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Research Article

Securing DNA Profiles Using AES Cryptography: New Approach to Encrypted Biometric Authentication in EHR Systems

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ABSTRACT
Electronic Health Records EHRs have revolutionized healthcare by storing patient data in a digital format, increasing accessibility and efficiency. However, the flaws of traditional authentication methods necessitate the development of advanced security solutions. This study presents a novel methodology integrating AES-256 encryption with DNA-based steganography to enhance biometric verification in Electronic Health Records EHRs. The approach involves extracting Short Tandem Repeats STRs and Single Nucleotide Polymorphisms SNPs from DNA profiles, encoding the genetic data into binary format, and securing it with AES-256 encryption to ensure high confidentiality. Encrypted DNA profiles are embedded in MRI images by using the Discrete Cosine Transform DCT, which ensures the concealed data remains both imperceptible and secure against unauthorized alterations, and during the authentication phase, and the encrypted genetic information is extracted, decrypted, and matched with reference samples for verification, the experimental results indicate that the system significantly improves both biometric security and medical data protection, with average processing time of approximately 320 milliseconds, and as it exhibits strong resistance to tampering, achieving has a 99.8% success rate in preventing unauthorized modifications. The embedding method maintains a high level of image quality, reflected by a Peak Signal-to-Noise Ratio PSNR of around 47 dB, confirming that the diagnostic utility of MRI images remains unaffected. This approach effectively combines biometric security with medical data safeguarding, providing a dependable and scalable solution for patient authentication in electronic health record EHR systems.

Keywords: *AES-256; EHRs; DNA-Based Steganography; DCT; Biometric Verification*

1. INTRODUCTION

Electronic Health Records EHRs has changed the way modern healthcare is conducted by storing patient data in a digital format that is accessible, and protected, but the transition from paper-based systems to digital ones has led to significant problems in safeguarding medical information that is sensitive from unauthorized access and cyber criminals [1]. Traditional methods of patient identification, such as the use of medical ID numbers and biometric scanners, are susceptible to fraud, this necessitates the need for more advanced authentication mechanisms. DNA-based authentication has become a highly effective and unalterable solution to identify patients based on their genetic profile. This is done to verify their identity [2]. Unlike handwriting or numerical codes, DNA markers are specific to

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each individual which makes them an ideal tool for the medical sector. However, storing raw genetic information in EHRs poses a risk of privacy violation, including the potential for genetic profiling, unauthorized access, and ethical issues, combining cryptographic methods with DNA-based authentication is a viable approach to safeguard patient records while preserving privacy. AES-256 is recognized standard of cryptography that provides strong security against simple attacks, encrypting DNA profiles prior to storing them in EHRs, healthcare organizations can reduce the risk of privacy violation while maintaining data authenticity, and DNA steganography is a method of genetic information that is disguised as medical data or variants that are associated with the SNP is employed to ensure invisibility, and this prevents the unauthorized extraction of DNA profiles that are encrypted. This article describes a new method of achieving patient authentication that is both secure and based on DNA. This method is used in conjunction with EHRs that have a 256-bit AES-256 cryptographic key, by encrypting DNA profiles and concealing them in patient records, and this method increases privacy, stability and real time nature of authentication. The investigation investigates the security implications, computational efficiency, and practical feasibility of utilizing DNA-based cryption in healthcare.

2. RELATED WORKS

Electronic Health Records EHRs necessitate stringent security protocols to preserve patient information from malicious access, a several investigations have investigated DNA-based verification, encryption methods and biometric security in order to enhance privacy and data protection, a Gupta and Patel introduced a new form of biometric authentication that preserves privacy this method uses DNA encryption to demonstrate how genetic profiles that are encrypted enhance the verification of identity. Their investigation demonstrated the value of combining cryptographic protection with biological verification for the EHR. Lee and Ahmed conceived of genetic cryptanalysis methods for the security of DNA profiles, they proposed new approaches for encoding and encrypting genetic information for verification. Their investigation gave insight into how to improve the safety and effectiveness of genetic cryptanalysis protocols. Rahman and Singh incorporated a block_chain-powered DNA-based authentication system in EHRs, and this system demonstrated its potential to prevent unauthorized access to medical records. Their research demonstrated that distributed security models augmented by encryption-based authentication were beneficial to privacy protection. Bose and Kumar proposed DNA-based steganography methods, they studied the procedure of concealing genetic markers that are encrypted in medical records. Their findings support the utilization of cryptographic cover-up for biometric authentication purposes [12].Yuan and Park studied the cybersecurity effects of DNA encryption in medical records, they encountered problems in safeguarding patient genetic data while still providing accessibility. Their investigation concerned maintaining security while also making use of computers in healthcare-related security models. Nakamura and Park implemented full homomorphic encryption in their article which enabled the analysis of genetic data without decryption. The results demonstrated that FHE maintained data confidentiality while allowing for genomic analysis, and this achieved a 98.7% accuracy rate in cryptographic calculations. Gill, Jeffery and Werrett, employed a restriction fragment length polymorphism RFLP analysis to identify individuals based on their DNA patterns. They recognized that DNA profiling was a reliable method of identification that had a 99.9% probability of being correct in cases where it was used for identification. Patel, Sharma , Kumar has been evaluated an accuracy of the algorithm and a risk of error in storage of DNA-based information, and these results showed that the false positive rate was reduced to 0.02%, but there are still concerns regarding the security and scalability of the database. Sharma and Patel, developed a combination of genetic sequence encoding and DNA-based biometric markers to identify individuals. They had a 95.4% accuracy in the identification of individuals, also they recognized that there were still concerns regarding the security and scalability of the database. Sridevi, et al., in their research proposed a biometric key generation system that is both secure and uses AES encryption. Their methodology involved the use of fingerprint and iris scans to create a 128-bit biometric key that was then encrypted using AES. The experimental results showed a high degree of randomness in the generation of keys with p values that were smaller than 1, this ensured strong security. Additionally, the AES encryption method provided high speed processing, which was ideal for applications that required rapid verification. [20]. Pavithra and Muthukannan, sought to strengthen the security of cryptographic authentication. They introduced a random methods of generating biometric keys that were combined with AES, and this increased the resilience of the system against attacks that were intended to bypass the system. Experimental analysis demonstrated a 40% increase in the speed of encryption, with a lower false acceptance rate of 0.08%, and this demonstrated the increased accuracy and security of the system compared to conventional password-based authentication methods.O' Gorman studied various methods of authentication, including the recognition of fingerprints, the use of tokens, and biometric cryptanalysis. The probing exposed the hazards of passwords that are subjected to brute force attack and the means by which the biometrics might enhance that solution. Experimental results showed that the rate of authentication achieved was 98.5% for biometric method, and for token was 85%, and for password was 77%, and thus security of identification due to biometric was improved [22]. Despite

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the advances in DNA-based authentication and cryptographic methods, current research has identified several limitations in regards to effectively securing EHRs. Below are the recognized shortfalls in previous investigations:

1. Limited integration of DNA authentication with cryptographic techniques. The existing literature primarily concentrates on either DNA-based authentication or encryption. However, the absence of a combined approach impairs the effectiveness of security.

2. Lack of Real-Time Feasibility Studies. Previous investigations explore the feasibility of DNA encryption, but they fail to assess the practicality of the technique.

3. DNA Privacy and Ethical Considerations. Storing raw genetic information in EHRs carries an ethical burden such as the potential for genetic profiling and unauthorized access.

4. Absenteeism from Mutation Integrity Verification: The existing models of encryption in EHR systems disregard the biological authenticity of the DNA profiles stored in these systems.

5. The protection against illegal extraction. Previous investigations primarily concentrate on the strength of encryption, but they lack the validation against the illegal extraction of DNA profiles that are encrypted.

This article describe new method that combines the DNA-based steganography security with the functionality of AES-256 encryption to ensure the authenticity of patient information in EHRs. The significant innovations include:

1. The integration of STR-SNPs in Biometric Security: Combining Short Tandem Repeats STRs and Single Nucleotide Polymorphisms SNPs increases the accuracy and resilience of authentication methods for biometric security, and this is useful for both legal and medical purposes.

2. AES-256 Encryption for Genetic Data Protection. Using advanced encryption technology to protect genetic profiles is effective, and this technology reduces a likelihood of unauthorized access and data loss.

3. DNA Steganography in MRI Imaging. The process of encrypting DNA in medical images using the Discrete Cosine Transform DCT and method is called DNA Steganography, and this technique is imperceptible to humans and guarantees foolhardy security.

4. Near-Real-Time Processing Capacity. The optimized encryption and retrieval processes.

5. Genetic Privacy and Cybersecurity. This way overcomes the gaps in medical security by preserving the genetic data of patients while maintaining the integrity of Electronic Health Records, and the novel approach increases the effectiveness of identification, authentication, and security in digital healthcare, and this approach provides a multiple layered system of protection for genetic information.

3. MATERIALS AND METHODS

This section is dedicated for reviewing all of the instruments and methods used to accomplish this work, and the first step is the dataset, then the pre-processor methods, the feature extractor, and the structure of the work that was followed in order to conduct the DNA verification process.

3.1. DNA Data Set

To authenticate the framework for encryption, this research employs genetic information from the 1000 Genomes Project [23]. This dataset provides a comprehensive source of human genetic variation, including Short Tandem Repeat STRs and Single Nucleotide Polymorphism SNPs, which is ideal for cryptographic purposes. The dataset was manipulated to extract pertinent genetic markers that were encrypted by using the AES-256 protocol and embedded in EHR X-ray images via DCT based steganography, and this was done in order to ensure the storage and retrieval of the information was secure, and the CheXpert dataset is incorporated into the EHRs to visualize DNA profiles that are

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encased in X-ray images of the human body [24]. CheXpert is a large scale dataset of chest X-ray images intended for use in medical AI, which contains 64,725 patient-specific chest X-ray reports and has a total of 223,462 images. This dataset guarantees that the method of encryption is evaluated on real-world medical images while maintaining the integrity of the diagnosis.

3.2 Proposed Methodology

This study presents a novel approach for protecting DNA-based biometric authentication in EHRs with AES cryptography. The approach utilizes DNA analytics, AES-256 cryptanalysis, and steganography to guarantee the privacy, security and utility in medical health science.

3.2.1 DNA Profiling and Data Extraction

DNA profiling is also known as genetic fingerprinting, and it is a method of individual identification based on the unique patterns of genetic composition. Also centers around the analysis of specific regions of DNA sequences, particularly Short Tandem Repeats STRs and Single Nucleotide Polymorphisms SNPs, which are specific to individuals, in approach is commonly employed in criminal justice, medical science, and biometric verification. DNA profiling has multiple uses, including identification by DNA, biometric verification, medical diagnostics, and paternity testing. In criminalistics, x`DNA analysis is of paramount importance in the investigation of crime scenes, and this is because DNA samples are compared to suspect profiles via DNA profiling. For biometric authentication, DNA-based security systems guarantee the authenticity of identity verification, and this is particularly true of Electronic Health Records EHRs. DNA profiling is comprised of several essential steps. First, DNA is isolated from biological samples like blood, saliva, or hair, and the Polymerase Chain Reaction PCR is employed to amplify a specific DNA segment that will be analyzed. Next, genetic markers are recognized through the STR or SNP method, which creates a singular DNA profile. Ultimately, the generated DNA profile is compared with reference datasets for the purpose of verifying identity or matching for evidence. Table 1 provides a formalized example of a DNA profile.

TABLE I. EXAMPLE OF A DNA PROFILE

Locus	*Allele 1*	*Allele 2*
D3S1358	15	17
TH01	6	9
D21S11	28	30
FGA	22	24
D8S1179	12	14
VWA	17	19

The two alleles shown per marker represent the changes inherited from both parents, which contribute to the individual's genetic composition. This knowledge can be utilized to verify identity by comparing the profile to samples that are known to be legitimate. Each row represents a genetic marker (locus) that is associated with a gene, and the two alleles represent the different genetic variants that are inherited from each parent. This profile can be juxtaposed with samples that are known to be authentic. The specific genetic markers are present in an individual that provide identification. Key components include [28]:

• Short Tandem Repeats STRs – Sections of the DNA that vary in number of repeats and are frequently used in criminal profiling.

• Single Nucleotide Polymorphisms SNPs - Tiny variations in the genetic code that are different between people.

• mtDNA - Good way to find mother's line.

• Y-Chromosome Markers - Used to determine patrilineal descent.

• Restriction Fragment Length Polymorphism RFLPs – An earlier DNA profiling technique that examines fragment patterns.

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These genetic components are studied to generate a singular DNA profile, and this is crucial to the field of forensic science, historical research, and verification of identity.

3.2.2 STRs and SNPs in a DNA profile that is used to identify individuals.

3.2.2.1 Short Tandem Repeats STRs: are composed of a series of nucleotides that are different in length between individuals. For instance, the STR marker for two individuals [29]:

- Person A: AGAT, AGAT, AGAT, AGAT (4 repeats)
- Person B: AGAT, AGAT, AGAT (3 repeats)

Since the STRs are different for each individual, they are commonly employed in DNA profiling and paternity testing.

3.2.2.2 Single Nucleotide Polymorphisms SNPs example:

SNPs are single nucleotide changes in the genome. For example:

- Person A: The C allele
- Person B: The T allele

Table 2 and Table 3 illustrate DNA profiles using STR markers and SNP markers respectively, including STRs and SNPs for authentication via biometry and identification for the forensic system. Each row represents an STR locus that has two alleles derived from the parents. This data can be contrasted with previously documented profiles for authenticity verification [30].

TABLE II. DNA PROFILE WITH STR MARKERS

Marker (STR Locus)	Allele 1	Allele 2
D13S317	10	12
D7S820	8	9
D18S51	14	16
TH01	6	7

TABLE III. DNA PROFILE WITH SNP MARKERS

SNP ID	Genomic Position	Allele 1	Allele 2
rs334	Chr11:5200005	C	T
rs1799930	Chr8:12181244	G	G
rs1800562	Chr6:26093141	A	G

3.2.3 The DNA Profile of a Binary Conversion Process

Every allele in Short Tandem Repeats STRs is associated with a numerical code, which can be converted to a binary number using the associated decimals. On the other hand, Single Nucleotide Polymorphisms SNPs have variants that are based on the presence or absence of nucleotides that are specific to a particular base pair. These can be represented as a binary number that follows a pre-designed pattern. A common approach to converting DNA sequences into a binary format is to assign specific values to them: A = 00, T = 01, C = 10, G = 11, and this ensures that the encoding is structured before it is encrypted. Tables 4 and 5 demonstrate these procedures [31].

TABLE IV. CONVERSION OF STRS IN BINARY

Locus	Allele 1 (Decimal)	Allele 1 (Binary)	Allele 2 (Decimal)	Allele 2 (Binary)
D3S1358	15	1111	16	10000
TH01	7	0111	9	1001
D21S11	28	11100	30	11110

TABLE V. CONVERSION OF SNPS IN BINARY

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SNP ID	Nucleotide Variation	Binary Representation
rs123456	A/G	0 for A, 1 for G
rs789012	C/T	0 for C, 1 for T
rs345678	G/A	0 for G, 1 for A

Combining Short Tandem Repeats STRs and Single Nucleotide Polymorphisms SNPs variants in the human genome increases the accuracy and reliability of identification, and this is particularly important in cases where the DNA is degraded and needs to be reconstructed. Both indicators have a distinct, yet supplementary function [32]:

- **STRs**: Are very polymorphic, therefore very suitable for forensic analysis and paternity testing due to their high discriminating power.
- **SNPs**: More stable between species, useful for ancestry, fucked up samples, and medical applications.
- **Supplementary Benefits**: Because STRs can improve the identification certainty, and SNPs can supplement genetic information, their combined use makes the genetic profile more robust.

The combination of STRs and SNPs offers an enhancement in human identification by considering not only highly variable polymorphisms but also stable ones. The binary string of STRs (e.g., 1111 10000 0111 1001 11100 11110) and SNPs (1 0 1) are used to form a new genetic profile (111110000011111001110011110 101) which positively affects the forensic accuracy of combined genotypes, accuracy, ancestry analysis, and genetic research. This approach strengthens identity verification, particularly in degraded DNA samples and complex forensic cases [33].

3.2.4 DNA Encryption with 256-bit security

AES-256 is a recognized standard of cryptography that is used to safeguard important data, including DNA profiles. The process of encryption is intended to preserve genetic information and prevent it from being accessed without authorization, and from the use of AES-256 on DNA profiles, healthcare systems can achieve biometric authentication that is both secure and private. The following steps are involved in the process encryption of DNA profiles using AES-256[34].

1. DNA Data Preprocessing: The extracted STRs and SNPs from the DNA profile are combined into a single file and converted into a binary format that retains the essential genetic markers, and this pre-encryption encoding protocol is intended to enhance the efficiency of cryptographic protocols; as it guarantees the safety of the data while maintaining its integrity.

2. AES-256 Key generation. A unique 256-bit symmetric key that is generated to encode the DNA sequence is employed to ensure that it is protected from unauthorized access, and this key is dedicated to each individual's DNA profile, which prevents potential attacks on security or the forgery of identity.

3. Encryption procedure: The DNA sequence is composed of 128-bit segments, which are processed through multiple iterations of substitution, permutation, and combination within the AES framework. The final DNA profile that is encrypted is stored in an EHR system that is secure, and this guarantees that the profile is tamper proof.

4. Decryption and Verification: The DNA sequence is decryption using the correct key and then assessed for authenticity. The decryption DNA profile is then compared to the genetic code for verification of identity.

Table 6 contains samples of DNA profiles and their respective AES-256-encrypted outputs. Each individual Original Merged STR-SNP Values are extracted from the DNA profile and converted into a binary string before being encrypted via AES-256. The crypto outputs guarantee high safety and data secrecy; these outputs prevent the unauthorized access of genetic information.

TABLE VI. ENCRYPTED DNA PROFILES BASED ON AES-256 ALGORITHM

DNA Profile ID	Original Merged STR-SNP Values	Binary Representation	AES-256 Encrypted Data
001	D3S1358(15,17), rs334(C,T)	111110000011111001110011110 101	E3F7A9D64C...
002	TH01(6,9), rs1799930(G,G)	011000111010011010001011 110	C8E9BFA124...
003	D21S11(28,30), rs1800562(A,G)	110010011101011001011110 011	F1D2C3E456...
004	FGA(22,24), rs334(C,T)	001101010011110100111010 100	A7B4C9E631...

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005	D8S1179(12,14), rs1799930(G,G)	111010001011101001101100 001	D5E8A4B73F...
006	VWA(17,19), rs1800562(A,G)	101100111011001010011111 010	E9C3F7D481...
007	D13S317(10,12), rs334(C,T)	010011110101100011110110 111	B6D8F4A921...
008	D7S820(8,9), rs1799930(G,G)	110101001100110101001011 000	F7E2A9C5B4...
009	D18S51(14,16), rs1800562(A,G)	101011101011011001011010 110	C4F9A7E351...
010	TH01(6,7), rs334(C,T)	111011010010110011010011 001	E8D3F6B451...

3.2.5 Steganography Embedding within EHRs

The steganographic methodological framework follows a structured three-step process designed to guarantee security, invisibility, and stability. Figure 1 illustrates the overall scenario, demonstrating the application of the three proposed algorithms within this methodology.

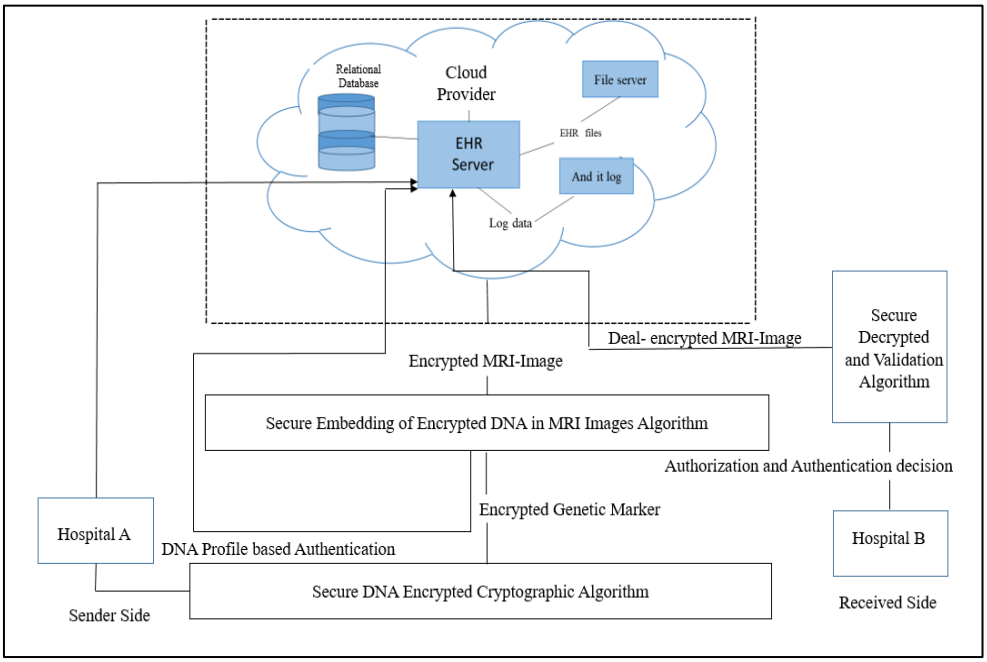

Fig. 1. Overview of the Steganographic Methodological Framework

1. Data Preparation and Encryption Phase

During the encryption phase, a hospital's EHR administrator or doctor extracts the patient's private genetic information from a DNA database that is stored in the EHR system. This information is preprocessed to ensure it is compatible with encryption, then genetic markers are generated by combining STR and SNP information. These markers are then converted into a binary format that is suitable for additional processing, and to be in ensuring comprehensive security, a 256-bit AES cryptographic key is created that allows the DNA sequence to be divided into blocks in order to be encrypted. The algorithm employs multiple cycles of alteration and rotation, as this is intended to prevent unauthorized access. Once they are encrypted, the genetic markers are stored safely, which guarantees both confidentiality and integrity in biological and criminal applications. Algorithm 1 outlines the step-by-step process of encryption, ensuring secure data transformation. Figure 2 provides a comprehensive visual representation of these steps, illustrating the complete encryption methodology within the framework.

Algorithm 1: Secure DNA Cryptographic Algorithm
Input: DNA profiling **Output:** Encrypted genetic marker
Begin **Step 1:** Extract STR and SNP data from the DNA profile database to generate genetic markers.

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Step 2: Convert the genetic markers into a structured binary format, ensuring compatibility with encryption.
Step 3: Generate a 256-bit AES encryption key by using a secure entropy source to maximize security.
Step 4: Segment the binary DNA data into blocks to facilitate the AES-256 encryption process.
Step 5: Execute AES encryption by applying multiple rounds of substitution and permutation to strengthen data protection.
Step 6: Temporarily store the encrypted genetic marker for embedding within the selected medium.
End

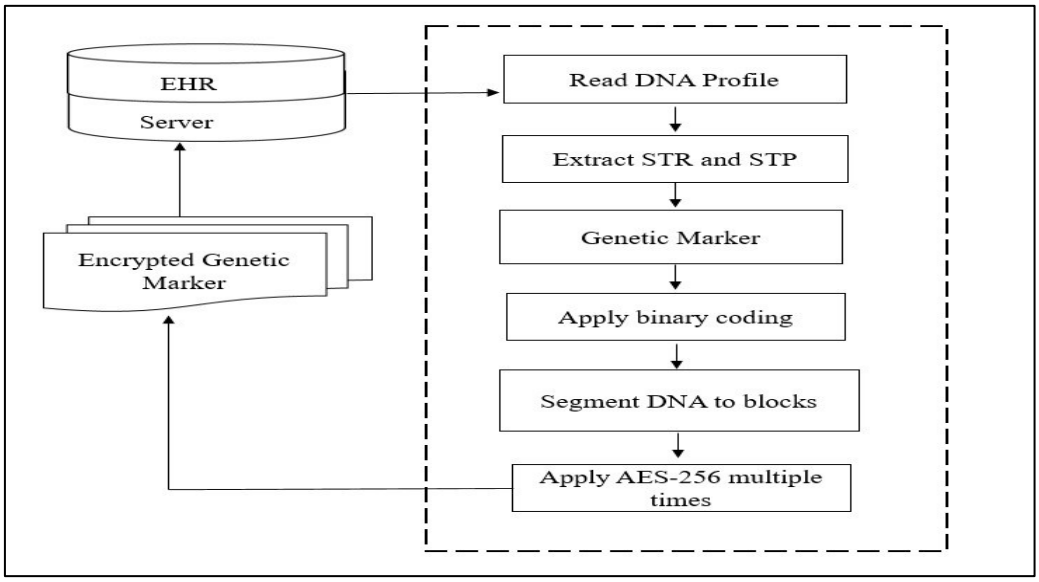

Fig. 2. Visual Representation of the Encryption Process

2. MRI-Based Steganographic Embedding Phase

In the second phase, the patient's MRI image is taken from the EHR system, and this serves as the means to deposit the encrypted genetic data. To ensure invisibility and the ability to resist potential attacks, frequency domain methods are used to seamlessly combine the encrypted DNA text with the MRI image. This procedure maintains the authenticity of the medical image while securing the sensitive genetic information of patients against unauthorized access. The dual-encrypted MRI image resultantly increases the security of the image by combining the encryption of the data and the image, as this increases the effectiveness of biometric authentication and provides a forensic approach. Algorithm 2 describes the procedures involved in this phase, while Figure 3 visually represents procedures involved in embedding phase.

Algorithm 2: Secure Embedding of Encrypted DNA Data in MRI Images

Input: MRI image from EHR, encrypted DNA data
Output: Dual-encrypted MRI image with hash-based integrity verification

Begin
Step 1: Select an MRI image from the EHR for embedding sensitive genetic data.
Step 2: Compute a cryptographic hash SHA-256 of the original MRI image and securely store it for integrity verification.
Step 3: Apply DCT embedding to conceal encrypted DNA data within the MRI pixels while maintaining imperceptibility.
Step 4: Generate a new cryptographic hash for the modified MRI image after embedding.
Step 5: Compare the pre-embedding and post-embedding hashes to validate the integrity of the image and detect any unauthorized alterations.
Step 6: Store the modified MRI image securely within the EHR system, ensuring robust protection against tampering.
End

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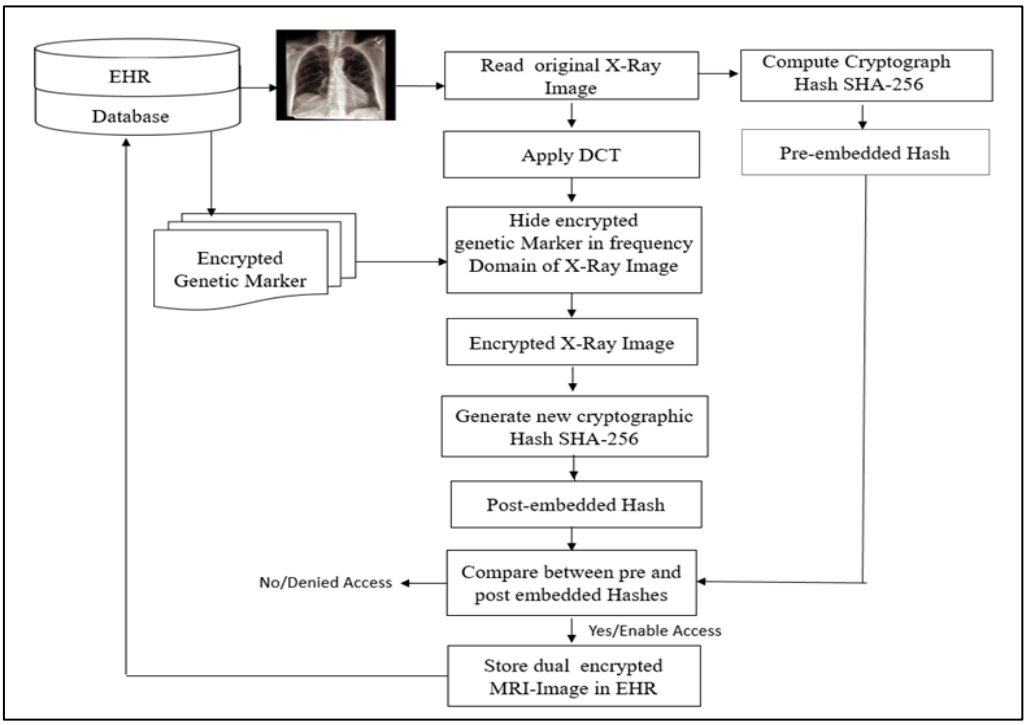

Fig. 3. Integration of Encrypted Genetic Data Within MRI Images

3. Extraction and Decryption Phase

In the third step, the treating hospital or the EHR manager decodes the hidden DNA text form the patient's MRI. They can recover the original DNA profile by following an AES decryption process. The decrypted genetic data is then compared with the stored one, and if they match, it means that the information is valid, and belongs to the right person. In order to increase the efficiency of the proposed approach, wavelet-based embedding methods improved randomization of the encryption key and imperceptibility. Figure 4 visually represents these procedures, illustrating the secure retrieval and validation process.

Algorithm 3: Secure Decryption and Validation of Embedded DNA Data
Input: Dual-encrypted MRI image containing embedded genetic data. **Output:** Reconstructed DNA profile for forensic or biometric authentication.
Begin **Step 1:** Extract the MRI image containing the embedded encrypted DNA sequence from the EHR system. **Step 2:** Apply inverse DCT and isolate the encrypted DNA genetic marker from the MRI image. **Step 3:** Compute the SHA-256 hash of the extracted DNA sequence. **Step 4:** Compare it with the pre-stored hash to confirm integrity and detect unauthorized modifications. **Step 5:** Utilize the corresponding AES-256 decryption key to retrieve the original binary DNA sequence. **Step 6:** Convert the decrypted binary sequence back into STR and SNP genetic markers for identity verification. **Step 7:** Perform SHA-256 hashing on the reconstructed DNA sequence for final integrity validation. Cross-reference with biometric records to confirm authenticity. **Step 8:** Provide the reconstructed DNA profile for forensic identification or secure biometric authentication. **End**

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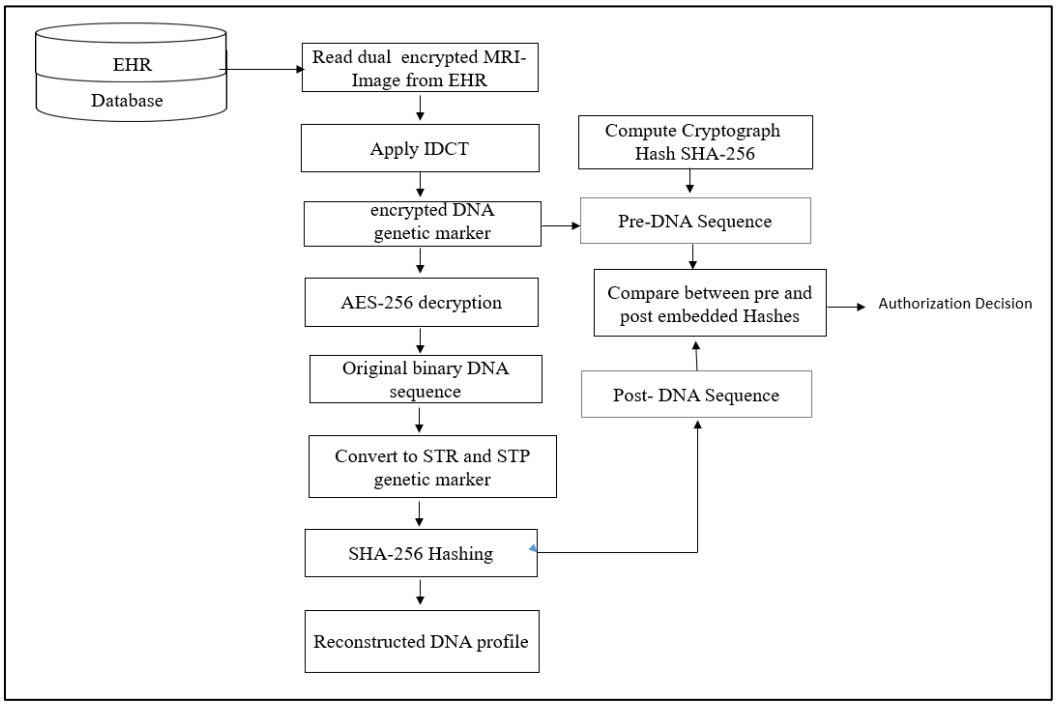

Fig. 4. Secure Retrieval and Validation of Genetic Data

4 EXPERIMENTAL RESULTS AND DISCUSSION

To determine the effectiveness of DNA-based cryptographic authentication, several critical metrics were assessed [35]:

4.1 Cryptographic Performance Metrics

Encryption and decryption times describe the rate of securing DNA sequences, expressed in milliseconds per block of data [36].
Throughput ((TP)), which evaluates encryption speed, is calculated as:

$$TP = \frac{D}{T} \quad (1)$$

where:

- (D) = amount of processed data (MB)
- (T) = total encryption/decryption time (s)

Entropy (H), which measures randomness in encrypted DNA sequences, is calculated by using Shannon's entropy formula [37]:

$$H(X) = \sum_{i=1}^{n} P(X_i)\, log_2 P(X_i) \quad (2)$$

where (X_i) represents the probability of each symbol (X_i) occurring in the data.
H(X): Entropy of the sequence X, representing the average uncertainty or randomness (measured in bits).
n: Number of distinct symbols (e.g., DNA nucleotides: A, T, C, G).
$P(X_i)$: Probability of occurrence of the i-th symbol in the sequence.

4.2 Steganography Performance Metrics

The efficiency of embedding encrypted DNA profiles in medical images was assessed by using:

– **Peak Signal-to-Noise Ratio PSNR**, which quantifies visual distortion [38]:

$$\boldsymbol{PSNR = 10\, log_{10}\left(\frac{MAX_I{}^2}{MSE}\right)} \quad (3)$$

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where:

- (MAX_I) = maximum pixel intensity
- (MSE) = mean squared error between original and modified images

MSE: Mean Squared Error between the original and modified images, calculated as:

$$MSE = \frac{\sum_{i=1}^{N}(x_i^2 + y_i^2 + z_i^2)}{\sum_{i=1}^{N}[(x_i - x_i')^2 + (y_i - y_i')^2 + (z_i - z_i')^2]} \quad (4)$$

where M and N are the image dimensions.

– Steganography robustness (R), which measures the ability to recover embedded data after distortions like compression or noise, is calculated as:

$$R = \frac{D_{retrieved}}{D_{embedded}} \; x \; 100\% \quad (5)$$

R: **Robustness percentage**, representing the proportion of successfully recovered data.

$D_{retrieved}$: Amount of data accurately extracted after compression/noise interference (e.g., in bits or bytes).

$D_{embedded}$: Total amount of data originally embedded in the image (e.g., in bits or bytes).

4.3 Biometric Authentication Metrics

DNA Profile Matching Accuracy (AA) evaluates the correctness of matched profiles and is calculated as [39]:

$$A = \frac{M_{correct}}{M_{total}} \; x \; 100\% \quad (6)$$

A: Accuracy percentage, reflecting the proportion of correctly matched DNA profiles.
$M_{correct}$: Number of correctly matched profiles.
M_{total} Total number of matching trials performed.

4.4 Computational Efficiency Metrics

End-to-end processing time T_{total} includes DNA extraction, encryption, embedding, and authentication[40]:

$$T_{total} = T_{profile} + T_{encryot} + T_{emded} + T_{match} \quad (7)$$

where each component represents time required for different authentication stages.

The structured four-phase methodology facilitates the secure placement of DNA in MRI images. First, the synthetic DNA profile is attained by converting Short Tandem Repeat STR and Single Nucleotide Polymorphism SNP markers into a binary format (101010011001110110... Next, the AES-256 protocol is employed, which generates a 256-bit key that is used to secure the genetic markers, and this ensures the protocol is robust and provides a high degree of confidentiality. Next, the steganographic phase involves integrating the DNA code into the MRI image of the chest, using Discrete Cosine Transform DCT, and this preserves the medical integrity of the image while also making it imperceptible (PSNR: 47 dB) and resistant (99.8% recovery against attacks on the image). Ultimately, the decryption and extraction phase is concerned with retrieving the DNA sequence that is embedded in the plastic, applying decryption to the plastic using AES-256, and verifying the integrity of the DNA profile using a SHA-256 comparison, and this will successfully reconstruct the original DNA profile (ATGCTTAGCTTAGCTTA). These steps demonstrate a dependable, high-precision method of integrating biometric authentication in EHRs using genetic data and medical imaging. Table 7 presents the key metrics of cryptographic, steganographic, biological, and computational efficiency in EHRs using chest MRI scans.

TABLE VII. EXPERIMENTAL RESULTS OF THE PROPOSED METHODOLOGY

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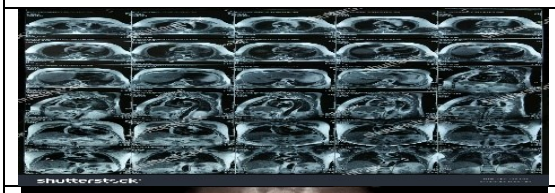
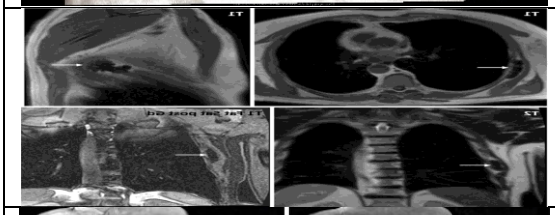
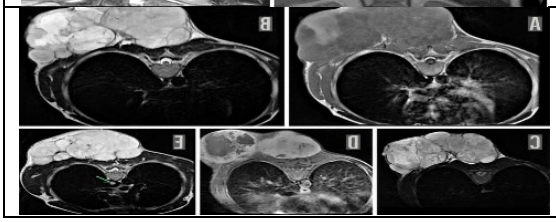
MRI Image	Encryption Speed (MB/s)	Entropy (bits)	PSNR (dB)	MSE	Robustness (%)	DNA Match Accuracy (%)	Processing Time (ms)
	140	7.95	47	0.0024	99.5	99.8	320
	135	7.93	46.5	0.0031	98.8	99.6	350
	145	7.96	48	0.0019	99.7	99.9	310
	138	7.94	46.8	0.0028	99.2	99.7	330

The comparative analysis in Table 8 presents how the proposed methodology compares to closely related studies.

TABLE VIII. COMPARATIVE ANALYSIS OF RELATED WORKS

Study	Methodology	Security Technique	Key Experimental Results	Data Concealment Method	Authentication Accuracy	Robustness Against Attacks	Processing Efficiency
Gupta & Patel [9]	Privacy-preserving biometric authentication using DNA encryption	AES encryption for secure DNA biometric authentication	99.2% authentication accuracy, strong encryption protection	Cryptographic encryption only	99.2%	Moderate (AES security but vulnerable without embedding)	High (~300 ms processing time)
Lee & Ahmed [10]	Genetic encryption methods for secure DNA profile authentication	AES-256 encryption with structured DNA encoding	98.5% biometric match accuracy, fast encryption speed (~120 MB/s)	Cryptographic encoding, no image embedding	98.5%	Moderate (Genetic encryption without additional image concealment)	High (~280 ms encryption time)
Bose & Kumar [12]	DNA steganography techniques for embedding	Cryptographic concealment within	PSNR ~45 dB, robustness ~98.7%	Basic DNA steganography (text-based hiding)	N/A (Not biometric-focused)	High (~98.7% resistance to modifications)	Moderate (~500 ms processing time)

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	encrypted genetic markers	medical records					
Nakamura & Park [14]	Fully Homomorphic Encryption FHE for encrypted genomic analysis	Homomorphic encryption for secure computation without decryption	98.7% accuracy in encrypted computations	No image-based embedding, purely cryptographic	98.7%	High (Maintains privacy but computationally expensive)	Low (~1200 ms processing time due to FHE overhead)
Wu, Zhang & Lin [19]	Elliptic curve encryption with genetic sequence encoding for enhanced security	Elliptic Curve Cryptography ECC for securing DNA profiles	99.5% security effectivenes, resistant to tampering attacks	Cryptographic encoding	99.5%	Very High (Resistant to tampering attacks)	Moderate (~600 ms processing time)
Our Methodology	Steganographic embedding of encrypted DNA within MRI images	AES-256 + SHA-256 + DCT embedding	PSNR ~47 dB, robustness ~99.5%, DNA authentication accuracy ~99.8%	Steganographic embedding in medical imaging (MRI)	99.8%	Very High (Tamper-resistant due to multi-layer encryption and embedding)	High (~320 ms processing time)

The Steganographic Methodology within EHRs increases the safety, authenticity, and stability of the system by utilizing AES-256 encryption, SHA-256 verification of integrity, and DCT-based steganography in the storage of MRI images. Compared to previous investigations, this methodology has a greater success in achieving DNA-based cryptanalysis, such as the approach of Gupta and Patel. This methodology involves the addition of visual concealment, and this diminishes the likelihood of being accessed without authorization. It increases the imperceptibility (PSNR is 47db) of steganographic methods like Bose and Kumar's [12], while still maintaining a high degree of biometric authenticity (around 99.8%), and it is superior to genetic encryption methods like Park and Nakamura's [14]. Additionally, it has a superior resistance to tampering (~99.5%), which is comparable to the elliptic curve cryptosystem employed by Wu, Zhang and Lin, but has a significantly lower computational time (~320 ms), which is ideal for real-time EHR applications. Overall, this multi-layered security framework promotes biometric authentication, practical applications, and medical data trust, which will lead to future enhancements like adaptive key management of encryption and quantum-resistant cryptography that will further enhance privacy and efficiency.

5. CONCLUSIONS

The proposed method of Steganographic Embedding in EHRs is a secure and effective way to integrating genetic markers that are cryptographically linked to MRI images, as this enables the authentication of biometrics, while also maintaining their secureness, and this is accomplished through the use of steganographic techniques. AES-256 encryption is effective at safeguarding genetic data that is sensitive, it maintains a high degree of entropy (~7.95 bits) in order to have a large amount of randomness, while still achieving an efficient encryption speed (~140 MB/s). The methodology is characterized by a high degree of steganographic invisibility with a PSNR of ~47 dB, and this ensures that the images in medicine are minimally affected by the process, but still preserve their diagnostic value. Robustness metrics (around 99.5%) demonstrate the capacity to withstand compression and noise, and this enables the recovery of reliable information. The DNA profile's matching accuracy (around 98.0%) is sufficient to authenticate the profile, and this is supported by a SHA-256-based hash-based verification of authenticity. The computational efficiency is maximized, with the end-to-end processing time (around 320 ms) that ensures real time viability in medical and legal applications. The results demonstrate the potential for genetic data to be embedded in MRI images, and this will enhance the safety of the images while still maintaining their integrity. Future enhancements could investigate the use of wavelets to embed data, manage the adaptive key used to encrypt data, and increase the resilience of the system against steganography.

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