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Blockchain Technology in Healthcare: Applications, Benefits, Challenges, and Future Prospects

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Abstract: *Blockchain technology offers a data structure with built-in security features, such as consensus, decentralisation, and cryptography, which guarantee transaction trust. It covers a wide range of applications, particularly in the areas of medical data security and privacy protection, as well as intelligent manufacturing, finance, the Internet of Things (IoT), medicine, and health. Its inherent features, like contracts and consensus processes, offer cutting-edge benefits for safeguarding the availability, confidentiality, and integrity of data. With thorough investigation and rapid development, the security flaws are progressively exposed. Modern medical records are stored electronically, as opposed to on paper, as was the case in the past. Without third-party guarantees, blockchain technology offered a decentralised solution to trust-less problems between distrusting parties. However, the technology's "trust-less" security was readily misinterpreted and hindered the security distinctions between public and private blockchains. The aforementioned benefits and drawbacks inspired to present a thorough analysis and progress report on the suitability of blockchain technology in healthcare.*

Key Words: *Blockchain, Healthcare, Electronic Health Records (EHRs), Data decentralization, cryptography.*

I.INTRODUCTION

Human health, which impacts social, mental, and physical well-being, is essential to a happy and fruitful existence. The effective provision of patient care is hampered by a number of issues facing traditional healthcare systems. Data fragmentation, poor interoperability, privacy violations, and ineffective administrative processes are some of the problems that the healthcare industry is facing more and more. Single points of failure, illegal access, and a lack of transparency are common problems with centralised data storage systems [1], [2]. Furthermore, worldwide occurrences like the COVID-19 pandemic, which revealed the serious flaws in the current health information systems, have increased the need for a safe, patient-centered, and effective digital health infrastructure [3].

The fragmentation of medical records, where patient data is kept in separate systems across different clinics, hospitals, and labs, is one of the main problems. This raises the possibility of medical errors, causes treatment delays, and results in incomplete medical histories. In addition, a lot of healthcare providers use disparate software platforms that are incompatible with one another, which hinders data exchange and compromises continuity of care. Concerns about security and privacy are also common because centralised databases are extremely susceptible to ransomware attacks, breaches, and unauthorised access. These events frequently lead to large-scale data leaks that damage patient confidence and break laws like GDPR and HIPAA. Moreover, administrative inefficiencies that waste time and raise operating costs, such as manual data entry and redundant paperwork, plague traditional healthcare systems. The lack of patient control over medical data is another important drawback; most patients have little access to their medical records, which limits their capacity to receive individualised care and make educated decisions.

This paper presents thorough analysis of blockchain applications in the healthcare ecosystem with insights into how blockchain is changing clinical trials, public health surveillance, patient empowerment, health data exchange, and pharmaceutical supply. The review also analyses scalability limitations, and integration issues, while highlighting important advantages like enhanced data privacy, interoperability, and operational efficiency. Future viewpoints are also covered, such as how blockchain technology is combining with cutting-edge gadgets like edge computing, the Internet of Things, and artificial intelligence (AI), which are opening the door for intelligent and decentralised healthcare systems.

Blockchain

Blockchain technology is a distributed, decentralised digital ledger system that tracks assets and securely logs transactions over a network of computers. Each participant (node) in a blockchain maintains a copy of the ledger, ensuring redundancy and removing single points of failure, in contrast to traditional databases run by a central authority. Fundamentally, a blockchain is made up of a number of blocks, each of which contains a list of transactions. Cryptographic hashes are used to connect these blocks in chronological order, creating a chain, hence the term "blockchain". It is very difficult to change or remove data once it has been added to a block and the block has been appended to the chain. This makes the ledger unchangeable and impervious to tampering. [4-7]

A number of essential characteristics of blockchain technology make it an effective instrument for transparent and secure data management. One of its fundamental characteristics is decentralization, which implies that data is dispersed over a network

of computers, or nodes, rather than being under the direction of a single authority. This decentralized structure enhances trust and reliability among participants [6]. Immutability, which guarantees that data cannot be altered once it is recorded in a block without modifying all subsequent blocks—a practically infeasible task—is another critical attribute, making blockchain highly secure and tamper-resistant [7, 8]. Transparency is also central to blockchain; since all participants can view and verify transactions, it fosters accountability and trust within the network [9]. Furthermore, blockchain employs cryptographic techniques and consensus mechanisms such as Proof of Work (PoW) and Proof of Stake (PoS) to validate transactions and protect the network from fraud and unauthorized alterations [5, 10]. Lastly, the consensus process ensures that all nodes in the system agree on the validity of data before it is added to the blockchain, thereby maintaining overall consistency and integrity of the ledger [11].

Need of blockchain in healthcare

Blockchain technology offers a revolutionary approach to addressing many of the challenges plaguing traditional healthcare systems by ensuring data security, transparency, and patient empowerment [12]. One of its key features is the ability to maintain data integrity and immutability, as each transaction on the blockchain is time-stamped and cannot be altered, making medical records tamper-proof [13]. It also enhances privacy and consent management by allowing patients to control access to their health information using smart contracts and secure digital identities [14].

Additionally, blockchain improves interoperability by serving as a common, decentralized platform that connects various healthcare systems through standardized protocols and APIs. This ensures seamless data exchange among hospitals, clinics, insurers, and patients [15]. In the realm of clinical trials and research, blockchain ensures the integrity of data while simplifying processes such as participant recruitment, consent tracking, and result verification [16]. Fraud prevention is another critical benefit, as blockchain's transparency and verifiability help detect and reduce false insurance claims and billing errors. Furthermore, blockchain can streamline supply chain management by providing end-to-end tracking of pharmaceuticals and medical equipment, thereby minimizing the risk of counterfeit drugs entering the system. Overall, blockchain plays a pivotal role in driving a secure, efficient, and patient-centered transformation in healthcare.

Although blockchain technology was first used to create cryptocurrencies like Bitcoin, it is now used in a wide range of sectors, including supply chain management, healthcare, and finance. The blockchain market for healthcare is expanding quickly on a global scale. It is expected to grow at a compound annual growth rate (CAGR) of 36.4% from its estimated $2.23 billion in 2024 to $3.04 billion in 2025. Trends like decentralised clinical trials, personalised medicine, tokenisation of healthcare assets, and cross-border healthcare transactions are expected to propel this market's growth to $11.04 billion by 2029 [17]. The pressing need to enhance security and interoperability in healthcare information systems is driving the adoption of blockchain.

II.APPLICATIONS OF BLOCKCHAIN IN HEALTHCARE

Blockchain in Electronic Health Records (EHRs)

Blockchain allows cryptographic hashes and EHR metadata to be stored in a distributed ledger, protecting data integrity and lowering single-point-of-failure vulnerabilities. The real records are stored in off-chain systems (like IPFS and the cloud), but blockchain preserves tamper-proof references, which combine scalability and immutability. This hybrid architecture is economical and safe [13, 18]. for how long by using smart contracts to set fine-grained access permissions. This method restores data ownership to individuals while enforcing GDPR/HIPAA compliance [2, 19]. While maintaining traceability and auditability of all accesses, blockchain acts as a standardised interoperability layer (for example, through FHIRChain), facilitating easy, encrypted data exchange between labs, hospitals, clinics, insurers, and researchers.

Trusted organisations such as hospitals, insurers, and regulators can control data writes with permissioned blockchains (like Hyperledger Fabric and PoA consensus) [20]. This configuration provides reliable and efficient throughput, making it perfect for stakeholder management of EHR systems [7]. Large medical files are handled by architectures that store cryptographic pointers on-chain and heavy data off-chain. This hybrid design guarantees effective retrieval while reducing blockchain bloat [21]. Without revealing raw data, blockchain facilitates encrypted metadata sharing to facilitate collaborative research, privacy-preserving analytics, and federated learning. This protects patient privacy while advancing population-health research. [22, 23]

Blockchain's potential for managing Electronic Health Records (EHRs) is demonstrated by a number of practical applications. MedRec, created at MIT, gives patients clear control over their medical history by using Ethereum smart contracts to handle authentication, data sharing, and record access [31]. Proof of Authority (PoA) consensus is used in HealthChain and Ancile's consortium blockchain models to enable safe and effective updates to health data among reliable participants [20]. To facilitate safe, scalable clinical data exchange, FHIRChain combines blockchain technology with HL7 FHIR standards [21]. While issues like scalability and regulatory compliance still need to be resolved, these projects demonstrate how blockchain can improve interoperability, data integrity, and patient empowerment in the healthcare industry.

Blockchain in clinical trials and medical research

Blockchain provides a powerful framework for guaranteeing the integrity of clinical data by automatically time-stamping and permanently recording each entry [33]. Using a hybrid private/public blockchain, platforms such as TrialChain validate biomedical research data, ensuring authenticity and enabling reliable audit trails and public verifiability [24]. Similar to this, comprehensive analyses have highlighted how blockchain can stop selective reporting and data manipulation, increasing confidence in clinical findings [25]. Blockchain-based smart contracts simplify the development, administration, and implementation of informed-consent procedures. To automate consent workflows and preserve unchangeable records of participant consent events, for instance, Ethereum-based solutions have been suggested [1, 26]. These mechanisms support traceability throughout multi-site trials by enforcing step-by-step adherence to study protocols and regulatory requirements such as ISO 27789 and 21 CFR Part 11 [27].

A permissioned blockchain framework enables real-time auditing, protocol enforcement, and private data sharing in decentralised, multi-site clinical trials. To securely standardise and monitor data across various research sites, Choudhury et al. created a clinical-trial framework utilising smart contracts and private channels [26]. Data provenance and auditability issues arise when IoT and EHR data are integrated (for example, from wearables). In order to comply with regulatory requirements, systems such as Scrybe use permissioned blockchains to integrate time-stamped clinical data from IoT devices into conventional EDC/CDMS platforms via secure audit trails [28].

Blockchain makes it possible for patient privacy to be respected through auditable and controlled data-sharing models. Blockchain-enabled federated learning architectures facilitate cooperative model training amongst institutions without requiring the exchange of raw data [29]. This method preserves data confidentiality for AI-driven research and predictive analytics while supporting decentralised trial designs [35]. A conceptual model that incorporates blockchain elements—like cryptographic indexing, consent management, and interoperability—into a single framework for clinical research platforms was created by a recent systematic review [35]. This model helps researchers and developers create blockchain-based systems that comply with the rules and specifications of actual trials.

Blockchain in Health Data Interoperability

The smooth and safe transfer, retrieval, and interpretation of health data between various healthcare systems and providers is known as health data interoperability. Data silos, inconsistent standards, and security issues impede traditional interoperability systems. Blockchain provides a standardised, decentralised, and impenetrable solution that can greatly enhance interoperability and sharing of health data. By tackling the drawbacks of conventional healthcare data systems, including fragmentation, security issues, and a lack of patient control, blockchain technology provides revolutionary ways to improve health data interoperability. Decentralised data access is one of the main uses for blockchain, as it enables safe and easy clinical information exchange between several healthcare facilities without the need for a central authority [21]. Platforms like FHIRChain, which use cryptography and smart contracts to guarantee that data can be shared securely and scalably using standardised formats, are prime examples of this. Patient-centric control over data sharing is another crucial use case. The MedRec system demonstrates how blockchain uses private keys and permissioned networks to allow patients to grant, restrict, or revoke access to their medical records [22].

Furthermore, blockchain facilitates consistent interoperability across disparate Electronic Health Record (EHR) systems by integrating with frameworks like HL7 FHIR, which supports unified data standards [41]. Immutability and auditability are further features of blockchain that guarantee all patient data access, changes, and transactions are transparently documented and traceable, boosting stakeholder accountability and trust [2, 30]. Last but not least, blockchain technology's integration with wearable health monitors and Internet of Things devices enables safe real-time health data sharing, supporting remote and individualised healthcare management without sacrificing data integrity or privacy [30, 31].

Blockchain in Public Health surveillance

In order to track epidemiological trends, monitor and control disease outbreaks, and carry out prompt interventions, public health surveillance entails the methodical collection, analysis, and distribution of health data. Conventional surveillance systems frequently have issues with data manipulation, delayed reporting, and a lack of cross-jurisdictional transparency. With its decentralised, tamper-resistant, and real-time data management features, blockchain technology offers a promising answer to these problems.

Blockchain allows government agencies, labs, and healthcare facilities to share data in real time without jeopardising individual security or privacy. Because every data entry on a blockchain is timestamped and unchangeable, test results, vaccination statuses, and outbreak records cannot be changed after the fact. For example, by connecting validated health data across geographical locations, blockchain can be used to monitor disease transmission chains during pandemics [32]. In order to enable prompt public health responses, smart contracts can also automate alerts when data shows threshold exceedances in infection rates or anomalous health patterns [33]. Blockchain can also help decrease underreporting and improve data granularity, especially for stigmatised diseases, by enabling anonymous but verifiable reporting from patients and medical professionals [39]. Also, by avoiding the drawbacks of centralised data silos and guaranteeing fair access to public health insights, blockchain's decentralised structure enables better collaboration between international health organisations and regional health departments [34].

III.BENEFIT OF BLOCKCHAIN IN HEALTHCARE

Blockchain technology offers the healthcare industry a number of important advantages, greatly enhancing the management, access, and storage of medical records. Improved data security and privacy is one of the main benefits. Blockchain lowers the risk of data breaches by ensuring that health records are tamper-proof and only accessible by authorised parties through the use of cryptographic techniques and a decentralised architecture [35]. Improved interoperability is another important advantage. Blockchain eliminates data silos and promotes smooth communication between healthcare providers by facilitating safe and standardised data exchange across various health information systems [2, 21]. Additionally, blockchain encourages greater trust and transparency in the healthcare system. By making every transaction on a blockchain permanently recordable and auditable, stakeholders can confirm the history and authenticity of medical records, fostering trust between insurers, providers, and patients [36, 37]. By using smart contracts to automate typical administrative tasks like billing, claims processing, and record transfers, the technology also significantly lowers costs and increases efficiency while minimising operational delays and human error [23]. Last but not least, blockchain empowers patients by giving them complete control over their health information, including who can access it and under what circumstances. This enhances patient involvement and is consistent with modern healthcare values regarding data ownership and privacy [35, 38].

IV.CHALLENGES AND LIMITATIONS OF BLOCKCHAIN IN HEALTHCARE

Blockchain technology in healthcare has many significant obstacles and restrictions, despite its revolutionary potential. Uncertainty surrounding regulations and compliance is a significant problem. Implementation is hampered by a regulatory mismatch caused by blockchain's immutable nature, which clashes with laws like HIPAA and GDPR that demand the ability to change or remove personal data upon patient request [37, 38]. Integrating blockchain technology with legacy systems presents another significant challenge. Many healthcare organisations still use antiquated infrastructure that was not built for decentralised technologies, and it would be expensive, technically demanding, and require retraining staff to adapt these systems to support blockchain [35]. Furthermore, blockchain's capacity to manage massive amounts of healthcare data is constrained by scalability and performance issues. Access to vital medical records and diagnostic data may be delayed due to public blockchains' high latency and low throughput [19]. Although blockchain's decentralisation improves security, privacy issues still exist. Off-chain data storage creates new vulnerabilities at the interface between blockchain networks and external databases, and public ledgers may reveal metadata that could be used for identity inference [23, 39]. Furthermore, smooth interoperability between healthcare providers is hampered by the lack of standardisation across blockchain platforms, data formats, and protocols. A major obstacle to widespread adoption and sector-wide coordination is the lack of widely recognised technical and regulatory standards [44].

V.FUTURE DIRECTIONS AND TRENDS OF BLOCKCHAIN TECHNOLOGY IN HEALTHCARE

Blockchain technology is poised to transform healthcare delivery and data management as it develops and integrates with new technologies like cloud computing, artificial intelligence (AI), and the Internet of Things (IoT). For example, blockchain and AI work together to guarantee the integrity and traceability of datasets used to train medical algorithms, opening up new possibilities in automated diagnostics and predictive analytics [3]. Similar to this, blockchain can safely handle real-time data produced by wearable technology and remote patient monitoring systems when paired with IoT, improving continuity of care while maintaining the integrity and provenance of data [40]. The rise of decentralised clinical trials (DCTs), where blockchain enables transparent and impenetrable documentation of patient consent, trial protocols, and data capture, is an important new trend. Blockchain lowers trial costs and timelines while increasing participant trust and regulatory compliance by decentralising clinical data control [1].

Blockchain provides a safe framework for exchanging and storing private biometric and genomic information in the field of personalised medicine. In order to enable more precise and customised treatment plans without jeopardising privacy, patients can choose which aspects of their health information to share with researchers or clinicians [41]. The application of blockchain technology to international healthcare transactions, specifically medical tourism and transnational health record access, is another important future direction. Blockchain ensures continuity of care while adhering to jurisdiction-specific regulations by offering a safe, standardised framework for international data exchange [42]. Additionally, hospitals, insurers, pharmaceutical companies, and regulators are working together to create interoperable platforms, cut costs, and expedite innovation through the emergence of blockchain consortia in the healthcare industry. These collaborations, like the Synaptic Health Alliance, show how shared governance models can promote blockchain adoption and get around institutional barriers [43].

VI.CONCLUSION

Blockchain technology is quickly becoming a game-changer in the healthcare industry, providing innovative answers to many of the enduring problems that traditional healthcare systems face. The urgent need for digital transformation in healthcare is highlighted by the growing complexity and volume of health data, as well as growing concerns about interoperability, privacy, security, and inefficiencies. Blockchain technology has enormous potential to improve global healthcare systems' efficiency, security, and transparency. Unlocking its full potential and guaranteeing its responsible and equitable integration into healthcare practices will require ongoing research, innovation, and regulatory alignment, even though there are still obstacles to overcome.

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