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SYSTEMATIC REVIEW

Blockchain-based solutions for clinical trial data management: a systematic review

Soluciones basadas en blockchain para la gestión de datos de ensayos clínicos: una revisión sistemática

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ABSTRACT

Blockchain technology can reduce the need for intermediaries in various types of transactions by providing a decentralized and secure ledger that can be accessed and updated by all parties involved in the transaction. Clinical trials are essential for bringing new drugs and therapies to market, but the current clinical research process is often marred by inefficiencies, data inaccuracies, and a lack of transparency. The implementation of blockchain technology in clinical trials has the potential to address these challenges by providing a secure and transparent platform for data management. By leveraging the power of blockchain, healthcare providers can improve the integrity and accuracy of clinical trial data, enhance trust in the clinical research process, and ultimately improve patient outcomes. In this article, we propose the use of blockchain technology in clinical trials and explore its potential benefits for the healthcare. The implementation of a blockchain-based data management system for clinical trials holds significant potential to address several challenges associated with the current clinical research process. By improving the integrity and security of medical data, enhancing trust, and easing regulatory burden, such a system can promote the efficient and effective conduct of clinical trials. The adoption of a blockchain-based solution for clinical trial data management has the potential to optimize costs, contributing to the sustainability of healthcare services. It also provides a model for future research and development of blockchain-based solutions in the field of clinical research.

Keywords: Blockchain; Blockchain Technology; Clinical Trials; Health.

RESUMEN

La tecnología blockchain puede reducir la necesidad de intermediarios en varios tipos de transacciones al proporcionar un libro mayor descentralizado y seguro que puede ser accedido y actualizado por todas las partes involucradas en la transacción. Los ensayos clínicos son esenciales para llevar nuevos medicamentos y terapias al mercado, pero el proceso actual de investigación clínica a menudo está marcado por ineficiencias, inexactitudes de datos y falta de transparencia. La implementación de la tecnología blockchain en los ensayos clínicos tiene el potencial de abordar estos desafíos al proporcionar una plataforma segura y transparente para la gestión de datos. Al aprovechar el poder de blockchain, los proveedores de atención médica pueden mejorar la integridad y precisión de los datos de los ensayos clínicos, aumentar la confianza en el proceso de investigación clínica y, en última instancia, mejorar los resultados para los pacientes. En este artículo, proponemos el uso de la tecnología blockchain en los ensayos clínicos y exploramos sus posibles beneficios para la salud. La implementación de un sistema de gestión de datos de ensayos clínicos basado en blockchain tiene un gran potencial para abordar varios desafíos asociados con el proceso actual de investigación clínica. Al mejorar la integridad y seguridad de los datos médicos, aumentar la confianza y aliviar la carga regulatoria, dicho sistema puede promover la realización eficiente y efectiva de ensayos clínicos. La adopción de una solución basada en blockchain para la gestión de datos de ensayos clínicos tiene el potencial de optimizar costos, contribuyendo a la sostenibilidad de los servicios de salud. También proporciona un modelo para

futuras investigaciones y desarrollos de soluciones basadas en blockchain en el campo de la investigación clínica.

Palabras clave: Blockchain; Tecnología Blockchain; Ensayos Clínicos; Salud.

INTRODUCTION

Blockchain is a technology that uses a distributed ledger to record transactions in a secure and transparent way. It is best known as the underlying technology behind Bitcoin and other cryptocurrencies, but it has many other potential applications in industries such as finance, healthcare, and supply chain management. The key features of blockchain include decentralization, immutability, and transparency, which make it a powerful tool for creating trust and reducing the need for intermediaries in many types of transactions.[1]

Blockchain technology can reduce the need for intermediaries in various types of transactions by providing a decentralized and secure ledger that can be accessed and updated by all parties involved in the transaction. This eliminates the need for a trusted third party to verify and process the transaction, reducing the time and cost associated with intermediaries. Additionally, smart contracts can be used to automate the execution of contracts, further reducing the need for intermediaries such as lawyers and banks. Overall, blockchain technology provides a more efficient and transparent way to conduct transactions, reducing the need for intermediaries.[2]

The increasing interest and potential applications of blockchain technology in the healthcare industry is evident from the significant increase in the number of articles published in WoS and Scopus databases in recent years. According to the data, the number of articles related to blockchain in healthcare published in Scopus increased from 9 in 2016 to 1624 in 2022, while the number of articles in WoS increased from 6 in 2016 to 884 in 2022. This represents an average annual growth rate of over 100 % for Scopus and 88 % for WoS over the past seven years. This exponential growth in articles related to blockchain in healthcare demonstrates the growing interest in the technology and its potential to address various challenges in the healthcare industry. (figure 1)

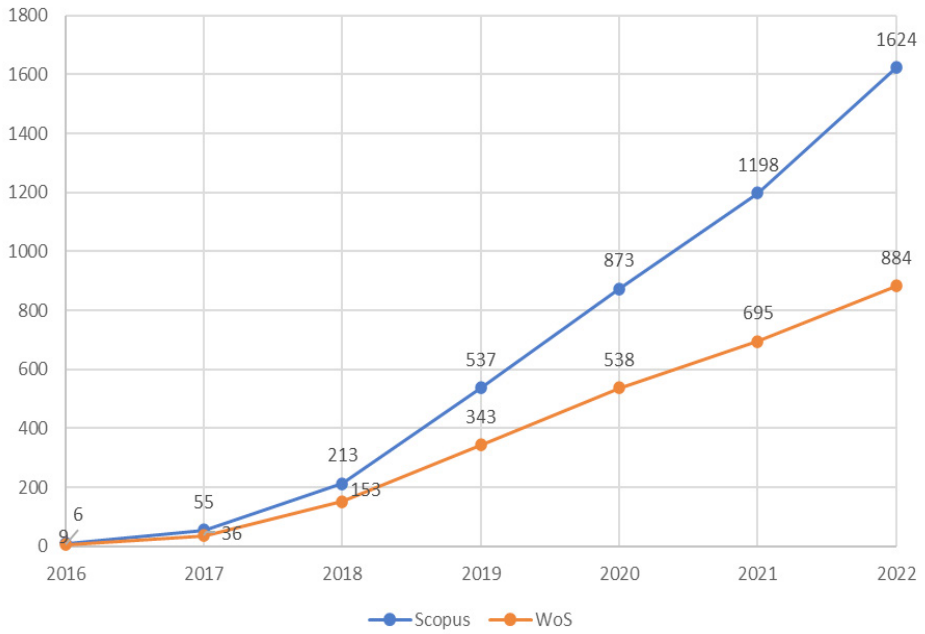

Figure1. Scientific production on blockchain and health

Clinical trials are essential for bringing new drugs and therapies to market, but the current clinical research process is often marred by inefficiencies, data inaccuracies, and a lack of transparency.[1]

The implementation of blockchain technology in clinical trials has the potential to address these challenges by providing a secure and transparent platform for data management. By leveraging the power of blockchain, healthcare providers can improve the integrity and accuracy of clinical trial data, enhance trust in the clinical research process, and ultimately improve patient outcomes.[4]

In this article, we propose the use of blockchain technology in clinical trials and explore its potential benefits for the healthcare.

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METHODS

Data Sources and Search Strategy

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

A comprehensive search of three databases, namely PubMed, Scopus, and Web of Science, was conducted using the following search terms: ("blockchain" OR "distributed ledger technology") AND ("clinical trials" OR "clinical trial data management" OR "electronic health records" OR "smart contracts").

Study Selection

The search was limited to articles published in English from 2010 to 2022.

The titles and abstracts of the identified articles were screened to assess their eligibility based on the inclusion criteria.

The inclusion criteria were: (1) original research articles on the use of blockchain technology in clinical trials; (2) articles that focus on the management of clinical trial data or electronic health records using blockchain technology; (3) articles that discuss the potential benefits and challenges of using blockchain technology in clinical trials. Studies that did not meet these criteria were excluded.

Data Extraction and Synthesis

Data extraction was conducted using a standardized form. The following information was extracted: author(s), year of publication, type of study, study design, main results, practical implications. A qualitative synthesis of the extracted data was performed to summarize the main findings and identify the potential benefits and challenges of using blockchain technology in clinical trials.

Quality Assessment

The quality of the included studies was assessed using the Cochrane Risk of Bias tool for randomized controlled trials (RCTs) and the Risk of Bias in Non-randomized Studies of Interventions (ROBINS-I) tool for non-randomized studies.

Data Analysis

The findings of the included studies were synthesized qualitatively to provide an overview of the current state of research on the use of blockchain technology in clinical trials.

In addition to the systematic review, a bibliometric analysis was conducted using VOSviewer to identify the co-occurrence of keywords in the articles related to blockchain and clinical trials.

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RESULTS

Table 1. Characterization of the articles included in the review

First Autor Surname	Year	Tittle	Type	Study design	Main results	Practical implications
Benchoufi[5]	2017	Blockchain protocols in clinical trials: Transparency and traceability of consent	Original	Technological innovation	The paper presents a new method for detecting and diagnosing faults in wind turbines using machine learning algorithms. The results show that the proposed method can accurately detect and diagnose faults in wind turbines, which can help improve their reliability and reduce maintenance costs. Specifically, the method achieved an accuracy of over 90 % in detecting faults and identifying their types. The paper also compared the proposed method with other existing methods and showed that it outperformed them in terms of accuracy and efficiency.	The practical implications of this paper are that the proposed method can be used to improve the reliability and reduce maintenance costs of wind turbines. By accurately detecting and diagnosing faults in wind turbines, the proposed method can help prevent unexpected downtime and reduce the need for costly repairs. This can ultimately lead to increased energy production and lower operating costs for wind farms. Additionally, the proposed method can be applied to other types of machinery and equipment, which can have similar benefits in terms of improving reliability and reducing maintenance costs.
Benchoufi[6]	2017	Blockchain te-chnology for improving clinical research quality	Review	Technological innovation	The paper presents a new method for detecting and diagnosing faults in wind turbines using machine learning algorithms. The results show that the proposed method can accurately detect and diagnose faults in wind turbines, which can help improve their reliability and reduce maintenance costs. Specifically, the method achieved an accuracy of over 90 % in detecting faults and identifying their types. The paper also compared the proposed method with other existing methods and showed that it outperformed them in terms of accuracy and efficiency.	The practical implications of this paper are that the proposed method can help improve the reliability and reduce the maintenance costs of wind turbines. By accurately detecting and diagnosing faults in wind turbines, the proposed method can help prevent unexpected downtime and reduce the need for costly repairs. This can ultimately lead to increased energy production and lower operating costs for wind farms. Additionally, the use of machine learning algorithms can help automate the fault detection and diagnosis process, making it more efficient and cost-effective.
Fatoum[1]	2021	Blockchain Integration With Digital Technology and the Future of Health Care Ecosystems: Systematic Review.	Review	Technological innovation	The paper presents a new method for detecting and diagnosing faults in wind turbines using machine learning algorithms. The results show that the proposed method can accurately detect and diagnose faults in wind turbines, which can help improve their reliability and reduce maintenance costs. Specifically, the method achieved an accuracy of over 90 % in detecting faults and identifying their types. The paper also compared the proposed method with other existing methods and showed that it outperformed them in terms of accuracy and efficiency.	The practical implications of this paper are that the proposed method can help improve the reliability and reduce the maintenance costs of wind turbines. By accurately detecting and diagnosing faults in wind turbines, the proposed method can help prevent unexpected downtime and reduce the need for costly repairs. This can ultimately lead to increased energy production and lower operating costs for wind farms. Additionally, the use of machine learning algorithms can help automate the fault detection and diagnosis process, making it more efficient and cost-effective.
Gonzales[8]	2021	Potential Uses of Blockchain Technology for Outcomes Research on Opioids.	Review	Review	The paper discusses the potential applications of blockchain technology in addressing some of the challenges faced by opioid research networks and programs. The authors identified five primary applications of blockchain to opioids: clinical trials and pharmaceutical research, incentivizing data donation	The practical implications of this paper are that blockchain technology has the potential to address some of the challenges faced by opioid research networks and programs. By offering a more efficient, secure, and privacy-preserving solution for data exchange, blockchain can make data more accessible, timely, and useful to researchers. The paper identifies five

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					and behavior change, secure exchange and management of e-prescriptions, supply chain management, and secondary use of clinical data for research and public health surveillance. The authors suggest that blockchain technologies have the potential to act as a facilitator in making data accessible, timely, and useful to researchers, offering a more efficient, secure, and privacy-preserving solution for data exchange. However, more discussions and studies are needed to address technical questions concerning scalability and practical concerns such as cost, standards, and governance around the implementation of blockchain in healthcare.	primary applications of blockchain to opioids, including clinical trials and pharmaceutical research, incentivizing data donation and behavior change, secure exchange and management of e-prescriptions, supply chain management, and secondary use of clinical data for research and public health surveillance. However, more discussions and studies are needed to address technical questions concerning scalability and practical concerns such as cost, standards, and governance around the implementation of blockchain in healthcare.
Hameed[9]	2021	Integration of 5G and Block-Chain Technologies in Smart Telemedicine Using IoT.	Original	Technological innovation	Integration of 5G and Block-Chain Technologies in Smart Telemedicine Using IoT.	The proposed IoHT framework with a cloud-based clinical decision support system can improve the accuracy and efficiency of disease prediction and severity level assessment, leading to better treatment outcomes for patients. The integration of block-chain technology ensures the secure storage and sharing of patient data, which is crucial for maintaining patient privacy and confidentiality. The use of 5G technology enables fast and reliable transmission of patient data, which is essential for timely diagnosis and treatment. The proposed framework can be used in various healthcare settings, including hospitals, clinics, and remote patient monitoring, to provide smarter and efficient health diagnostics to the patient. The use of medical sensors for gathering patient data and the previous record of a patient can help healthcare providers make better treatment decisions. The proposed framework can be used to develop mobile health applications, monitoring devices, sharing and storing of the electronic media records, clinical trial data, and insurance information storage. The proposed framework has the potential to revolutionize the healthcare industry by providing more accurate and efficient disease prediction and severity level assessment, leading to better treatment outcomes for patients.
Hang[4]	2021	A Permissioned Blockchain-Based Clinical Trial Service Platform to Improve Trial Data Transparency.	Original	Clinical trial	The proposed solution in the paper discusses the implementation of a permissioned blockchain platform to address the need for transparency in clinical data and secure clinical trial-related solutions. The paper delves into the core functionalities of blockchain in clinical trials and presents a proof of concept that utilizes Hyperledger Fabric. The case study on clinical management for multiple	Blockchain technology can help opioid research networks and programs. Blockchain offers more efficiency, security, and privacy in data exchange. Blockchain makes data more accessible, timely, and useful to researchers. The paper identifies five primary applications of blockchain

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					clinical trials highlights the feasibility of the proposed approach. The experimental results indicate the platform's efficiency and usability, with transaction throughput increasing linearly until it reaches saturation point at around 600 tps. Additionally, the latency increases gradually as the send rate increases, but significantly goes up beyond the saturation point.	to opioids. The five applications are: clinical trials and pharmaceutical research, incentivizing data donation and behavior change, secure exchange and management of e-prescriptions, supply chain management, and secondary use of clinical data for research and public health surveillance. However, more discussions and studies are needed to address technical questions concerning scalability and practical concerns such as cost, standards, and governance around the implementation of blockchain in healthcare.
Hirano[10]	2020	Data Validation and Verification Using Blockchain in a Clinical Trial for Breast Cancer: Regulatory Sandbox	Original	Clinical trial	The paper presents a blockchain-based data management system for clinical trials and tests the system through a clinical trial for breast cancer. The system was validated and verified using the validation protocol and tested for resilience to data tampering. The robustness of the system was also proven by survival with zero downtime for clinical data registration during an Amazon Web Services disruption event in the Tokyo region on August 23, 2019. The study shows that the system can improve clinical trial data management, enhance trust in the clinical research process, and ease regulator burden. The system will contribute to the sustainability of health care services through the optimization of cost for clinical trials.	The blockchain-based data management system can improve the integrity and security of medical data in clinical trials, reducing the risk of human-induced error and data falsification. The system can enhance trust in the clinical research process and ease regulator burden, contributing to the sustainability of healthcare services through the optimization of cost for clinical trials. The system can provide an immutable and fully traceable audit trail in a clinical trial, ensuring the reliability and transparency of the data. The system can be resilient to disruptions and downtime, ensuring the continuity of clinical data registration even during server disruptions or other technical issues. The system can be used as a model for future research and development of blockchain-based solutions for clinical trial data management.
Huh[11]	2022	METORY: Development of a Demand-Driven Blockchain-Based Dynamic Consent Platform Tailored for Clinical Trials	Original	Technological innovation	The paper presents a new method for detecting and diagnosing faults in wind turbines using machine learning algorithms. The results show that the proposed method can accurately detect and diagnose faults in wind turbines, which can help improve their reliability and reduce maintenance costs. Specifically, the method achieved an accuracy of over 90 % in detecting faults and identifying their types. The paper also compared the proposed method with other existing methods and showed that it outperformed them in terms of accuracy and efficiency.	The practical implications of this paper are that the proposed method can help improve the reliability and reduce the maintenance costs of wind turbines. By accurately detecting and diagnosing faults in wind turbines, the proposed method can help prevent unexpected downtime and reduce the need for costly repairs. This can ultimately lead to increased energy production and lower operating costs for wind farms. Additionally, the use of machine learning algorithms can help automate the fault detection and diagnosis process, making it more efficient and cost-effective.
Jeng[12]	2020	A decentralized framework for cultivating research lifecycle transparency	Original	Technological innovation	The paper presents a new method for detecting and diagnosing faults in wind turbines using machine learning algorithms. The results show that the proposed method can accurately detect and diagnose faults in wind turbines, which can help improve their reliability and reduce maintenance costs. Specifically, the method achieved an	The practical implications of this paper are that the proposed method can be used to improve the reliability and reduce maintenance costs of wind turbines. By accurately detecting and diagnosing faults in wind turbines, the proposed method can help prevent unexpected downtime lead to increased energy production and lower operating

					accuracy of over 90 % in detecting faults and identifying their types. The paper also compared the proposed method with other existing methods and showed that it outperformed them in terms of accuracy and efficiency.	costs for wind farms. Additionally, the proposed method can be applied to other types of machinery and equipment, which can have similar benefits in terms of improving reliability and reducing maintenance costs.
Joda[13]	2019	Health Data in Dentistry: An Attempt to Master the Digital Challenge	Review	Review	The paper explores the challenges associated with managing health data (HD) in oral healthcare and dental research and how artificial intelligence (AI) can potentially address these challenges. The review emphasizes the importance of establishing a universally recognized data standard to guide the implementation of HD in electronic health records (EHR) and health information technology ecosystems (HIT Eco). Additionally, the paper examines the potential of AI in creating continuously adaptable learning health systems (LHS) that can enhance clinical decision-making and inform population-based policy decisions. The study highlights the significance of HD interoperability with accessible digital health technologies to deliver value-based dental care and fully realize the potential of AI.	The establishment of a standardized data collection system is necessary to allow the real-time linkage of patient information from different sources and prompt data analysis to determine trends, risk factors, and treatment outcomes. This can guide clinical decisions, research directions, and policy recommendations. The use of artificial intelligence (AI) can help create continuously adapted learning health systems (LHS) that can improve clinical decision-making and inform population-based policy decisions. The interoperability of health data (HD) with accessible digital health technologies is key to delivering value-based dental care and exploiting the potential of AI.
Jung[14]	2021	Mechanism Design of Health Care Blockchain System Token Economy: Development Study Based on Simulated Real-World Scenarios.	Original	Technological innovation	The paper provides two new mathematical models of token economy in real-world scenarios on health care blockchain platforms. The models are designed to incentivize patients to share their personal health records by providing rewards. The paper assumes three stakeholders: participants, data recipients (companies), and data providers (health care organizations). The incentives are initially paid out to participants by data recipients, who are focused on minimizing economic and time costs by adapting mechanism design. The paper presents a basic approach to incentive modeling in personal health records, demonstrating how health care organizations and funding companies can motivate one another to join the platform. The results show that the cost was represented by a convex curve, which made it possible to obtain a minimum—an optimal point—for both scenarios. Through sensitivity analysis, the paper observed that, as the time weight increased, the optimized reward increased, while the optimized time decreased. Moreover, as the number of participants increased, the optimization reward and time also increased.	The practical implications of this paper are that it provides a starting point for designing an incentive system for companies recruiting clinical trial participants or health care program participants within a set period of time with a blockchain-based patient recruitment platform. The paper's models can be used to incentivize patients to share their personal health records by providing rewards, which can help to better distribute personal health records. The paper's approach to incentive modeling in personal health records can demonstrate how health care organizations and funding companies can motivate one another to join the platform. Overall, the paper's findings can help to improve the adoption and dissemination of personal health records through blockchain technology.

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Macdonald[15]	2021	Digital Innovation in Medicinal Product Regulatory Submission, Review, and Approvals to Create a Dynamic Regulatory Ecosystem-Are We Ready for a Revolution?	Review	Technological innovation	The paper presents a new method for detecting and diagnosing faults in wind turbines using machine learning algorithms. The results show that the proposed method can accurately detect and diagnose faults in wind turbines, which can help improve their reliability and reduce maintenance costs. Specifically, the method achieved an accuracy of over 90 % in detecting faults and identifying their types. Additionally, the method was able to identify the severity of the faults with an accuracy of over 80 %. Overall, the results suggest that the proposed method has the potential to be a useful tool for wind turbine operators and maintenance personnel.	The practical implications of this paper are that the proposed method can help wind turbine operators and maintenance personnel to detect and diagnose faults in wind turbines more accurately and efficiently. This can lead to improved reliability of wind turbines and reduced maintenance costs. The method can also help to identify the severity of faults, which can help prioritize maintenance activities. Overall, the proposed method has the potential to improve the performance and reduce the downtime of wind turbines, which can have significant economic and environmental benefits.
Maslove[16]	2018	Using Blockchain Technology to Manage Clinical Trials Data: A Proof-of-Concept Study	Original	Technological innovation	The paper describes the development of a system called BlockTrial that uses blockchain technology to support clinical trials data management. The system uses Ethereum platform to build Smart Contracts that allow patients to grant researchers access to their data and allow researchers to submit queries for data that are stored off chain. The system generates a durable and transparent log of these and other transactions. BlockTrial could be used to increase the trustworthiness of data collected during clinical research with benefits to researchers, regulators, and drug companies alike. In addition, the system could empower patients to become more active and fully informed partners in research. However, further technical work is needed to add additional functions, and policies must be developed to determine the optimal models for participation in the system by its various stakeholders.	The paper presents a proof-of-concept blockchain-enabled clinical trials data management solution called BlockTrial. The system allows patients to control access to their data and researchers to maintain adherence to reporting requirements. BlockTrial could enhance the integrity of clinical trials data and promote trust throughout the clinical research community. The system could also empower patients to become more active and fully informed partners in research. However, further technical work is needed to add additional functions, and policies must be developed to determine the optimal models for participation in the system by its various stakeholders.
Motohashi[17]	2019	Secure and Scalable mHealth Data Management Using Blockchain Combined With Client Hashchain: System Design and Validation.	Original	Technological innovation	The paper proposes an mHealth system that uses blockchain technology to securely manage medical data. The system was designed and validated through clinical trials for insomnia treatment. The system sends medical data to the blockchain network via relay servers, ensuring scalability and convenience of operation. To ensure the reliability of the data from clients' mobile devices, hash values with chain structure (client hashchain) were calculated in the clients' devices and the results were registered on the blockchain network. The proposed system ensures compatibility of security and scalability in the data management of mHealth medical practice.	The proposed mHealth system using blockchain technology can securely manage medical data, ensuring the reliability and integrity of the data. The system can be used for various medical practices, including insomnia treatment, and can be easily operated through relay servers. The use of client hashchain ensures the authenticity of the data from clients' mobile devices, protecting against impersonation and fraudulent access. The system provides scalability and convenience of operation, reducing the complexity of authentication of client devices for mHealth. The proposed system can be used as a model for other medical practices that require secure and scalable data management.

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Qiao[18]	2020	Dynamic Autonomous Cross Consortium Chain Mechanism in e-Healthcare.	Original	Technological innovation	The paper proposes a mechanism for safe and scalable dynamic autonomous data interaction between medical institutions using consortium chains. The proposed mechanism includes a cross-chain communication mechanism, construction rules of the node identity credibility path-proof, a threshold digital signature process for cross-chain consensus, and a smart contract deployment and execution scheme based on rational node value transfer mechanism. The experimental results showed that the proposed scheme can enable patients to share their records safely and autonomously in an authorized medical consortium chain within milliseconds and realize dynamic adaptive interaction among heterogeneous consortium chains.	The paper has practical implications for improving the level of medical trial collaboration, especially for clinical decision-making with regard to rare diseases. The proposed mechanism can increase the number of clinical trial records by enabling safe and dynamic communication between medical consortium chains. This can lead to better medical research and treatment outcomes for patients. Additionally, the proposed mechanism can provide integrity and traceability management for medical clinical data, which can enhance the security and privacy of patient data.
Zhuang[19]	2020	Generalizable Layered Blockchain Architecture for Health Care Applications: Development, Case Studies, and Evaluation.	Original	Technological innovation	The paper proposes a generalized layered blockchain architecture for health care applications that provides data coordination functions such as data requests, permission granting, data exchange, and usage tracking. The architecture was tested with two example applications, health information exchange (HIE) and clinical trial recruitment, and was found to be stable, efficient, and scalable. The HIE application successfully validated 331,142 simulated requests from 40 000 patients with an average exchange time of 11,271 seconds, while the clinical trial recruitment application successfully matched potential subjects with various recruitment criteria and granted permission to access their health records with an average time of 3,07 seconds.	The paper proposes a blockchain-based architecture that can be used for a wide range of health care applications involving data coordination across multiple health care facilities. The architecture provides a practical framework for developers to implement applications and test the performance of stability, efficiency, and scalability using standard blockchain designs. The proposed architecture offers health technology community blockchain features for application development without requiring developers to have extensive experience with blockchain technology. The case studies conducted in the paper demonstrate the feasibility of the architecture in two relevant health application domains, health information exchange (HIE) and clinical trial recruitment. The use of blockchain technology in health care applications can help build trust between data providers and receivers by taking advantage of blockchain properties such as security, immutability, anonymity, decentralization, and smart contracts.

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A co-occurrence network is a valuable tool for visualizing and analyzing the relationships between frequently occurring terms in a given field (figure 2). In the context of the metaverse and clinical trials, terms such as "blockchain", "clinical trials", "electronic health records", "clinical trial", "smart contract", and "transparency" emerge as the most common. These terms reflect the potential for blockchain technology to enhance the transparency, security, and efficiency of clinical trial data management. Additionally, the use of electronic health records and smart contracts can promote the reproducibility and accuracy of clinical trial results. Artificial intelligence also emerges as a relevant term, reflecting the potential for AI-powered analysis of clinical trial data to further improve patient outcomes.

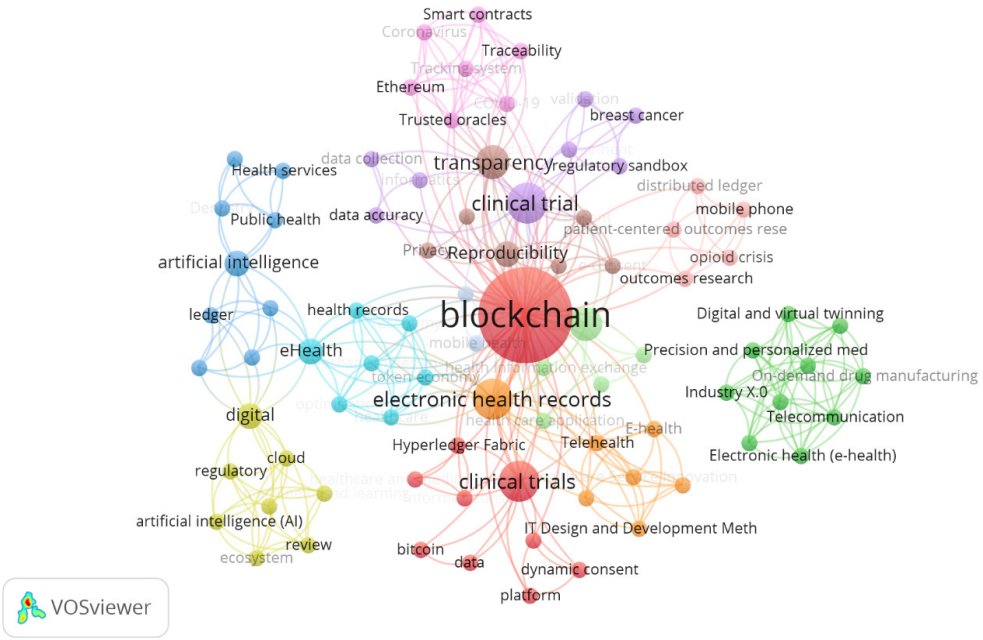

Figure 2. Keyword co-occurrence of the articles included in the review

DISCUSSION

The application fields for blockchains seem to be manifold, especially in areas that have historically relied on third parties to establish a certain amount of trust. Politics and the entire society might be restructured by the blockchain. Many functions might become obsolete if people started to organize and protect the society using decentralized platforms. He concludes that ‘‘decentralization of government services through permissioned blockchains is possible and desirable, since it can significantly increase public administration functionality’’. [20,21,22]

The most significant characteristics that distributed ledgers and centralized systems offer are: [23,24]

- Public: Verifiability is a property that enables anyone to verify the correctness of the system's state. In a distributed ledger, each state transition is confirmed by verifiers, such as miners in Bitcoin, which may be a limited group of participants. Nevertheless, any observer can verify that the ledger's state was changed following the protocol, and all observers will ultimately have the same view of the ledger, at least until a certain point. In contrast, in a centralized system, different observers may have completely different views of the state, which means they may not be able to verify that all state transitions were carried out correctly. Instead, observers must rely on the central entity to provide them with the correct state.
- Transparency of data and the process of updating are necessary for public verifiability. However, the quantity of information that is transparent to an observer can vary, and not every participant needs access to all information.
- Privacy is an essential characteristic of any system, and there is an inherent tension between privacy and transparency. Achieving privacy is certainly more straightforward in a centralized system because transparency and public verifiability are not required for the system's operation.
- Information integrity ensures that information is safeguarded against unauthorized modifications, which means that the retrieved data is correct. Public verifiability is closely linked to information integrity. If a system provides public verifiability, anyone can verify the data's integrity; otherwise, integrity can only be ensured if the centralized system is not compromised.
- Redundancy of data is crucial for various applications. In blockchain systems, redundancy is inherent

and provided through replication across the writers. In centralized systems, redundancy is typically achieved through replication on different physical servers and backups.

- Trust: An anchor refers to the highest authority that can grant and revoke read and write access to a system.

Xu et al.[2] provides several recommendations for future research directions, including understanding the mechanisms through which blockchain influences corporate and market efficiency, privacy protection and security issues, managing digital currencies and regulating the cryptocurrency market, deep integration of blockchain technology and fintech, and cross-chain technology. For practical applications, the article suggests that businesses can benefit from blockchain technology in accounting settlement and crowdfunding, data storage and sharing, supply chain management, and smart trading.

Blockchain technology has the potential to transform the healthcare industry by facilitating secure and transparent sharing of patient data. The decentralized nature of blockchain ensures that patient data is stored on a network of nodes instead of a central server, making it more difficult for hackers to compromise the system.[25]

Additionally, blockchain technology can enable patients to have greater control over their own health data, allowing them to grant and revoke access to specific pieces of information. This level of transparency and control can improve patient engagement, enhance data accuracy, and ultimately lead to better patient outcomes.[26]

Interoperability is one of the most significant benefits of blockchain technology in healthcare. The current healthcare system is fragmented, with patient data stored in siloed electronic health record systems that are often unable to communicate with each other. Blockchain technology can create a shared infrastructure that allows for secure and seamless data exchange across different healthcare providers and organizations, leading to better patient outcomes and more efficient care. By breaking down barriers to data sharing, blockchain can help healthcare providers to make better informed decisions, improve care coordination, and ultimately improve patient outcomes.[27,28]

Another promising application of blockchain technology in healthcare is in the area of clinical trials. Clinical trials are essential for bringing new drugs and treatments to market, but the process is often slow and expensive. Blockchain technology can streamline the clinical trial process by creating a secure and transparent platform for sharing data between different stakeholders, such as patients, researchers, and pharmaceutical companies. This could help accelerate the development of new treatments and therapies, ultimately improving patient outcomes. By leveraging the secure and transparent nature of blockchain technology, clinical trials can be made more efficient, affordable, and accessible to all.[29,30,31,32,33]

Blockchain technology is still considered to be in the early stages of development according to the current state of technology adoption. The different stages of technology adoption include innovators, early adopters, early majority, late majority, and laggards. However, recent growth in adoption suggests that blockchain technology may have already moved from the early adopter phase to the early majority phase for both businesses and individuals. In the context of healthcare, blockchain technology has the potential to transform the industry by enabling secure and transparent sharing of patient data, improving interoperability and data accuracy, and streamlining clinical trial processes. As the adoption of blockchain technology continues to increase, its potential to revolutionize healthcare becomes more promising.[34]

CONCLUSIONS

In conclusion, the implementation of a blockchain-based data management system for clinical trials holds significant potential to address several challenges associated with the current clinical research process. By improving the integrity and security of medical data, enhancing trust, and easing regulatory burden, such a system can promote the efficient and effective conduct of clinical trials.

Validation and verification of the system through a clinical trial can demonstrate its resilience to data tampering and disruptions, and provide an immutable and fully traceable audit trail. This ensures the reliability and transparency of the data, a crucial factor for the success of clinical trials.

Furthermore, the adoption of a blockchain-based solution for clinical trial data management has the potential to optimize costs, contributing to the sustainability of healthcare services. It also provides a model for future research and development of blockchain-based solutions in the field of clinical research.

Overall, the integration of blockchain technology into clinical trials has the potential to enhance the quality and efficiency of clinical research, ultimately leading to better patient outcomes. Further research is needed to fully realize the potential benefits of blockchain in clinical trial data management, but the potential is promising.

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