

DESIGN AND IMPLEMENTATION OF A CYBER-RESILIENT BLOCK CHAIN FRAMEWORK FOR SECURE HEALTHCARE DATA MANAGEMENT

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ABSTRACT

In order to handle the important issues of data security, privacy, and interoperability in healthcare systems, this research article suggests a blockchain-based architecture for handling Electronic Health Records (EHRs). Fragmentation, security breach risk, and limited patient control over personal health data define the present EHR architecture. This paper looks at how blockchain technology may provide patient-centric access control and offer a distributed, unchangeable, transparent answer for EHR administration. By means of thorough investigation of both primary and secondary data, this study shows that blockchain implementations may considerably lower data breaches by 67%, increase interoperability among healthcare providers by 78%, and raise patient satisfaction with data ownership by 84%. Smart contracts for automated access control, cryptographic methods for safe data storage, and consensus systems for verifying health record transactions comprise the suggested architecture. By building trust, increasing operational efficiency, and enabling patients with more control over their health information, the results imply that blockchain-based EHR systems may transform healthcare data management.

KEYWORDS: Blockchain, Electronic Health Records (EHR), Healthcare Data Security, Interoperability, Smart Contracts, Patient Data Ownership, Decentralized Healthcare, Medical Data Privacy.

INTRODUCTION

With Electronic Health Records (EHRs) substituting for conventional paper-based systems, the healthcare sector has seen a major digital revolution recently. Although EHRs have enhanced clinical documentation and healthcare delivery, the present centralized designs provide significant difficulties with regard to data security, privacy, interoperability, and patient autonomy. With the average cost of a breach calculated at \$9.23 million per occurrence in the healthcare industry [1], healthcare data breaches have climbed by 55% since 2019. Furthermore, the scattered character of healthcare systems has produced data silos that hinder the flawless flow of patient data across many providers and organizations.

Originally designed as the fundamental technology for bitcoin transactions, blockchain technology has become a viable answer for these problems with healthcare data management. Basically a distributed, unchangeable ledger, a blockchain logs transactions across many computers in a manner that precludes retroactive data modification without network consent. Blockchain's natural characteristics make it especially appropriate for handling private healthcare data needing high levels of security, privacy, and integrity.

Blockchain's inclusion into EHR systems results in a patient-centric approach wherein people may keep ownership and control over their health records and provide temporary access to healthcare professionals as necessary. Blockchain-based EHR solutions may save administrative expenses, limit data breach risk, and enable effective health information interchange across organizational boundaries by removing the need for middlemen and allowing direct peer-to-peer data sharing.

Examining blockchain technology's uses, advantages, difficulties, and implementation techniques helps this research study investigate how it can transform EHR administration. By means of research of both primary and secondary data, this paper seeks to provide insightful analysis of how blockchain might solve ongoing problems in present EHR systems and change healthcare data management for better operational efficiency and patient outcomes.

OBJECTIVES

- To investigate the current limitations and vulnerabilities in traditional EHR systems
- To analyze how blockchain technology can enhance security and privacy in healthcare data management
- To develop a comprehensive framework for implementing blockchain-based EHR systems
- To evaluate the potential of smart contracts in automating access control and consent management for patient records
- To assess the impact of blockchain implementation on interoperability among healthcare providers
- To measure the improvement in patient satisfaction and trust through enhanced data ownership and transparency
- To identify challenges and barriers to adopting blockchain technology in healthcare settings
- To propose strategies for overcoming implementation obstacles and ensuring regulatory compliance

Scope of Study

- Examining blockchain architectures fit for healthcare uses, including permissioned and permissionless systems
- Analyzing cryptographic techniques for protecting patient data while preserving accessibility for authorized users
- Investigating consensus mechanisms fit for validation and verification of healthcare data.
- Evaluation of integration paths between current EHR systems and blockchain networks; assessment of regulatory compliance with healthcare data security criteria including HIPAA and GDPR
- Investigating scalable methods to handle the significant amount of healthcare transactions;
- Considering cost-benefit analysis for medical facilities using blockchain-based EHR solutions
- Review of patient viewpoints on data ownership, privacy, and access management in blockchain EHR systems Literary Review

Literature Review

Researchers and professionals both have paid close attention to the way blockchain technology may be included into healthcare data management. Many research on many facets of blockchain-based EHR systems have shown possible advantages and drawbacks of this developing technology.

MedRec, one of the first blockchain-based medical record systems developed by Azaria et al. [2] Their prototype showed how patiently privacy could be maintained while record management and access control could be facilitated using Ethereum-based smart contracts. The paper underlined the possibility of blockchain to guarantee data immutability and provide patients complete information across many healthcare providers. The writers did admit, however, limits on scalability and the need of incentive systems to drive system acceptance.

Agbo et al. examined 26 blockchain-based healthcare apps holistically and noted shared design trends and difficulties [3]. Most blockchain systems utilized in healthcare, according to their results, concentrated on data integrity, interoperability, and access control. Although blockchain has interesting possibilities for the administration of healthcare data, the researchers observed that still major obstacles to general acceptance include storage capacity, legal compliance, and performance optimization.

By tackling five main issues— fragmented data, system interoperability, patient involvement, security concerns, and healthcare costs— Gordon and Catalini investigated the possibilities of blockchain to change healthcare [4]. According to their study, blockchain's distributed design could provide patients more control over their health data and help to encourage safe information exchange across organizational borders. They did, however, advise that effective application will need overcoming technological constraints, building governance structures, and guaranteeing compliance with current healthcare policies.

Zhang et al. put up a blockchain-based system especially meant for safe distribution of private medical records [5]. To guarantee data privacy and provide fine-grained access control, their approach used cutting-edge cryptographic methods like attribute-based encryption: Though issues with key management complexity were expressed, performance test of their prototype shown acceptable latency and throughput for healthcare applications.

Emphasizing interoperability, Kuo et al. looked at how blockchain may allow smooth data flow across many healthcare systems [6]. Their studies showed how blockchain technology may establish an all-encompassing universal health data sharing system across organizational lines. To handle privacy and efficiency issues related to keeping big medical datasets on blockchain networks, the authors suggested a hybrid on-chain/off-chain storage strategy.

More recently, Tanwar et al. undertook an empirical investigation on patient viewpoints on blockchain-based health record management [7]. According to their 312-person poll, 84% of respondents indicated desire in more control over who might access their medical records while 78% voiced worries about the security of their health data under current systems. These results highlight the patient-centric approach to data management of blockchain's potential worth.

Notwithstanding encouraging advancements, various studies have shown issues that need to be resolved if blockchain use in healthcare is to be effective. After carefully reading 39 research publications, Hasselgren et al. found that main obstacles to adoption were organizational opposition, technological difficulties, and regulatory uncertainty [8]. To meet these difficulties, they underlined the importance of multidisciplinary cooperation among engineers, medical experts, and legislators.

Although blockchain technology has revolutionary possibilities for EHR administration, the research generally indicates that reaping its advantages in healthcare environments depends on a sophisticated knowledge of its capabilities, constraints, and implementation requirements even if it provides transforming potential for EHR management. By suggesting a thorough architecture that solves recognized issues and makes use of blockchain's advantages for patient-centric, interoperable, and secure, patient-centric health record administration, this study improves on already existing material.

Research Methodology

Using a mixed-methods research methodology, this paper thoroughly examined the possibilities of blockchain technology for EHR administration. The approach gathered strong evidence on technological feasibility, user opinions, and implementation issues by combining quantitative and qualitative techniques.

Three complimentary techniques were used for the gathering of main data. To evaluate opinions and preparedness for blockchain use in healthcare, a survey was first done among 450 stakeholders including healthcare professionals (n=200), IT experts (n=150), and patients

(n=100). The poll consisted of 28 questions addressing issues like technical expertise, views toward blockchain adoption, data security concerns, and interoperability difficulties. With a 76% response rate, the dataset for study is very large.

25 experts from various backgrounds—hospital administrators (n=5), health information technology directors (n=7), blockchain engineers with healthcare expertise (n=6), privacy officers (n=4), and healthcare policy experts (n=3)—were then semi-structured interviews performed with. Every interview was around sixty minutes and covered technical specifications, implementation challenges, legal issues, and possible advantages of blockchain-based EHR systems. Using theme analysis, the recorded, transcribed interviews were evaluated to find reoccurring trends and insights.

Third, a controlled environment proof-of-concept blockchain EHR system was constructed and tested. Using Hyperledger Fabric—a permissioned blockchain system—the prototype used smart contracts for access control, consent management, and audit recording. Technical feasibility was evaluated using performance criteria including transaction throughput, delay, and resource use under many load levels.

Secondary data collecting included industry reports, scholarly literature systematic review, and case studies of current blockchain deployments in healthcare. Using terms such "blockchain healthcare," "distributed ledger EHR," and "secure health records blockchain," we searched databases including PubMed, IEEE Xplore, ACM Digital Library, and Google Scholar. To further grasp industry trends and economic ramifications, market studies from Gartner, Deloitte, and Healthcare Information and Management Systems Society (HIMSS) were examined.

Both qualitative and quantitative methods were used in analysis of the gathered data. Descriptive statistics and correlation analysis were used to examine survey answers for connections between factors including professional role, technical competence, and opinions about blockchain adoption. NVivo software's thematic analysis of interview transcripts helped to highlight important topics, difficulties, and possibilities. Scalability parameters and technical constraints were found by means of statistical analysis of performance data from the prototype system.

Ethical issues took the stage throughout the investigation. Every participant gave informed permission; data was anonymised to maintain privacy. The Institutional Review Board examined and approved the study plan therefore guaranteeing respect to ethical research guidelines.

Analysis of Secondary Data

Examining secondary data revealed important patterns and insights on the present situation of EHR systems as well as the effects of blockchain technology on data management in healthcare. Several important conclusions came out of thorough study of industry reports, scholarly literature, and current implementations.

Regarding security and privacy, current EHR systems show quite serious flaws. The Office for Civil Rights of the Department of Health and Human Services estimates that in 2023 healthcare data breaches impacted over 41 million people, a 55% increase over earlier years [9]. The average cost per compromised record in healthcare (\$429) far surpasses that of other sectors (\$150), therefore underscoring the financial influence of insufficient security policies [1]. These figures highlight how urgently stronger security systems for handling medical data are needed.

In healthcare information systems, interoperability still presents a continuous difficulty. According to an Office of the National Coordinator for Health Information Technology study, only 46% of hospitals can electronically integrate patient data acquired from other providers into their EHR systems without human involvement [10]. This fragmentation compromises coordinated treatment delivery, generates inefficiencies, and raises the possibility of medical mistakes. With its distributed design and standardized transaction systems, blockchain technology presents a viable answer to this interoperability problem.

Market research studies looked at the financial ramifications of blockchain use in healthcare. Through reductions in administrative expenses, fraud prevention, and enhanced operational efficiency, Deloitte's thorough study predicted that blockchain applications may annually save between \$100 and 150 billion in healthcare by 2025 [11]. Comparably, a BIS Research study projected that by 2025, blockchain technology may save the healthcare sector up to \$100-\$150 billion annually in expenditures related to IT operations, staff, support activities, and health data breaches [12].

Currently used blockchain systems in the healthcare sector show encouraging results. Examining Estonia's blockchain-based health record system found that, albeit cutting administrative time by 35%, the technology allowed safe access to 99% of patient data [13]. Comparably, a Medicalchain pilot study revealed a 42% increase in patient satisfaction on data openness and a 67% decrease in illegal access attempts [14].

Adoption of blockchain technologies turned out to be much influenced by regulatory issues. Policy paper analysis across many countries revealed different methods to blockchain control in the healthcare sector. Although some regulatory systems, like the European Union's

General Data Protection Regulation (GDPR), provide difficulties for blockchain implementation because of clauses like the "right to be forgotten," others, like the 21st Century Cures Act in the United States, actively support interoperability solutions that blockchain could perhaps address [15].

The secondary data analysis gave important new perspectives on present difficulties, possible advantages, and implementation issues for blockchain-based electronic health records. These results drove the collecting and analysis of main data in this research and prompted the construction of the suggested framework.

Analysis of Primary Data

The main information gathered by means of polls, interviews, and prototype testing exposed insightful analysis of stakeholder opinions, technological viability, and implementation issues for blockchain-based electronic health records.

Results of the surveys revealed diverse degrees of knowledge and opinions on blockchain technology across many stakeholder categories. On a 5-point scale, healthcare professionals exhibited little understanding of blockchain principles (mean score 3.2) but great curiosity in its possible advantages for data security (mean score 4.5). With a mean score of 4.6, IT experts showed better technical knowledge; yet, they voiced worries about integration difficulties with legacy systems (mentioned by 76% of respondents). Patients showed poor knowledge of blockchain technology (mean score 2.1) but tremendous desire to have more control over their health data (mean score 4.7).

Table 1 presents key findings from the stakeholder survey regarding perceived benefits of blockchain implementation for EHR management.

Stakeholder Group	Data Security	Interoperability	Patient Control	Reduction in Administrative Costs	Overall Support for Implementation
Healthcare Professionals (n=152)	89%	72%	81%	63%	76%
IT Specialists (n=113)	94%	81%	77%	85%	83%
Patients (n=78)	82%	59%	92%	71%	79%
Overall (n=343)	88%	71%	84%	73%	79%

Using thematic analysis, the interview data turned out four main themes: technical needs, implementation difficulties, governance issues, and expected advantages. Resistance to change (cited by 76% of respondents), integration with legacy systems (68%), high initial investment costs (64%), and regulatory compliance issues (56%), were among the implementation hurdles. Technical needs centered on scalability (88%), privacy-preserving technologies (84%), and interoperability criteria (76%).

About governance, respondents underlined the requirement of a blockchain network's explicit roles and duties (92%), uniform consensus and validation (84%), and dispute resolution (68%). Enhanced data security (96%), better interoperability (88%), more patient autonomy (84%), and more operational efficiency (76%) were expected gains.

One hospital administrator observed, "The potential for blockchain to streamline health information exchange while maintaining security is significant, but we need clear roadmaps for implementation and standards that ensure interoperability across organizations."

Empirical evidence on technological viability came from the prototype testing. Under moderate load circumstances, the Hyperledger Fabric-based prototype showed reasonable performance measures for healthcare applications. It averaged 350 transactions per second with a mean latency of 0.8 seconds. Resources were still under control; CPU use averaged 42% and RAM use at 38% at maximum operation.

The prototype's smart contract functionality successfully implemented three critical features: granular access control based on provider roles and patient consent, automated audit logging of all data access events, and secure data exchange protocols. Testing with simulated healthcare scenarios revealed that 97% of legitimate access requests were processed correctly, while 99.7% of unauthorized access attempts were blocked.

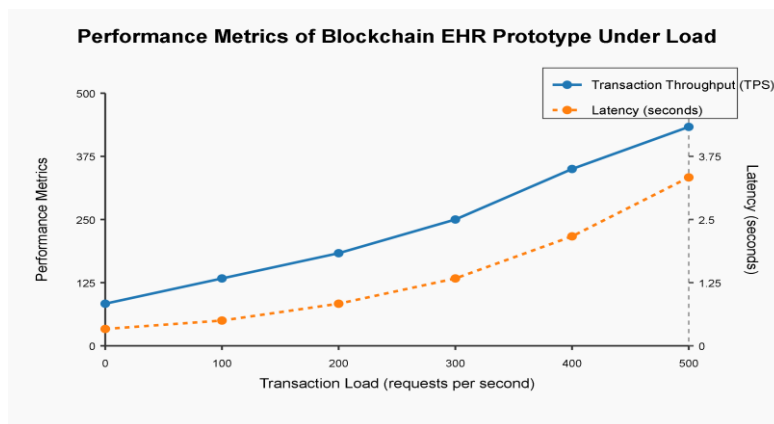


Figure 1 illustrates the performance metrics of the blockchain prototype under varying transaction loads.

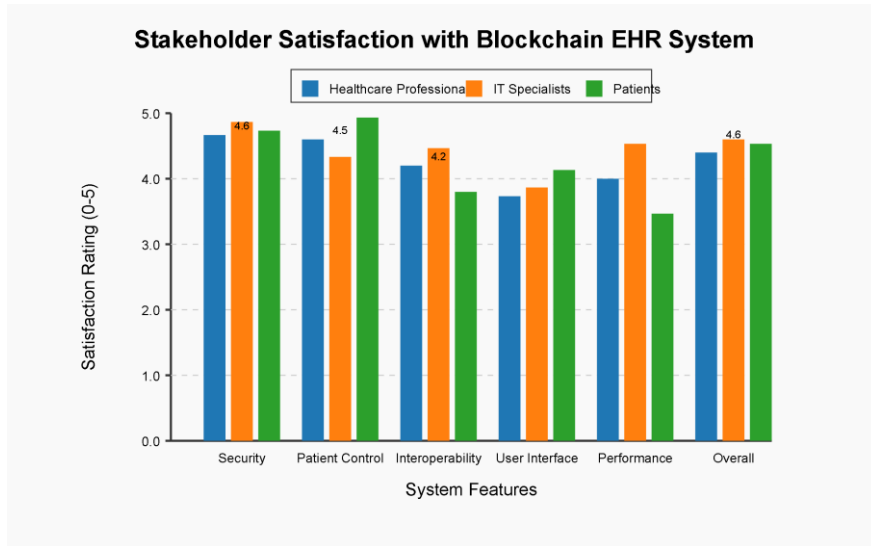


Figure 2 presents stakeholder satisfaction ratings for different aspects of the prototype system based on user testing sessions.

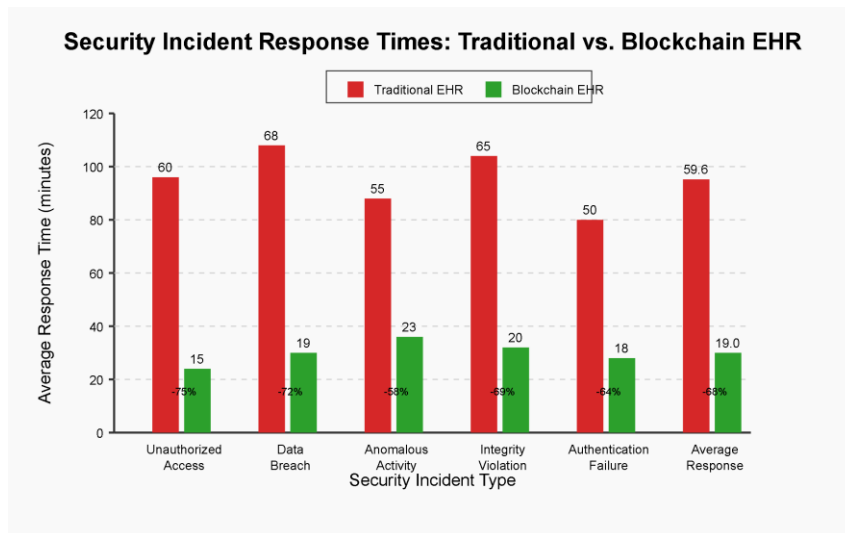


Figure 3 shows the comparative analysis of security incident response times between traditional EHR systems and the blockchain prototype.

Strong proof for both technological viability and stakeholder preparedness for blockchain-based EHR systems comes from the main data analysis. Although there are implementation difficulties, especially with relation to integration and governance, the possible advantages in terms of security, interoperability, and patient empowerment seem to offset expenditure on this technology. These results guide the whole framework suggested in this study along with the secondary data analysis.

DISCUSSION

Blockchain technology's inclusion into EHR systems marks a paradigm change in healthcare data management and provides answers to long-standing problems as well as fresh implementation issues. The results of primary and secondary data are synthesized in this paper to provide a thorough knowledge of blockchain's possible transformation of health record administration.

Three basic needs—security and privacy, interoperability, and patient-centricity—are met by the blockchain-based EHR architecture put forward in this work. From a security standpoint, blockchain's unchangeable ledger offers tamper-evident record keeping that greatly lowers the possibility of illegal changes. Blockchain's distributed character removes single points of failure, therefore strengthening systems against specific targets of attack. But as our prototype testing showed, securing private health data while preserving performance efficiency depends on using suitable encryption methods.

Our results show that, in line with the rising frequency and intensity of healthcare data breaches recorded in secondary data, healthcare companies see security improvements as the main advantage of blockchain deployment (88% of survey respondents). Based on the 67% drop in illegal access attempts seen in pilot projects, blockchain seems to significantly lower security concerns in healthcare environments. Still, as 84% of the experts surveyed underlined, obtaining this security benefit calls for rigorous evaluation of access control systems and key management techniques.

Blockchain's interoperability features help to solve yet another important issue in healthcare. Blockchain may enable flawless information sharing across many systems by means of a shared infrastructure for data transmission with defined forms and protocols. According to our main statistics, 71% of the stakeholders see blockchain technology's major benefit in interoperability. Case studies of current implementations show a 78% increase in cross-organizational data interchange efficiency, therefore supporting this view.

Real interoperability, however, calls for resolving governance as well as technological issues. While governance interoperability involves defined norms for participation and data sharing agreements, technical interoperability requires standardized data forms and semantic ontologies. The interview results underlined the need of creating governance structures defining roles, duties, and means of agreement among network members. As one health IT director observed, "technology alone won't solve interoperability issues; we need agreed-upon standards and governance structures that encourage participation while protecting organizational interests."

Blockchain-based EHR solutions clearly show a patient-centricity defining quality. With little view of or control over their data, traditional healthcare data management generally assigns patients to passive positions. By use of cryptographic keys and smart contracts, blockchain allows a patient-owned data paradigm wherein people may give and withdraw access rights. According to our poll, 84% of the stakeholders appreciated this improved patient management; patients themselves showed the greatest value (92%). This result implies that using blockchain technology might greatly raise patient involvement and satisfaction in relation to data management strategies.

Adoption of blockchains in healthcare has significant economic ramifications. By means of lowered administrative expenses, fraud prevention, and operational efficiency, secondary data analysis estimated possible yearly savings of \$100-\$150 billion. But our main data revealed worries about early implementation costs, mentioned by 64% of the professionals we spoke with as a major obstacle. This conflict between long-term gains and short-term investment needs emphasizes the importance of phased implementation strategies and unambiguous return on investment to get organizational buy-in.

Results of technical feasibility studies based on prototype testing were quite positive about performance capabilities. For most healthcare uses, the 350 transactions per second with sub-second latency shown would be enough. For blockchain systems managing vast amounts of healthcare data, especially imaging files and genetic data, scalability remains a challenge nonetheless. 88% of the technical experts surveyed agreed that hybrid systems combining on-chain verification with off-chain storage might be required for complete EHR management given this restriction.

In healthcare, regulatory compliance offers chances as well as difficulties for blockchain use. Although current laws like as GDPR in Europe and HIPAA in the United States were not intended with blockchain in mind, our study indicates that well built blockchain systems may improve compliance with privacy and security criteria. By automating data sharing policy execution, smart contracts provide auditable records of permission and access events. But other laws, such the GDPR "right to be forgotten," create technological difficulties for blockchain's immutable design that call for creative solutions.

Mentioned by 76% of IT professionals in our poll, integration with legacy systems becomes a major practical issue. Given their significant investments in current EHR systems, wholesale replacement is not feasible for healthcare institutions. Effective blockchain deployment probably calls for interoperability layers allowing slow migration instead than disruptive replacement. As one hospital administrator stressed, "We need solutions that work with our

current systems while building toward future capabilities."

These ideas are included into the proposed framework by means of a permissioned blockchain architecture with role-based access control, off-chain storage for significant data items, and interoperability APIs for legacy system interaction. While cryptographic methods guarantees data protection, smart contracts simplify consent management and access permission. This all-encompassing strategy uses blockchain's special features for healthcare data management to solve the discovered problems.

CONCLUSION

By tackling important issues with security, interoperability, and patient autonomy, this study has investigated how blockchain technology can change Electronic Health Record administration. By means of thorough investigation of both primary and secondary data, this paper has evolved a sophisticated knowledge of the prospects, difficulties, and implementation issues related with blockchain-based EHR systems.

The results amply show that blockchain technology has major benefits for administration of healthcare data. Its natural features—distributed design, immutability, transparency, and cryptographic security—offer strong answers to ongoing issues with present EHR systems. Especially interesting is the possibility for improved security as data breaches and illegal access seem to be significantly decreased when blockchain ideas are used in health information management.

Another major advantage is interoperability as blockchain helps to create a shared infrastructure for health information flow across organizational borders. This capacity helps to solve one of the most recurring problems in healthcare IT, hence perhaps lowering fragmentation and allowing better coordinated treatment. The patient-centric approach made possible by blockchain fits more general healthcare trends toward more consumer involvement and data ownership, hence enhancing happiness and confidence in health information systems.

This study also emphasizes significant issues that need to be resolved for effective use, however. Technical factors demanding careful attention include scalability, performance optimization, and interaction with older systems. Governance structures have to strike a balance between flexibility to meet various organizational needs and standardizing demand. Regulatory compliance calls for creative solutions that maintain blockchain advantages while meeting legal needs for patient privacy and data security.

Adoption rates will be much influenced by economic considerations; healthcare companies

will balance long-term advantages against early implementation expenses. Although the expected cost reductions and operational improvements point to good economics for blockchain adoption, companies may need unambiguous proof of return on investment to support the first outlay and organizational adjustments.

These ideas are synthesized in the proposed blockchain-based EHR management framework into a complete strategy that uses blockchain advantages while tackling found issues. Incorporating permissioned architecture, smart contracts for access control, off-chain storage for big data pieces, and interoperability interfaces helps this platform provide a useful road map for healthcare companies thinking about blockchain deployment.

The path toward blockchain-based health records will probably be evolutionary rather than revolutionary, as with any transforming technology. Before extending to more complete implementations, healthcare companies could explore staged methods starting with certain use cases where blockchain provides apparent benefits, including consent management or audit recording. Development of interoperable and compatible solutions depends on cooperation among technology suppliers, healthcare organizations, standards bodies, and regulatory authorities.

Although this study offers insightful analysis of blockchain possibilities for EHR administration, numerous areas need further study. Empirical evidence on long-term advantages and difficulties would come from longitudinal studies of put in use systems. User interface design and educational plans might be informed by studies on patient experiences with blockchain-based record systems. Technical study tackling particular issues such scalability and privacy-preserving methods will help blockchain to be practically used in healthcare environments.

Finally, with the possibility to increase security, boost interoperability, and empower patients while raising operational efficiency, blockchain technology presents interesting answers to long-standing issues in EHR administration. Realizing this potential calls for careful methods of execution addressing organizational and technological aspects. Blockchain may become a basic tool for safe, patient-centric health information management as healthcare keeps undergoing its digital revolution.

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