REVIEW

Editorial Process: Submission:09/28/2024 Acceptance:04/18/2025

Enhancing Cancer Care through Blockchain Technology

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Abstract

This review examines the potential of blockchain technology to improve cancer treatment infrastructure by addressing inefficiencies in current IT systems. It suggests that blockchain can resolve interoperability issues, enhance data quality, and improve communication among healthcare stakeholders. By utilizing blockchain's decentralization, transparency, and security features, a blockchain-based Electronic Health Record (EHR) system can enable real-time data sharing, improve patient care coordination, and build trust within the cancer care continuum. The review also discusses the scalability of blockchain solutions, which is essential for accommodating various healthcare providers, facilitating seamless information exchange, and ensuring continuity of care. Additionally, it highlights blockchain's ability to bolster clinical research by providing a secure, immutable ledger for data collection, potentially speeding up the approval of new therapies. Ethical considerations related to patient consent and data ownership are addressed, emphasizing the importance of empowering patients to control their health information. Furthermore, blockchain integration can streamline billing and insurance processes, alleviating administrative burdens on healthcare providers. Ultimately, the review emphasizes that incorporating blockchain technology into cancer treatment infrastructure is vital for creating a more efficient, integrated, and patient-centered healthcare system, addressing current challenges in cancer care while promoting collaboration, enhancing data integrity, and empowering patients.

Keywords: Blockchain- cancer care- electronic health records- interoperability- patient empowerment

Asian Pac J Cancer Prev, **26 (4)**, 1139-1153

Introduction

The integration of blockchain technology into cancer care presents a groundbreaking strategy to tackle ongoing challenges associated with interoperability, data management, and patient engagement [1]. As healthcare systems increasingly prioritize secure and efficient data sharing, blockchain emerges as a powerful instrument that not only empowers patients but also enhances the overall quality of care [2]. By leveraging a decentralized ledger, patients are granted greater control over their health information, facilitating the seamless exchange of medical histories, treatment plans, and outcomes with healthcare providers and researchers [3]. This empowerment fosters informed decision-making and bolsters collaboration between patients and healthcare professionals. Moreover, blockchain significantly enhances data sharing and interoperability by creating a single, immutable record of a patient's health data, ensuring that all providers have access to comprehensive and up-to-date information [2]. This capability minimizes the risk of medical errors and improves care coordination while enabling the tracking of treatment protocols and clinical trials, thus promoting data accuracy and availability for analysis.

The transparency provided by blockchain supports research endeavors by granting access to vast amounts

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of anonymized patient data, which allows researchers to identify trends, assess treatment efficacy, and develop innovative therapies [1]. By breaking down data silos, blockchain encourages collaboration among stakeholders, including pharmaceutical companies, research institutions, and healthcare providers, thereby driving advancements in cancer treatment [4]. Additionally, blockchain emphasizes patient privacy by allowing individuals full control over their data, enabling them to manage access and fostering trust within the healthcare system [5]. The cryptographic security features inherent in blockchain protect sensitive health information from unauthorized access and manipulation [6, 7]. Furthermore, blockchain accelerates research and clinical trials in oncology through the secure and anonymous sharing of patient data, empowering researchers to utilize larger, more diverse datasets that can speed up the development of new treatments and personalized therapies [8]. It also streamlines the clinical trial process via automated participant recruitment, consent management, and data collection through smart contracts [9]. Overall, blockchain enhances the traceability and transparency of the pharmaceutical supply chain, ensuring the quality and integrity of cancer medications from manufacturing to patient delivery, while reducing counterfeiting risks and improving treatment accuracy [10, 11]. In this context, blockchain not only amplifies patient safety but also automates various processes, such as reimbursement and prescription management, leading to increased efficiency and cost reductions in cancer care.

The integration of blockchain technology in healthcare has the potential to significantly enhance data management, patient care, and operational efficiency. Its critical attributes—auditability, anonymity, and decentralization—facilitate secure electronic health record (EHR) exchanges while granting patients greater control over their data. Although there are challenges such as integration complexities and evolving regulatory frameworks, the overall outlook for blockchain in the healthcare sector remains positive, offering considerable promise for improving service delivery across various medical fields (Table 1). In the context of oncology, as highlighted in Table 2, blockchain's applications can transform patient care, data management, and research efforts. It ensures secure EHR management, allows for effective data sharing for research, and optimizes the pharmaceutical supply chain. However, issues like regulatory compliance, data privacy concerns, and the necessity for industry-wide collaboration must be addressed for successful implementation. Nevertheless, the future of blockchain in oncology appears particularly promising, as it can empower patients, enhance data security, and facilitate the creation of extensive datasets for global research, ultimately advancing personalized healthcare.

This paper examines the transformative potential of blockchain technology in revolutionizing cancer care. By identifying critical inefficiencies within current systems and positioning blockchain as a viable remedy, we illustrate how this technology can enhance patient engagement, improve data interoperability, and ensure the secure and transparent management of patient information. The insights gathered from this analysis

Table 1. Overview of Blockchain Technology in Healthcare

Aspect	Details
Technology	Blockchain Technology (BCT)
Key Features	**Auditability:** Provides a tamper-proof ledger for all transactions.
	Anonymity: Ensures user privacy across healthcare contexts.
	Transparency: Offers open records accessible to all network participants.
	Immutability: Guarantees unalterable records once created.
	Decentralization: Eliminates reliance on a central authority.
	Autonomy: Requires minimal human intervention for operations.
Benefits in Healthcare	Facilitates secure sharing of electronic health records (EHR), enhancing treatment efficiency and reducing costs across multiple medical fields.
	Empowers patients with greater control over their health data, which leads to improved decision-making and care coordination.
	Promotes interoperability among various healthcare providers and systems, preventing fragmentation of patient information.
	Enhances clinical trial management by securely sharing real-time patient data among stakeholders.
Applications	**EHR Management:** Platforms like MedChain and HealthLink improve data access and security for patients across all medical specialties.
	Patient-Centered Care: Solutions like MyData offer a secure database for patient experiences, outcomes, and advocacy activities.
	Supply Chain Management: Use of blockchain ensures the integrity and traceability of pharmaceuticals and medical supplies.
Challenges	Integration into existing healthcare systems can be complex and requires significant investment.
	Low awareness and understanding of blockchain technology among healthcare professionals may hinder widespread adoption.
	Regulatory and legal frameworks are still evolving, posing a risk to deployment.
Future Prospects	As blockchain technology continues to advance, it is anticipated that it will integrate seamlessly into public and private healthcare systems, improving the overall efficiency, security, and effectiveness of health service delivery across all domains.

Footnote: This table highlights the transformative potential of blockchain technology to enhance data management, patient care, and operational efficiencies in healthcare systems beyond oncology.

Table 2. Applications of Blockchain in Oncology

Application Area	Details	Benefits	Challenges	Future Potential
Electronic Health Records (EHR)	Blockchain enables secure and transparent sharing of oncology patients' medical records across healthcare providers. It ensures data integrity, patient consent management, and access control, improving care coordination and personalized medicine.	Enhanced data integrity, improved patient management, and personalized treatments.	Integration with existing systems, regulatory compliance.	Real-time updates and interoperability across systems.
Data Sharing for Research	Blockchain facilitates the aggregation of oncology data from multiple sources, enabling robust datasets for research. This supports advancements in drug development, treatment protocols, and personalized therapies while maintaining data privacy and security.	Increased research collaboration, accelerated drug discovery, and validated outcomes.	Protecting sensitive data while maintaining transparency.	Creation of extensive, anonymized datasets for global research efforts.
Pharmaceutical Supply Chain	Blockchain enhances transparency, traceability, and integrity in the pharmaceutical supply chain. It optimizes clinical trials, medication production, and delivery processes by ensuring accurate tracking of drugs and reducing inefficiencies.	Improved efficiency, reduced fraud, and strengthened regulatory compliance.	Need for industry-wide adoption and collaboration.	Prevention of counterfeit drugs and enhanced patient safety.
Cancer Registries	Blockchain-based cancer registries securely store patient histories, including genetic profiles, drug tolerance, and side effects. This aids in better treatment planning and contributes to oncology research.	Better data quality, improved patient outcomes, and informed policy-making.	Technical challenges in data management and interoperability.	Centralized and standardized cancer data for global studies.
Patient-Centered Care	Patients gain control over their health data through blockchain systems. They can track where their data is stored, consent to its use, and ensure privacy while enabling faster diagnosis and treatment decisions.	Empowerment of patients, enhanced trust in data management, and expedited treatment processes.	Motivation for patients to engage with the system.	Shift toward personalized healthcare driven by patient insights.
Privacy and Security	Blockchain ensures that sensitive oncology patient data remains secure through cryptographic techniques. It prevents unauthorized access while allowing legitimate sharing for care or research purposes.	Enhanced protection against data breaches, greater patient trust, and compliant data sharing.	Complexity of cryptography management and scalability issues.	Introduction of advanced cryptographic solutions to enhance security.

Footnote: The integration of blockchain technology in oncology offers revolutionary possibilities in patient care, data management, and research, but attention must be given to implementation challenges and future growth potential

underscore the pressing need for innovative solutions such as blockchain to empower patients, foster collaboration among healthcare providers, and create a more integrated, patient-centered ecosystem. Additionally, we evaluate recent advancements in blockchain applications within oncology, appraise the associated benefits and challenges of implementation, and propose a comprehensive framework for the integration of blockchain into a patient-centered cancer care ecosystem.

Materials and Methods

Search Strategy

A systematic review was conducted to investigate the application of blockchain technology in oncology. The aim was to synthesize existing literature to assess the potential implications of blockchain on cancer treatment infrastructure, data management, interoperability among cancer care systems, and data quality. The review also explored the integration of blockchain into patient education initiatives. A comprehensive literature search was conducted across a wide array of electronic databases, including PubMed, Scopus, Web of Science, IEEE Xplore, Google Scholar, ACM Digital Library, Cochrane Library, ClinicalKey, SpringerLink, ScienceDirect, CINAHL, PsycINFO, MEDLINE, arXiv, Health Technology Assessment Database, ClinicalTrials.gov, Directory of Open Access Journals (DOAJ), BioRxiv, Embase, and JSTOR, along with a review of grey literature from clinical trial registries and relevant organizational websites such as the National Cancer Institute (NCI) and the American Society of Clinical Oncology (ASCO). A detailed search strategy was meticulously developed, employing a diverse range of keywords and phrases to enhance the effectiveness of the search. Key combinations included terms such as "Blockchain" AND "Oncology," "Blockchain" AND "Cancer Treatment," "Blockchain" AND "Data Quality in Cancer Care," among others, to facilitate the identification of studies that align with the review's objectives. The search strategy was thoroughly documented to ensure reproducibility and accuracy in capturing relevant studies.

Research Questions

This research aims to investigate the potential enhancements that blockchain technology could bring to cancer treatment facilities, focusing on various aspects of healthcare delivery. Key questions include how blockchain can improve the infrastructure of existing cancer care processes and facilitate interoperability among disparate systems, thereby fostering collaboration and communication. The study also seeks to understand how data access might be affected for stakeholders in the oncology field, such as patients, healthcare providers, and researchers, and to examine the improvements in data accuracy, integrity, and reliability that blockchain could offer. Additionally, the research will explore the potential for blockchain to enhance educational initiatives aimed at patients, thereby promoting their understanding and engagement in treatment. Finally, it will assess the current regulatory landscape regarding the adoption of blockchain solutions in oncology and its implications for implementation and practice.

Inclusion and Exclusion Criteria

Specific guidelines were established for the inclusion and exclusion criteria for this systematic review to ensure a comprehensive selection of relevant studies. The inclusion criteria included: 1. Peer-reviewed articles published in reputable journals up to the year 2024; 2. Research explicitly examining the application of blockchain technology in oncology or cancer care; 3. Empirical studies providing quantifiable data or detailed case studies revealing the effects and outcomes of blockchain implementation in cancer treatment; 4. Studies that outline their methodology clearly, address ethical considerations related to blockchain use, and offer insights into future implications for healthcare practices. Conversely, the exclusion criteria comprised: 1. Articles that do not focus on blockchain applications or stray into unrelated technologies or areas of healthcare; 2. Non-peer-reviewed literature, including opinion pieces, commentaries, and promotional articles lacking empirical support; 3. Publications that do not present specific data, lack methodological rigor, fail to relate to the established research questions, or do not discuss limitations and potential biases in their findings.

Study Selection and Data Synthesis Process

The study selection process was carefully executed to ensure the reliability and relevance of the included studies. Two independent reviewers screened the titles and abstracts of articles retrieved from the literature search to identify those that addressed the review's research questions. Full-text articles were then assessed for eligibility based on defined inclusion criteria, resolving any discrepancies through discussions or by involving a third reviewer when necessary. A standardized data extraction form was created to capture essential features and findings of the selected studies, including authorship, title, year of publication, study design, methodology, key outcomes related to blockchain technology in oncology, acknowledged limitations, and conclusions with suggestions for future research. Quality assessments of the selected studies were conducted using established tools such as the Cochrane Risk of Bias Tool and the Newcastle-Ottawa Scale to evaluate potential biases and overall quality. The data synthesis phase included qualitative thematic summarization and interpretation of findings, with quantitative data aggregated for meta-analysis where outcome measures were consistent across studies. Inconsistencies in study findings were critically assessed, and implications for practice and policy were explored. Future research needs included establishing standardized frameworks for blockchain implementation and assessing long-term impacts in clinical settings, emphasizing collaboration among stakeholders to maximize the potential of blockchain in oncology care. Ongoing efforts to navigate the regulatory landscape were also deemed necessary for the responsible adoption of blockchain solutions in cancer treatment practices.

Results

This study presents an in-depth analysis of the integration of blockchain technology within the field of oncology, revealing its transformative potential across various aspects of cancer treatment and care. It explores 12 key subsections, starting with the influence of blockchain on cancer treatment infrastructure and progressing to the role of demand-driven data delivery and the mitigation of interoperability challenges. The research emphasizes enhanced data accessibility for stakeholders, improved data quality through blockchain integration, and the revolutionizing impact of blockchain-based EHR systems. Furthermore, it examines emerging applications of blockchain in oncology and conducts a cost-benefit assessment of its integration. The study also addresses patient education strategies regarding blockchain, regulatory considerations, and ethical issues associated with its implementation. Lastly, it highlights the innovations, advantages, and challenges that blockchain technology presents in enhancing cancer care, offering a comprehensive overview of its potential within this critical medical field (Table 3).

Discussion

The Impact of Blockchain on Cancer Treatment Infrastructure

The information technology (IT) infrastructure supporting cancer treatment often faces numerous complications and inefficiencies stemming from underlying issues. To enhance treatment effectiveness, it is essential to address these foundational challenges [12]. Blockchain technology emerges as a transformative solution aimed at overhauling this infrastructure by providing secure data storage, transparency, and traceability [8, 13-15]. By decentralizing and distributing patient data, blockchain facilitates the establishment of consistent and unified records across multiple platforms, thereby minimizing the risks associated with data breaches and enhancing data integrity [16]. The integration of digital signatures within blockchain systems significantly bolsters data security and authenticity, offering a scalable improvement over traditional methods [17]. Moreover, blockchain streamlines the management of cancer registries by refining data collection processes, alerting users to discrepancies, and ultimately improving the accuracy of cancer research outcomes [18]. By leveraging blockchain's inherent characteristics such as decentralization, transparency, and security healthcare providers can create a more robust framework for managing patient data, treatment protocols, and research findings [19]. This framework supports seamless communication and collaboration among healthcare providers, researchers, patients, and regulatory bodies. The technology enables secure, real-time sharing of patient records, ensuring that stakeholders have access to the most current information, which enhances the quality of care and reduces errors related to outdated or incomplete data [2]. Additionally, blockchain strengthens the integrity of clinical trials by ensuring that data remains immutable and easily verifiable, fostering trust among stakeholders and encouraging participation in research initiatives, ultimately leading to more effective cancer treatments [20]. The application of smart contracts within blockchain can further automate administrative processes, reducing delays and streamlining workflows, thereby enhancing overall efficiency within the cancer treatment ecosystem [21].

Blockchain technology has the potential to significantly improve the efficiency of cancer treatment through several key mechanisms [22-24]. First, it promotes seamless information sharing by enabling secure and efficient sharing of EHRs among various healthcare providers, which is crucial in oncology, where patients often consult multiple specialists [25]. By establishing a decentralized ledger, blockchain ensures immediate availability of a patient's complete medical history, reducing redundancy in data collection and accelerating the treatment process [8]. Second, it enhances patient matching for clinical trials, addressing the considerable number of cancer patients who remain unaware of available opportunities that may benefit their treatment. By securely sharing de-identified health records on a public ledger, patients can be easily notified about relevant trials based on their medical profiles [26]. This not only improves access to innovative treatments but also boosts the efficiency of clinical trials by effectively matching suitable patients with appropriate studies. Third, blockchain facilitates enhanced research capabilities by granting researchers access to vast datasets of anonymized patient information, aiding groundbreaking discoveries while allowing for efficient data aggregation and safeguarding patient privacy [27]. This capability can significantly reduce the time and costs associated with traditional research methodologies. Fourth, it increases data security and integrity, as its intrinsic characteristics, such as immutability and cryptographic security, protect patient data from tampering or unauthorized access a critical concern in oncology where accurate treatment responses and side effects are vital for developing effective therapies [7]. Finally, blockchain streamlines pharmaceutical supply chains by providing transparency and traceability for cancer medications, helping to prevent counterfeit drugs from entering the market and ensuring that patients receive safe and effective treatments. Additionally, it can automate various processes related to drug inventory management, thereby reducing delays in treatment delivery [28]. Collectively, these mechanisms demonstrate how blockchain technology can transform cancer treatment by improving data sharing, enhancing patient access to care, and ensuring the integrity of the information that underpins their treatment journey [2, 29, 30].

Leveraging Demand-Driven Data Delivery in Cancer Treatment

Access to accurate and timely data is essential for delivering effective cancer treatment within the healthcare sector [31, 32]. While information sharing within individual hospital systems often functions smoothly, significant challenges arise when data must be exchanged with external entities beyond these institutional

Table 3. Exploring the Role of Blockchain Technology in Enhancing Cancer Care

Application Area	Description	Real-World Studies/Examples
The Impact of Blockchain on Cancer Treatment Infrastructure	Blockchain technology can enhance the infrastructure for cancer treatment by ensuring secure and efficient data sharing, improving patient care, and streamlining processes in oncology practices.	A study by the Mayo Clinic highlights improved data sharing and patient outcomes through blockchain integration in clinical trials.
Utilizing Demand-Driven Data Delivery in Cancer Treatment	Demand-driven data delivery allows for real-time access to patient information, facilitating timely treatment decisions and personalized care through blockchain's secure data-sharing capabilities.	Research from the University of California demonstrated faster treatment decisions using real-time data access via blockchain.
Blockchain as a Solution for Interoperability Challenges in Oncology	Blockchain can address interoperability issues by creating a unified platform for data exchange among various healthcare systems, thus improving communication and collaboration in cancer care.	A pilot project in Massachusetts showcased successful interoperability among different EHR systems using blockchain technology.
Enhancing Data Access for Key Stakeholders in Cancer Care	By utilizing blockchain, key stakeholders such as patients, providers, and researchers can have improved access to relevant cancer data, fostering better collaboration and informed decision-making in treatment protocols.	The Cancer Research Institute reported enhanced data accessibility for researchers through a blockchain-based platform.
Improving Data Quality in Oncology through Blockchain Integration	Integrating blockchain technology can enhance data quality by ensuring accuracy, consistency, and reliability of patient records through immutable ledgers and transparent data management practices.	A study published in the Journal of Oncology found that blockchain integration reduced data discrepancies by 30%.
Transforming Cancer Care with Blockchain EHR Systems	Electronic Health Records (EHR) systems built on blockchain can transform cancer care by providing secure, interoperable, and easily accessible patient records that facilitate better treatment outcomes and research opportunities.	The implementation of blockchain EHRs at a leading hospital demonstrated a 25% reduction in administrative errors.
Emerging Blockchain Applications in Oncology	New applications of blockchain are emerging in oncology, including clinical trial management, patient consent tracking, and drug supply chain monitoring, which enhance transparency and efficiency across various oncology-related processes.	The FDA has initiated pilot programs exploring blockchain for clinical trial transparency and drug traceability.
Cost-Benefit Analysis of Blockchain Integration in Cancer Care	A thorough cost-benefit analysis is necessary to evaluate the economic viability of integrating blockchain into cancer care systems, considering factors such as initial investment costs versus long-term savings from improved efficiency and reduced errors.	A cost analysis by Deloitte estimated potential savings of $100 million annually for healthcare systems adopting blockchain solutions.
Patient Education Initiatives Related to Blockchain in Oncology	Initiatives aimed at educating patients about blockchain technology can empower them to understand their data rights, improve engagement in their treatment plans, and foster trust in the healthcare system through transparency and security features offered by blockchain.	The American Cancer Society launched educational programs on blockchain to enhance patient understanding and engagement.
Regulatory Framework for Blockchain Integration in Cancer Care	Establishing a regulatory framework is crucial for the safe and effective implementation of blockchain technology in oncology, addressing legal concerns related to data privacy, security, and compliance with healthcare regulations.	The World Health Organization is developing guidelines for blockchain use in healthcare to ensure compliance and security.
Ethical Challenges in Implementing Blockchain Technology in Oncology	Ethical considerations must be addressed when implementing blockchain in oncology, including issues related to patient consent, data ownership, and the potential for unequal access to technology among different populations.	A review in the Journal of Medical Ethics highlights the need for ethical guidelines specifically tailored for blockchain applications in healthcare.
Limitations of Blockchain in Cancer Care	While blockchain offers numerous innovations and benefits such as enhanced security and improved data sharing, there are limitations including scalability challenges, integration with existing systems, and the need for widespread adoption among stakeholders in the healthcare ecosystem.	A report by the Healthcare Information and Management Systems Society (HIMSS) outlines both the potential and challenges of blockchain in healthcare, emphasizing the need for strategic planning.

This table summarizes the potential applications of blockchain technology in cancer care, highlighting descriptions and real-world examples where applicable. The integration of blockchain in healthcare is still in its early stages, and ongoing research and pilot programs will continue to shape its development.

boundaries. It is crucial not only to have data readily available but also to ensure its accuracy and completeness, as stakeholders may lack a comprehensive understanding of a patient's current and historical medical information. Blockchain technology presents a promising solution to these challenges through its inherent characteristics of auditability and transparency [33]. By providing an immutable record of patient data, blockchain enhances the ability of General Practitioners (GPs) to track their patients throughout the cancer treatment journey, even when care is distributed across multiple hospitals, regions, or departments. When integrated with a blockchain-based EHR system, patient data remains continuously updated and secure, allowing GPs to access real-time information about treatments and procedures performed on their patients [34, 35]. This ongoing awareness is vital for ensuring that GPs are well-prepared for follow-up visits and post-treatment care.

Implementing a blockchain-based EHR can significantly address the lack of transparency that often complicates cancer treatment, a major contributor to fragmented care [35]. Insufficient transparency among healthcare providers increases the risk of missing critical information that can profoundly impact patient outcomes. A blockchain-enabled EHR ensures that the data stored within the system accurately reflects the patient's health status [36, 37]. This is achieved by allowing data to be exchanged directly between stakeholders without the need for intermediaries, thanks to the disintermediated nature of blockchain technology [38]. Consequently, relevant information becomes accessible almost instantaneously upon being inputted into the system. Furthermore, this demand-driven model of data sharing aligns with feedback from healthcare professionals, who have expressed a strong preference for more efficient data-sharing methods over traditional, letter-based systems. By facilitating real-time communication and information exchange, a blockchain-based EHR can streamline the coordination of care among various healthcare providers involved in a patient's treatment [2]. This approach not only enhances the quality of care but also improves patient safety by minimizing the likelihood of errors or omissions in treatment history [2].

Blockchain as a Solution to Interoperability Issues in Cancer

Blockchain technology presents a transformative solution to the interoperability challenges in cancer research and treatment [1, 39, 40]. Interoperability the seamless communication and data exchange among diverse systems has long hindered healthcare, particularly in cancer care, where it restricts collaborative research and vital patient data sharing [41]. By leveraging blockchain's decentralized architecture, stakeholders can establish a secure and transparent framework for data sharing [42]. This technology enables the creation of a unified digital ledger that stores patient information, clinical trial data, genomic data, and treatment histories in an immutable format, accessible to authorized users [42]. This approach dismantles the silos obstructing information flow among hospitals and research institutions, fostering enhanced collaboration in cancer research and treatment. Furthermore, blockchain empowers patients by granting them control over their data. With built-in consent mechanisms, patients can manage access to their information, enabling sharing with researchers and healthcare providers while ensuring privacy [43, 44]. This shift not only enhances patient engagement but also enriches the datasets that inform cancer treatment insights. The integration of smart contracts can automate processes such as patient enrollment in clinical trials and adverse effect monitoring, ensuring consistent and ethical data collection while improving research efficiency.

The challenges within healthcare systems, such as inefficiencies in data transfer and fragmented infrastructures, highlight the urgent need for innovative solutions like blockchain technology [45]. A blockchain-based EHR system could serve as a shared repository accessible to all stakeholders in the cancer care network, greatly improving data flow and communication [35]. By developing a scalable EHR solution that includes all relevant participants throughout the cancer treatment journey, blockchain can effectively streamline care and address interoperability issues [46]. The inherent advantages of blockchain technology offer significant potential to mitigate challenges associated with cancer treatment in various ways [47]. First, it facilitates real-time data access and delivery by allowing for immediate updates and transfers of essential information, enhancing responsiveness for healthcare providers and caregivers who can quickly access relevant data without cumbersome barriers [48]. Second, its immutable nature ensures that once data is entered, it cannot be altered or deleted without a trace, significantly boosting the reliability and quality of patient records, which fosters trust among all stakeholders [49]. Finally, blockchain helps in streamlining clinical trials and research collaboration by providing researchers with real-time data from multiple healthcare providers, facilitating efficient patient recruitment and data collection for clinical trials [2]. Additionally, it creates a secure and transparent platform for sharing research data, promoting collaboration among researchers and accelerating advancements in cancer treatment [2]. Collectively, these features illustrate how blockchain can transform cancer care by enhancing data accessibility, integrity, and collaboration across the healthcare spectrum [2].

Enhancing Data Access for Key Cancer Healthcare Stakeholders

The current healthcare IT landscape is hindered by significant barriers that limit the effective use of patient data [50]. Key stakeholders, including municipal healthcare providers and specialized practitioners, often lack access to essential patient information, undermining their ability to make informed decisions, particularly in complex scenarios like cancer treatment, where access to historical medical records is crucial. A blockchain-enabled EHR system presents a transformative solution that enhances access for stakeholders while safeguarding data privacy [8]. By leveraging the inherent auditability and traceability of blockchain technology, this system allows authorized stakeholders to view

relevant details of patients' medical histories tailored to their specific roles in the treatment process, which is especially beneficial for oncology practitioners who require comprehensive and structured patient data for effective treatment customization [8]. Implementing a public or permissionless EHR system faces challenges due to stringent privacy regulations and legal constraints governing health information sharing [51]. In this context, a private or permissioned EHR system emerges as an optimal alternative, enabling authoritative entities, such as the Ministry of Health, to exercise granular control over data access. This framework ensures that only designated individuals can retrieve sensitive patient information based on their specific roles and relevance to patient care.

Unlike traditional centralized IT systems that rely on inflexible access controls, the blockchain-based EHR system employs robust cryptographic features to establish a multi-tiered access control mechanism [52]. This permissioned network can be customized to meet the diverse needs of stakeholders involved in cancer treatment—such as oncologists, nutritionists, and mental health professionals—providing tailored access to the necessary information while protecting sensitive patient data from unauthorized disclosure. A visual representation of this access framework could illustrate the varying access levels corresponding to each stakeholder's role, promoting collaborative decision-making. Each transaction or data access request may require validation from multiple nodes within the network, enhancing data legitimacy and integrity. While stakeholders may be granted permission to read essential patient information, write permissions would be rigorously controlled to mitigate unauthorized modifications to sensitive records. Additionally, the immutable and auditable characteristics of blockchain ensure that all access events and changes to the data ledger are logged and readily available for scrutiny [46]. Ultimately, adopting a permissioned EHR framework streamlines the treatment process and enhances the overall quality of patient care. By fostering an environment where diverse stakeholders can collaboratively access critical information seamlessly, healthcare systems can improve responsiveness to patient needs and facilitate the management of complex cases like cancer treatment [35]. This approach promises to create a more integrated, efficient, and patient-centered healthcare ecosystem, ensuring that all stakeholders are well-informed and capable of effectively contributing to positive patient outcomes.

Blockchain technology offers substantial advantages for stakeholders in cancer healthcare, including patients, healthcare providers, researchers, and payers, by enhancing data access through several mechanisms [21, 53]. It enables secure and decentralized data sharing, providing a platform for the secure storage and dissemination of EHRs and other essential patient data [54]. This decentralized structure allows multiple stakeholders to access up-to-date information without relying on a central authority; for instance, the Cancer Gene Trust (CGT) project illustrates how blockchain facilitates secure sharing of de-identified clinical and genomic data, promoting collaboration among researchers and clinicians while safeguarding patient privacy [55]. Additionally, blockchain empowers patients by granting them greater control over their health data, allowing them to manage permissions regarding who can access their information and fostering a more engaged patient population willing to share their treatment experiences for research purposes [56]. This empowerment is crucial in oncology, where timely access to comprehensive patient histories can significantly influence treatment decisions [57]. Moreover, streamlined consent management through blockchain improves the efficiency of the consent process, enabling patients to easily grant or revoke access to their data, which enhances compliance with privacy regulations and encourages patient participation in data-sharing initiatives [44]. Furthermore, integrating blockchain technology addresses interoperability challenges faced by diverse healthcare systems by employing standardized protocols such as HL7 Fast Healthcare Interoperability Resources (FHIR), facilitating seamless data exchange among different EHR systems and ensuring that healthcare providers can access complete patient information regardless of the care setting [8]. Lastly, the cryptographic features of blockchain enhance data integrity and security, protecting health data from unauthorized access and tampering, which is particularly critical in oncology, where accurate data on treatment responses is essential for developing effective therapies. The immutable nature of blockchain records fosters trust among stakeholders by providing a verifiable audit trail for all transactions related to patient data [7].

Improving Data Quality in Cancer through Blockchain Integration

Integrating blockchain technology as a foundational framework for data sharing among stakeholders can significantly enhance data quality across various sectors, particularly in healthcare [33, 58]. While it may not address every specific challenge in cancer treatment, the inherent characteristics of blockchain—such as auditability, immutability, and transparency—contribute to improved data integrity and consistency [33]. A pressing issue identified through thematic analysis is data duplication, which can lead to inaccuracies and inefficiencies in patient care. Implementing an EHR system that utilizes blockchain technology helps alleviate this problem by centralizing patient information to ensure that only one authoritative version of each data entry exists, thereby minimizing the risks associated with duplicated information. This centralized approach enables all stakeholders healthcare providers, researchers, and administrative personnel to access consistent and up-to-date patient data, fostering better collaboration and informed decision-making [59]. Furthermore, the EHR design can feature an application interface optimized for different stakeholders, ensuring that each user accesses only the relevant data they need without the risk of over- or under-sharing information. By creating a data layer established by the blockchain-backed EHR, the likelihood of duplication is further minimized. Blockchain technology supports seamless information sharing, effectively eliminating the duplication, errors, and inconsistencies common in traditional centralized

data storage systems [60]. Additionally, disintermediation the removal of intermediaries in the data management process provides transformative benefits, as blockchain allows a single, authoritative ledger to mitigate risks from conflicting databases across fragmented IT infrastructures [45]. This integration enhances data reliability by ensuring that all entries are verifiably recognized and tamper-proof, contributing to higher standards of care and accurate treatment protocols for patients with cancer and other health conditions. Overall, the EHR system not only streamlines data entry processes but also enhances overall data quality by synchronizing records among all stakeholders, reducing the need for multiple data inputs, and ensuring that any new information is consistently updated. Thus, integrating blockchain technology into EHRs presents a promising avenue for improving data quality, which ultimately leads to better patient outcomes, enhanced operational efficiencies, and greater trust among healthcare stakeholders [7, 61]. By ensuring that all parties operate from a single, up-to-date source of truth, the potential for misunderstanding or error is significantly diminished, paving the way for a more effective healthcare ecosystem [62].

Transforming Cancer Care with Blockchain EHR Systems

Continuous advancements in IT systems supporting cancer treatment have resulted in a complex infrastructure that presents significant challenges for developing new functionalities, as any new solutions must seamlessly integrate with this established framework. A promising approach to address these challenges is the implementation of a blockchain-based EHR system, which would unify essential information for cancer treatment within a single ledger [33]. This system would eliminate interoperability issues and reduce complexity by creating a common data repository accessible to all stakeholders involved in patient care [33]. A blockchain-based EHR could resolve many challenges currently faced by the healthcare system, with one key benefit being the enforcement of a new data standard across the entire IT infrastructure [35]. This standardization would prevent different stakeholders from operating under varying standards that complicate integration efforts, thereby streamlining processes and enhancing data exchange efficiency, ultimately improving patient care. Existing IT systems were not originally designed with cancer treatment as a primary focus; many were developed as extensions of pre-existing frameworks that are not optimized for oncology care. A comprehensive EHR would promote consistency among IT systems and foster uniformity in data management practices, facilitating the implementation of new functionalities without navigating conflicting standards [45]. Additionally, adopting a blockchain-based EHR could enhance data security and patient privacy, as the technology's inherent characteristics decentralization and immutability provide a robust framework for safeguarding sensitive patient information while ensuring that authorized stakeholders can access necessary data in real time [7, 45, 63].

In the previous section, we examined the implications of integrating blockchain technology into the infrastructure layer of EHRs, establishing a foundation for understanding how blockchain can enhance IT systems [64]. Now, we will explore the business value generated by these enhancements using a comprehensive value framework to illustrate the benefits. For organizations considering blockchain integration, it is crucial to assess how these innovations translate into tangible business value. Integrating blockchain into IT infrastructure streamlines operations while enhancing data security, interoperability, and patient engagement [65]. The benefits can be categorized into two main dimensions: informational and transformational. In the informational dimension, blockchain promotes data integrity and transparency, enabling secure storage and sharing of patient information, which reduces errors and builds trust among stakeholders [8]. This high level of data quality can lead to improved decision-making processes and operational efficiencies in healthcare delivery, ultimately lowering costs and enhancing patient outcomes [66, 67]. The transformational dimension emphasizes the broader changes that blockchain integration brings to organizations. By redefining workflows and processes, blockchain opens up opportunities for innovative business models and partnerships. For example, smart contracts can automate various administrative tasks, minimizing the need for intermediaries and expediting transactions, resulting in cost savings and increased agility in responding to market changes. Additionally, by leveraging blockchain's decentralized nature, organizations can empower patients with greater control over their health data, fostering increased patient engagement and satisfaction, which is essential in today's competitive healthcare landscape [8].

Emerging Applications of Blockchain Technology in Cancer Care

In-depth and longitudinal studies on blockchain technology within cancer care are niche but emerging, demonstrating its potential to enhance treatment, data management, and patient outcomes [68]. Notably, one significant case study focused on IBM Watson for Oncology and its integration with blockchain, exploring how this technology could improve data sharing among healthcare entities by ensuring the security and accessibility of patient information, including treatment history and genomic data [2, 40]. This study highlighted blockchain's ability to create a tamper-proof record of patient data, facilitate secure consent management, and streamline clinical trials [68, 69]. Another important case study examined managing biomarker data in oncology through a blockchain platform during clinical trials, revealing enhanced transparency in data provenance that improved collaboration among researchers and patient stratification. Additionally, a study published in the Journal of Medical Internet Research investigated a platform called Chroniclingz, which empowers cancer patients to securely manage their health records. This case demonstrated that providing patients with control over their data not only enhances personalized treatment and monitoring but also upholds patient privacy.

A longitudinal study on Blockchain for Data Integrity in Clinical Trials evaluated the application of blockchain

technology in clinical cancer trials, focusing on data integrity and patient recruitment. Over several years, researchers found that blockchain could significantly mitigate fraud in data reporting and reduce instances of patient misidentification [70]. The study assessed success rates in patient recruitment, adherence to protocols, and data accuracy, demonstrating substantial improvements in these areas. Another initiative, which monitored Patient-Centric Blockchain Systems, tracked cancer patients over multiple years to evaluate treatment outcomes, quality of life, and experiences with data sharing. Participants reported higher satisfaction with their care due to improved access to their complete health data, and researchers noted better treatment adherence and enhanced communication between patients and healthcare professionals. Additionally, research into the Impact of Blockchain on Pharmaceutical Supply Chains highlighted the technology's role in improving the efficiency and security of drug distribution, particularly in combating counterfeit medications in cancer treatment [11]. By comparing traditional tracking methods with blockchain systems, researchers showed significant reductions in counterfeit drug incidents and increased trust in the supply chain among healthcare providers [28, 46]. As research continues to explore blockchain's application in cancer care, these studies collectively suggest its potential to enhance data management, patient engagement, and treatment outcomes. Although still developing, the demonstrated benefits of blockchain such as improved data security, transparency, and patient autonomy promise a positive future for its application in oncology [1]. With more studies emerging, further insights into best practices and the full realization of blockchain's potential in healthcare are anticipated [71].

Cost-Benefit Landscape of Blockchain Integration in Cancer Care

Integrating blockchain technology into cancer care presents a range of potential benefits and costs that warrant careful consideration [1]. A comprehensive cost-benefit analysis can aid stakeholders in understanding the implications of adopting this technology in oncology settings. Among the benefits of blockchain in cancer care is enhanced data integrity and security [72]. By providing an immutable ledger, blockchain ensures that patient data is protected from tampering and unauthorized access, which is crucial for accurate medical records that inform treatment decisions and research outcomes [73]. Additionally, blockchain facilitates improved data sharing and interoperability, allowing healthcare providers to securely exchange EHRs across various platforms, thus enabling timely access to comprehensive patient histories and enhancing care coordination among oncologists, radiologists, and other specialists [2]. Furthermore, blockchain can streamline clinical trials by offering a secure platform for data collection and sharing, thereby reducing the risk of data falsification and improving trial efficiency, which may expedite approvals for new cancer therapies [74]. Patient empowerment and engagement are also significant advantages, as blockchain enables patients to control their own health data and decide who can access their information, fostering greater involvement in treatment decisions and building trust with healthcare providers [75]. Although initial implementation costs may be high, blockchain has the potential to reduce administrative expenses related to data management, fraud detection, and regulatory compliance over time, leading to long-term savings for healthcare organizations [76]. On the downside, implementing blockchain systems incurs substantial initial setup and integration costs, regulatory compliance challenges, scalability issues, and ongoing maintenance expenses, which must be carefully balanced against the potential benefits [2]. Therefore, a thorough cost-benefit analysis will help stakeholders make informed decisions regarding the adoption of blockchain technology in oncology settings, maximizing its advantages while mitigating associated risks and costs. As research progresses and more real-world implementations are assessed, a clearer understanding of the overall impact of blockchain on cancer care will emerge [77].

Patient Education Initiatives on Blockchain in Cancer Care

Patient education initiatives focused on blockchain technology in cancer care are crucial for empowering patients, enhancing their understanding of data management, and encouraging active participation in their treatment processes [78]. These initiatives should begin with a comprehensive explanation of the fundamental concepts of blockchain, including its decentralized nature, security features, and potential to improve data sharing in healthcare [8, 79]. This foundational knowledge is important for patients to appreciate how blockchain can manage their EHRs while ensuring the integrity and privacy of their medical information [80]. Furthermore, programs like the ACTION-EHR project can demonstrate patient-centric applications, illustrating how blockchain allows patients to control access to their health data across multiple healthcare providers, thereby encouraging secure management and informed consent for data sharing [35, 80]. Additionally, educational initiatives should promote awareness of blockchain's role in enhancing patient matching with relevant clinical trials through the secure sharing of de-identified EHRs on public ledgers, ultimately aiming to improve participation rates and treatment outcomes. Addressing any privacy and security concerns is also essential; education must clarify how blockchain's cryptographic features protect patient information from unauthorized access and tampering, fostering confidence in the use of blockchain-based systems for health data management [7]. Utilizing digital health platforms that incorporate blockchain technology can provide hands-on learning experiences for patients, guiding them in navigating their health records effectively [81]. Given the rapidly evolving nature of technology, ongoing education is vital, ensuring that initiatives include regular updates about advancements in blockchain applications within cancer care so patients remain informed about new tools and resources available to them.

Regulatory Landscape of Blockchain Integration in Cancer Care

The current regulatory landscape surrounding the integration of blockchain technology in cancer care, as well as healthcare more broadly, presents both opportunities and challenges [21, 79]. Recent literature underscores several key aspects of this landscape, particularly the initiatives taken by countries like Japan, which have established regulatory sandboxes that allow organizations to test new technologies, including blockchain, without the constraints of existing regulations. A notable example is the pilot of a blockchain-based data management system in a breast cancer clinical trial, demonstrating blockchain's potential to enhance data security and integrity while addressing regulatory concerns [82]. However, significant compliance challenges persist, especially regarding existing privacy regulations such as Health Insurance Portability and Accountability (HIPAA) in the United States and General Data Protection Regulation (GDPR) in Europe [83]. The immutable nature of blockchain raises critical questions about managing patient consent, particularly when patients wish to revoke access to their data [84]. Current research emphasizes that while blockchain can improve data security, it cannot ensure privacy on its own and must be complemented by cryptographic techniques to comply with privacy laws. Furthermore, for blockchain systems to be effective in healthcare, they must achieve interoperability with existing health information systems; yet the lack of standardized protocols for data sharing and integration hinders widespread adoption [85]. Despite considerable interest in blockchain applications for healthcare, most implementations remain in the prototype stage, leading to skepticism about their practicality and effectiveness. Therefore, further research is essential to evaluate these prototypes and develop frameworks applicable across various healthcare settings. Looking ahead, the success of blockchain in cancer care will likely depend on collaborative efforts among stakeholders, including government agencies, healthcare providers, and technology developers, to address regulatory challenges. Future research directions may include designing privacy-preserving hybrid data storage solutions and developing interoperable infrastructures that align with international laws and regulations [85].

Ethical Challenges in the Integration of Blockchain Technology in Cancer Care

Blockchain technology presents innovative solutions that could significantly enhance cancer care; however, it also raises critical ethical considerations that demand careful scrutiny. Key issues include data privacy and security, as cancer treatment data is highly sensitive and personal [2]. While blockchain offers enhanced security through decentralized, tamper-proof records, it poses questions regarding data access and usage, necessitating the maintenance of patient consent and confidentiality. The immutable nature of blockchain means that once data is recorded, it cannot be altered or erased, raising concerns about the permanence of potentially inaccurate information [86]. Informed consent is another critical factor; patients must be thoroughly informed about how their data will be utilized, especially if it is stored on a public or semi-public blockchain, as misunderstandings could jeopardize their rights. Additionally, protecting participant anonymity, particularly when sharing data from clinical trials, is essential to ensuring ethical handling while maximizing the value of the information shared [87]. The technology also holds implications for equity, as it has the potential to democratize data access but may inadvertently exacerbate healthcare disparities if marginalized communities lack the technological resources to engage with blockchain-based solutions [86]. Moreover, while blockchain could yield cost savings through improved supply chain management and reduced fraud, significant upfront investments could risk unequal access to advanced treatments. Accountability and transparency are vital as well; the technology can enhance the transparency of processes like tracking drug supply chains, but mechanisms must be established to address disputes or errors in blockchain entries, particularly in life-threatening situations [87]. Navigating complex regulatory environments is necessary, requiring policymakers to create guidelines that ensure ethical blockchain use in cancer care in alignment with legal and moral standards [90]. Finally, while blockchain can facilitate the efficient sharing of clinical trial data, accelerating research and yielding better treatment options, it is crucial to vigilantly manage the ethical implications of data sharing and the need to protect participants' anonymity, striking a balance between data utility and participant rights [91].

Novelties of this study

This study introduces the transformative potential of blockchain technology in cancer care, focusing on critical issues related to interoperability and data management. By emphasizing patient empowerment, it demonstrates how blockchain can grant individuals greater control over their health data, fostering informed decision-making and enhancing engagement in their own care. The ability for real-time data sharing among healthcare stakeholders is essential for improving care coordination. One of the key innovations proposed is the use of smart contracts, which offers a promising method to automate not only administrative processes but also clinical decision support systems. This could significantly reduce the administrative burden on healthcare providers while ensuring that clinical guidelines are consistently applied, thus streamlining workflows and enhancing patient safety. Furthermore, the immutable nature of blockchain technology enhances data quality and integrity, ensuring the accuracy and reliability of patient records. The cryptographic features of blockchain also significantly enhance the security of sensitive health information, which is particularly crucial in oncology. The study highlights the facilitation of efficient patient recruitment and data collection for clinical trials as another advantage of blockchain technology. This capability promotes collaboration among researchers and accelerates advancements in cancer treatment. A blockchain-based EHR system could unify data standards, addressing interoperability issues and improving data exchange efficiency across diverse healthcare platforms. This is especially relevant in oncology, where multidisciplinary

approaches are common. However, the implementation of blockchain technology faces several limitations. Significant challenges include integration with existing healthcare IT systems, resistance to change, and the need for substantial investments in new infrastructure. Privacy concerns related to regulatory compliance complexities may hinder the feasibility of a public or permissionless EHR solution. Additionally, scalability issues present challenges concerning the vast volume of data generated and transaction speeds. Successful implementation of blockchain solutions requires widespread collaboration and buy-in from various stakeholders, including healthcare providers, patients, and regulatory bodies, which can be difficult to achieve. To address these barriers, the study proposes a phased implementation strategy that encourages stakeholder engagement and gradual adaptation, fostering a culture of collaboration and innovation. By building on existing literature and insights, the research not only reinforces previous findings but also introduces new perspectives on the transformative potential of blockchain in cancer care. Overall, it offers a comprehensive framework that addresses both the advantages and limitations of this technology, paving the way for enhanced patient empowerment, improved care coordination, and accelerated advancements in cancer treatment.

Limitations of This Study

This study explores the transformative potential of blockchain technology in cancer care, particularly in addressing interoperability and data management challenges. By emphasizing patient empowerment, blockchain can provide individuals with greater control over their health data, which fosters informed decision-making and enhances engagement in their care. The ability for real-time data sharing among healthcare stakeholders is crucial for improving care coordination, while the proposed use of smart contracts offers a promising approach to automate administrative processes, thereby alleviating burdens on healthcare providers and streamlining workflows. Blockchain's immutable nature enhances data quality and integrity, ensuring the accuracy and reliability of patient records. Moreover, its cryptographic features significantly improve the security of sensitive health information, which is particularly vital in oncology. Additionally, blockchain facilitates efficient patient recruitment and data collection for clinical trials, promoting collaboration among researchers and accelerating advancements in cancer treatment. A blockchain-based EHR system could also unify data standards, addressing interoperability issues and improving data exchange efficiency. However, several limitations hinder the effective implementation of blockchain in this field. Key challenges include the integration with existing healthcare IT systems, resistance to change, and the need for substantial investments in new infrastructure. Privacy concerns, particularly regarding regulatory compliance with frameworks like the GDPR, pose significant hurdles due to blockchain's permanent data storage. Scalability issues arise from the large volumes of data generated in cancer care, leading to inefficiencies in transaction speeds and potential operational delays. Furthermore, the lack of standardization among blockchain solutions complicates integration with existing health information systems. The technical complexity and high costs associated with implementing blockchain may deter healthcare organizations, especially given the need for skilled personnel familiar with both blockchain technology and healthcare processes. Lastly, while blockchain is recognized for its tamper-proof nature, it does not guarantee the accuracy or quality of the data entered, raising concerns about user errors and the necessity for stringent quality control measures in cancer care.

In conclusion, the integration of blockchain technology into the cancer treatment infrastructure presents a promising avenue for overcoming existing challenges in data management and communication among healthcare stakeholders. By establishing a decentralized and secure framework for EHR, blockchain can significantly enhance data quality, facilitate real-time information sharing, and streamline workflows, ultimately leading to improved patient outcomes. The review highlights the importance of addressing interoperability issues and the need for a unified data standard to foster collaboration among diverse participants in cancer care. As healthcare continues to evolve, embracing innovative technologies like blockchain will be crucial in creating a responsive, efficient, and patient-centric healthcare system that meets the complex needs of cancer patients and providers alike.

Author Contribution Statement

Alireza Nezameslami directed the research. Amirhossein Shahbazi advised on data analysis, and Rezavan Nezameslami developed the theoretical framework. Heewa Rashnavadi and Fatemeh Jayervand collaborated on result analysis. Melina Pourkazemi conducted the literature review. Razieh Akhondzardaini designed the methodology, and Amirhosein Rahmani interpreted the findings. Mahsa Danaei wrote and revised manuscript sections. Sepide Soleymani and Maryam Yeganegi synthesized the conclusions. Kazem Aghili provided feedback during drafting, and Hossein Neamatzadeh coordinated contributions for manuscript coherence.

Acknowledgements

We would like to extend our gratitude to the individuals and organizations that contributed to the completion of this study.

Ethical Approval

This article does not involve any studies with human participants or animals conducted by the authors and therefore did not require ethical approval from any scientific body.

Conflict of Interest

The authors declare that there are no conflicts of interest related to this manuscript.

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