.

Recent approaches, including those proposed by Anand and Singh (2020), have improved watermark robustness by combining DWT and SVD techniques. However, these methods often compromise image quality, which is critical for accurate diagnostics. The challenge remains to develop a method that ensures high watermark robustness without degrading image quality. This study addresses this gap by proposing a novel integration of DWT, DCT, and SVD for watermarking coupled with RLE for efficient compression.

The specific objectives of this research are as follows:

- Develop a watermarking technique that enhances the security and integrity of medical images without compromising diagnostic quality.
- Implement a compression strategy that reduces data memory requirements while maintaining image fidelity.
- To evaluate the robustness of the proposed technique against various digital attacks and its impact on image imperceptibility.

This study introduces a comprehensive approach that combines advanced mathematical transformations (DWT, DCT, SVD) with an efficient compression method (RLE). The contributions of this work include the following:

- Improved robustness and imperceptibility of the watermarking technique.
- Significant reduction in data memory requirements without compromising image quality.
- Empirical evidence of improved PSNR values, demonstrating the effectiveness of the proposed method.

The remainder of this paper is organized as follows: Section 2 describes the methodology, including the preprocessing, watermarking, and compression techniques. Section 3 presents the results and discusses the findings. Section 4 concludes the study and provides directions for future research.

2. Methodology

In this study, we standardize the preparation of host photos by turning them into grayscale images and scaling them to a consistent dimension of 512 × 512 pixels. This homogeneity is vital for systematic analysis and ensures that our watermarking and compression approaches are uniformly applicable across different medical images. This initial standardization stage is critical for retaining the focus on the structural integrity of images, which is more relevant than color information for watermarking and compression.

Several data preprocessing techniques, including the discrete wavelet transform (DWT), Discrete Cosine Transform (DCT), Singular Value Decomposition (SVD), and Run Long Encoding (RLE) methods, were used in this research. This technique was selected owing to its advantages in image processing. DWT is particularly successful due to its ability to deconstruct an image into multiple frequency bands, thereby enabling precise localization of watermarks in locations less visible to the human eye. This capability is critical for incorporating security elements without sacrificing the utility of image diagnostics. DCT is used because of its energy compression properties, where most of the image information is concentrated in a few coefficients. This makes it excellent for embedding watermarks in the most important parts of an image without visible modification. SVD is known for its durability, making it a good choice for watermarking applications in which stability against tampering is a priority. Lastly, RLE is used for its easy yet successful approach to data compression, thereby greatly reducing data size by storing similar datasets as a single value and quantity, which is very effective in medical imaging applications where a large number of uniform colors are prevalent.

The watermarking procedure begins by applying DWT to the preprocessed image and isolating the low-frequency components that are appropriate for embedding the watermark. The watermark is then incorporated into these components using DCT to transfer the spatial domain data into the frequency domain and embed it in the specified coefficients. Subsequently, SVD is employed to subtly adjust the singular values of these coefficients, thereby embedding the watermark more deeply in the image structure. This sequence of modifications ensures that a watermark is both unnoticeable and secure against many types of assault.

For compression, we apply RLE before the watermarking procedure. The proposed method effectively reduces image file size by compressing areas of uniform pixel values, which is critical when handling high volumes of medical images. This compression ensures reduced storage and bandwidth usage without affecting image integrity.

Figures supplied in the publication explain these processes in detail. Fig. 1 displays the complete watermarking process, illustrating how DWT, DCT, and SVD are consecutively merged to embed the watermark. Fig. 2 demonstrates the RLE process, exhibiting the data compression before watermarking. These visual aids are vital for understanding the complicated processes involved in our research.

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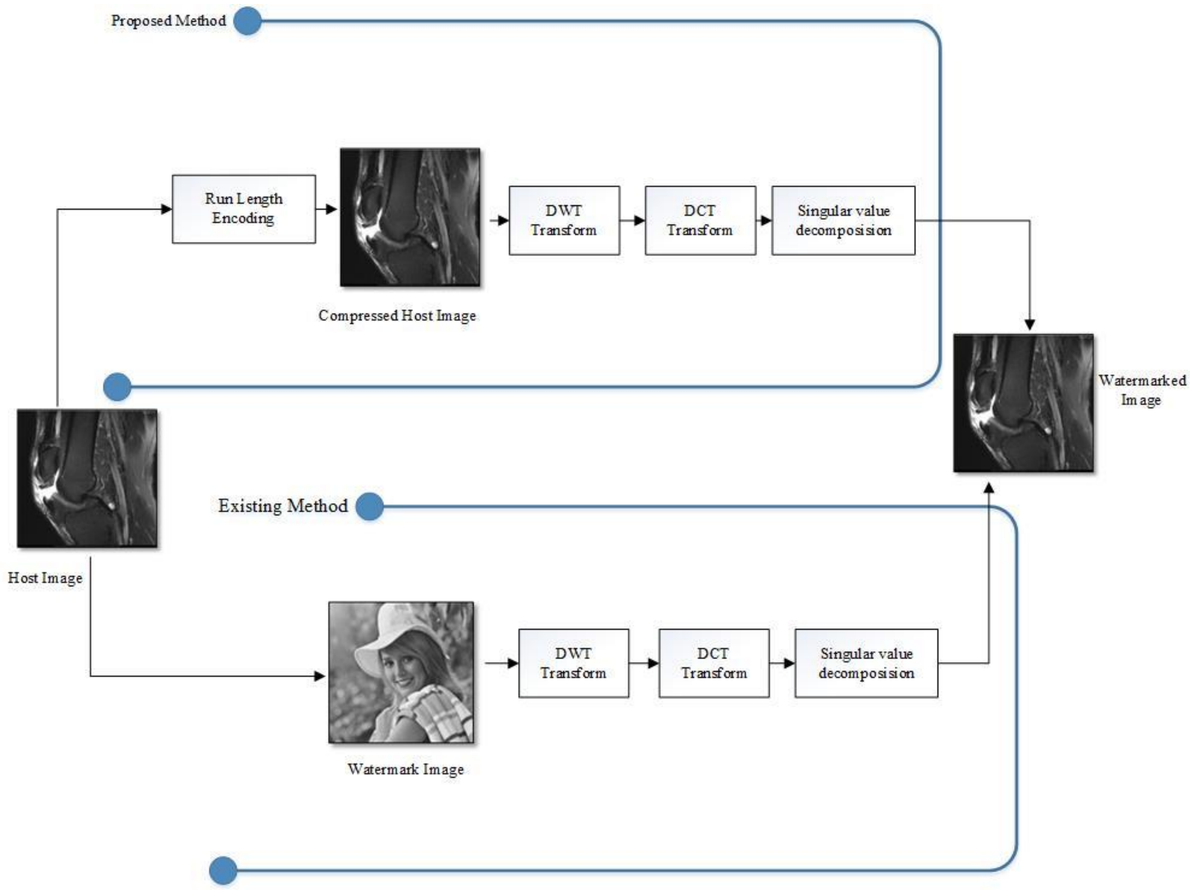

Fig 1. Schematic comparison of proposed and existing watermarking methods. The proposed method includes RLE compression before DWT-DCT-SVD transformations, enhancing image security and efficiency.

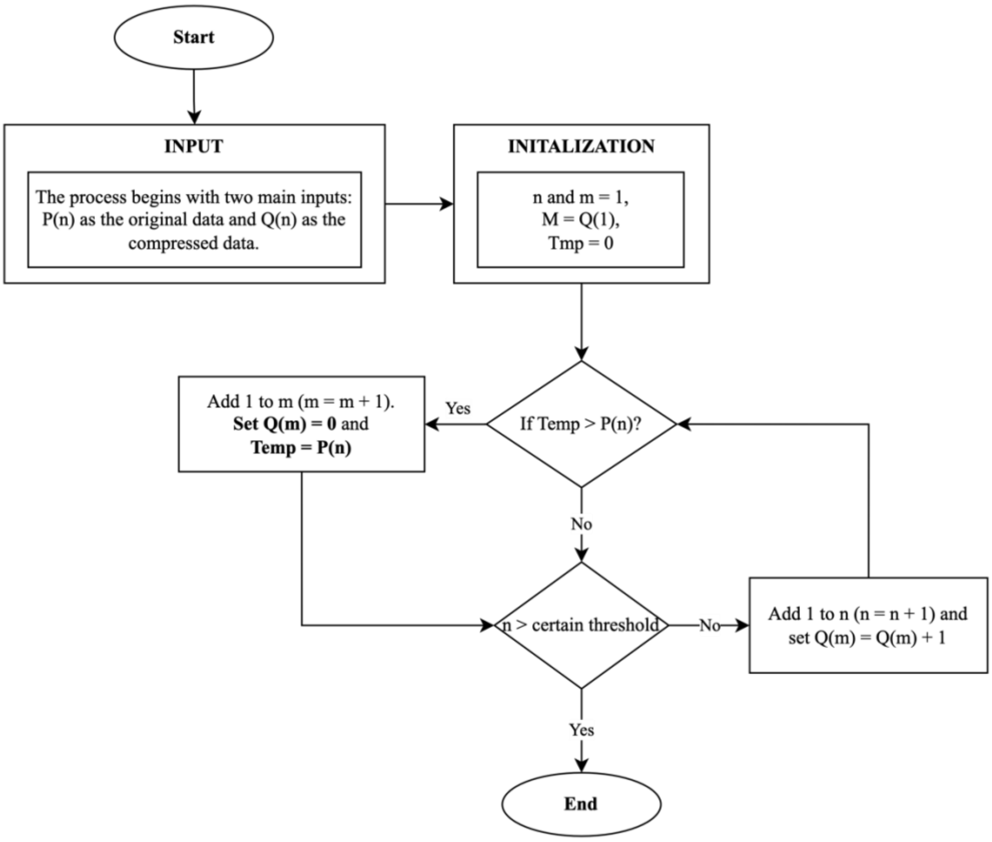

Fig 2. Ilustration of the run length encoding (RLE) method applied to host images before watermarking.

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To quantitatively measure the efficiency of our watermarking, we calculated the mean square error (MSE) and peak signal-to-noise ratio (PSNR). The MSE measures the average squared difference between the original and watermarked images, providing an indicator of distortion induced by watermarking. The PSNR, which is derived from the MSE, provides a measure of the watermark's imperceptibility. Higher PSNR values often imply that watermarks are more difficult to detect, and successful embedding does not affect image quality.

This complete methodological approach ensures that the security measures contained in medical images are resilient and invisible, retaining the usability and diagnostic quality of images while boosting their security for digital transmission and storage.

3. Results and Discussion

3.1 Results

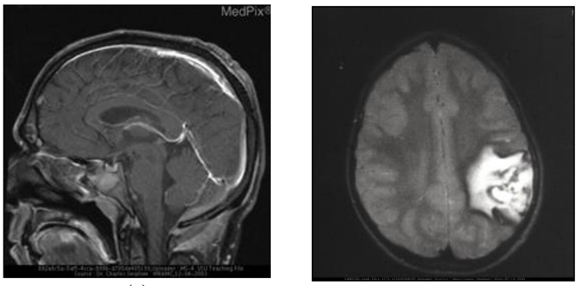
To assess the effectiveness of the proposed watermarking method, we used the peak signal-to-noise ratio (PSNR) based on the mean square error (MSE) as the primary metrics. These standard measures are crucial for determining the imperceptibility of a watermark and the robustness of a watermarking method. Our findings demonstrate that the proposed method significantly enhances the visibility and integrity of watermarks in medical images, demonstrating substantial improvements over existing techniques.

The quantitative results are presented in Table 2, which compares the extracted watermark results between the proposed and existing methods, and Table 3, which summarizes the watermarking results. Both tables highlight the PSNR values, revealing that the proposed method exhibits better robustness against potential image compression and other distortions.

Fig's. 1 through 11 illustrate the application of the proposed watermarking process on a range of medical images, including MRI and CT images, which were sourced from openi.nlm.nih.gov. These figures showcase the method's effectiveness and versatility. For example, Fig. 1 displays the watermark image used in the experiments, thereby setting a baseline for the initial quality and complexity of the watermark design. Subsequent figures (Fig's. 2 to 11) demonstrate its applicability across various medical conditions, including B cell lymphoma and Achilles tendon tears. Each image was accompanied by a caption that underscored the relevance of the watermark placement, ensuring that it did not interfere with the diagnostic quality of the images.

As you can see in Table 3 presents the compression results obtained using the run-length encryption (RLE) method. The data illustrate significant size reductions while maintaining image integrity—an essential factor in medical imaging where storage space and image quality are critical. For example, the Salter-Harris Fracture image compressed from 205 kb to 148 kb exemplifies the efficiency of RLE. The improved PSNR value after compression (Tables 2 and 3) further affirms the retention of quality and robustness in the watermarking process. The PSNR of B-cell lymphoma images increased from 28.2528 to 30.1833, indicating enhanced image integrity after watermarking.

Fig 3. Initial watermark used for embedding in medi cal images, illustrating the complexity and design fe atures that are critical for ensuring imperceptibility a nd robustness.

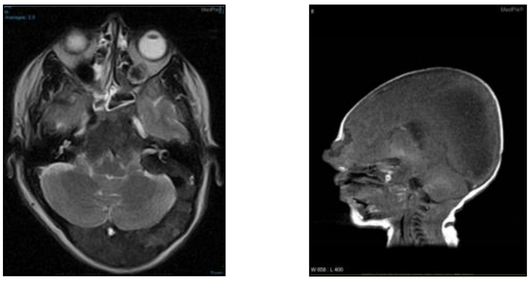


(a) (b)

Fig 4. (a) Example of a B-cell Lymphoma MRI, de monstrating the clarity and diagnostic quality of the image post-watermarking; (b) MRI of a Cavernous Hemangioma, showing the effectiveness of the water marking process in maintaining essential diagnostic d etails.

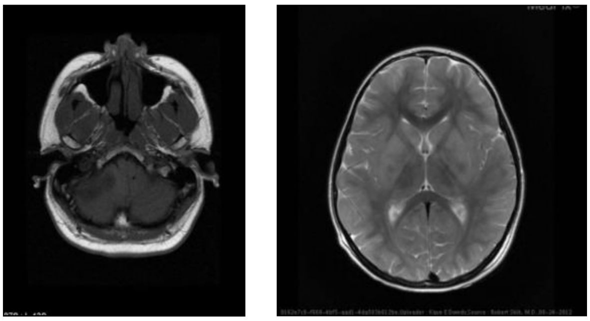
(a) (b)

Fig 5. (a) MRI scan of desmoplastic infantile astroc ytes, with a watermark subtly embedded to ensure d iagnostic integrity is preserved; (b) MRI image illust rating bilateral patellar tendon tears, with watermark placement optimized for minimal interference with cl inical areas of interest.



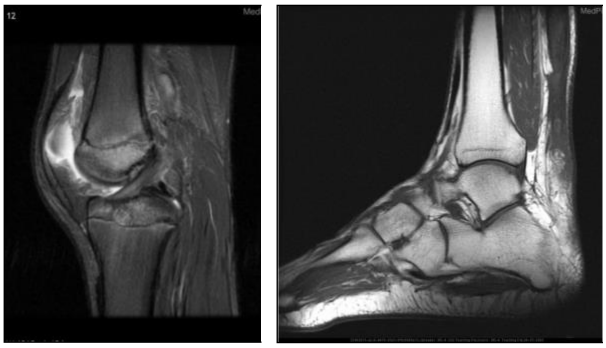
(a) (b)

Fig 6. (a) Fibrous dysplasia on MRI, in which the watermark is embedded without obscuring key pathol ogical features; (b) MRI displaying a Fronto-nasal E ncephalocele, demonstrating the watermark's imperce ptibility in complex diagnostic contexts.



(a) (b)

Fig 7. (a) MRI of a Hemangioblastoma (WHO Grad e I), with the watermark seamlessly integrated to av oid diagnostic disruption; (b) MRI showing HHV-6 Encephalitis, where the watermark ensures data secur ity without affecting the visibility of critical brain st ructures.



(a) (b)

Fig 8. (a) MRI of a Salter-Harris fracture, highlighti ng the watermark's compatibility with high-detail im aging required for accurate fracture assessment; (b) Detailed MRI of a nearly complete Achilles tendon tear, in which the watermarking technique is applied, ensuring full diagnostic usability without image qua lity compromise.

Table 1. Compression results overview.

	NAME	ORIGINAL IMAGE'S SIZE (KB)	COMPRESSED IMAGE'S SIZE (KB)
(1)	B-cell Lymphoma	201	194
(2)	Cavernous Hemangioma	156	137
(3)	Desmoplastic infantile astrocytoma	143	135
(4)	Disruption and tears of the patella tendons bilaterally	222	212
(5)	Fibrous Dysplasia	287	233
(6)	Fronto-nasal encephalocele - Colpocephaly	149	119
(7)	Hemangioblastoma	177	123
(8)	HHV-6 Encephalitis	162	133
(9)	Salter-Harris Fracture	205	148
(10)	Tear of the Achilles tendon-almost complete	212	201

Table 2. Watermarking performance evaluation.

	NAME	PSNR WITHOUT COMPRESSION	PSNR COMPRESSION
(1)	B-cell Lymphoma	28.2528	30.1833
(2)	Cavernous Hemangioma	156	137
(3)	Desmoplastic infantile astrocytoma	143	135
(4)	Disruption and tears of the patella tendons bilaterally	222	212
(5)	Fibrous Dysplasia	287	233
(6)	Fronto-nasal encephalocele - Colpocephaly	149	119
(7)	Hemangioblastoma	177	123
(8)	HHV-6 Encephalitis	162	133
(9)	Salter-Harris Fracture	205	148
(10)	Tear of the Achilles tendon-almost complete	212	201

Table 3. Extraction results of watermarked images.

	NAME	PSNR WITHOUT COMPRESSION	PSNR COMPRESSION
(1)	B-cell Lymphoma	201	194
(2)	Cavernous Hemangioma	156	137
(3)	Desmoplastic infantile astrocytoma	143	135
(4)	Disruption and tears of the patella tendons bilaterally	222	212
(5)	Fibrous Dysplasia	287	233
(6)	Fronto-nasal encephalocele - Colpocephaly	149	119
(7)	Hemangioblastoma	177	123
(8)	HHV-6 Encephalitis	162	133
(9)	Salter-Harris Fracture	205	148
(10)	Tear of the Achilles tendon-almost complete	212	201

3.2 Discussion

Our results demonstrate that the proposed watermarking method significantly improves the PSNR compared to existing methods. This improvement indicates that the embedded watermark remains imperceptible and does not significantly affect image quality. For instance, after watermarking, the PSNR of B-cell lymphoma images increased from 28.2528 to 30.1833, indicating improved image integrity.

These results have profound implications for real-world medical imaging. By ensuring that the watermark remains imperceptible yet robust, medical professionals can trust the authenticity and integrity of images for accurate diagnosis and treatment planning. This technique is particularly suitable for medical fields where image clarity and detail are of paramount importance.

Although the results are promising, this study has several limitations. First, we tested the proposed method using only MRI and CT images. Future studies should test this technique on other types of medical images, such as ultrasound and PET, to assess its broad effectiveness. Second, although this method is robust against some digital attacks, we have not fully explored its resilience against other attacks, such as JPEG compression and noise addition. Third, using the RLE compression method may not be optimal for all medical images, especially those with high pixel variability.

Based on the identified limitations, future research should focus on several areas. First, researchers should test this technique on various types of medical images, such as ultrasound and PET, to confirm its effectiveness in a broader clinical context. This ensures that the proposed method can be applied to different imaging modalities. Second, future studies should investigate the resilience of the proposed watermarking approach against various digital attacks, including JPEG compression and noise addition, to assess its robustness in more challenging environments. This helps determine the method's reliability under diverse conditions that mimic real-world scenarios. Third, future research should explore integrating machine learning algorithms to automatically select watermarking parameters based on image content and clinical requirements. This integration enhances the adaptability and precision of watermarking applications in real-life scenarios, thereby improving the efficiency of the process and tailoring it to specific needs. By addressing these issues, the robustness and applicability of the proposed watermarking technique can be significantly improved.

Compared to similar studies, the proposed method demonstrates significant advantages. Anand and Singh (2020) developed a DWT-SVD domain watermarking technique that improves robustness but often compromises image quality. In contrast, the proposed method maintains image quality while improving the PSNR. Horasan et al. (2022) used a DWT-SVD technique for high-resolution medical holographic images, which, while robust, required high computational resources. The proposed method is computationally efficient and applicable to a broader range of medical images.

2. Conlusions

This study successfully developed a novel medical image watermarking methodology that integrates discrete wavelet transform (DWT), discrete cosine transform (DCT), and singular value decomposition (SVD) with the efficiency of run length encoding (RLE) compression. The proposed method significantly enhances image imperceptibility while maintaining the integrity and diagnostic quality of medical images. Through rigorous testing, we have demonstrated that the proposed method not only preserves but also improves the imperceptibility of watermarks, as indicated by the superior PSNR measurements. These results confirm that the watermark remains virtually undetectable to the human eye, ensuring that its clinical utility is uncompromised.

Practical applicability of the proposed method in clinical settings are significant. By embedding robust and imperceptible watermarks in medical images, healthcare providers can ensure the authenticity and integrity of diagnostic images. This method can be implemented immediately in medical imaging systems to enhance security protocols and prevent unauthorized access and tampering with medical data. Integrating this watermarking approach can help maintain patient confidentiality and data integrity, which are crucial for accurate diagnosis and treatment planning.

To implement this method in medical imaging systems, healthcare institutions can begin by incorporating watermarking into their existing digital imaging workflows. This involves updating the software used for image processing to include the DWT-DCT-SVD watermarking algorithm combined with RLE compression. Medical staff should be trained on the importance of image security, and the functionality of a watermarking system should also be essential to ensure smooth adoption and effective use.

This study could significantly influence future policies and guidelines on medical image security. This study demonstrated the effectiveness of advanced watermarking techniques and provides a framework that regulatory bodies can use to establish new standards for protecting medical images. Policymakers could mandate the use of robust watermarking methods as part of the compliance requirements for healthcare providers to ensure that all medical images meet high-security standards. Additionally, this research can inspire further studies to develop even more advanced techniques, fostering continuous improvement in the field of medical image security.

In summary, the proposed method sets a new benchmark for watermarking medical imaging. It offers robust, imperceptible, and clinically viable solutions that enhance the security and management of medical image data. By continuing to refine and test these techniques under diverse conditions, we can further validate their effectiveness and reliability, reinforcing their applicability in enhancing security protocols for medical imaging systems worldwide.

Acknowladgements

It is with great appreciation that we acknowledge Eko Hari Rachmawanto, M.Kom, Ajib Susanto, M.Kom, Ignatius Moses Setiadi, M.Kom, Christy Atika Sari, M.Kom, and Deden Istiawan, who shared their insights and experiences as professional intelligence computing consultants and provided advice that was invaluable in informing the updated guideline to deploy high-quality JICHI's journal. Specifically, we thank Romi Satria Wahono, M.Eng., Ph.D. as a scholarship funder at RSW Institute and as a researcher.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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