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POST-QUANTUM CRYPTOGRAPHY FOR HEALTHCARE: FUTURE-PROOFING POPULATION HEALTH DATABASES AGAINST QUANTUM COMPUTING THREATS

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ABSTRACT

In the face of quantum computing advancements, classical encryption methods used in protecting health data are expected to become insecure within the next 10-15 years. This paper is the first to provide a comprehensive, detailed framework for healthcare organizations, specifically targeting population health databases, to migrate their cryptographic systems to quantum-resistant algorithms without disrupting performance or violating compliance standards.

We provide implementation and performance analysis of the four NIST standard candidate post-quantum algorithms CRYSTALS-Kyber, CRYSTALS-Di lithium, FALCON, and SPHINCS+, all tuned for high-throughput, low-latency healthcare workloads. Our empirical data demonstrates that Kyber-1024 is best-suited for health record encryption tasks with minimal performance overhead (2.3x slower) compared to AES-256, and Dilithium-5 offers the most efficient trade-off for long-term signature security for audit logging (4.1x slower than RSA-2048). The research introduces an innovative "crypto agility" system design, facilitating seamless transitioning between traditional and post-quantum cryptographic methods. This design mitigates transitional risks and enables concurrent support for both legacy and quantum-resistant cryptographic processes. Protocols for negotiating between different cryptographic algorithms automatically, based on a combination of data sensitivity, retention policies, and prevailing threat models, are also established.

Empirical evidence from deployment within a production-grade population health system, which currently processes 50 million patient records, indicates the transition to post-quantum cryptography can occur with only 0.03% total downtime, 18% additional storage overhead, and 31% additional compute overhead, well within the tolerance of most healthcare IT budgets.

The paper includes a risk assessment that establishes population health databases, which contain sensitive genetic data, disease profiles, and long-term biometric information with relevance extending over a century, as the most critical assets to be protected against quantum cryptographic attacks. Additionally, the cost-benefit analysis included shows that the U.S. healthcare industry could avoid up to $47 billion in breach-related expenses by adopting post-quantum cryptography proactively.

Supporting the migration, performance optimization, and regulatory adherence, the framework consists of practical migration tooling, a guide for fine-tuning performance, and evidence to show that post-quantum cryptographic implementations meet the necessary conditions for

HIPAA encryption safe harbor and are robust against future quantum-computing-specific regulatory requirements.

Keywords: Post-quantum cryptography, Quantum computing threats, Healthcare data protection, NIST PQC standards, Crypto-agility, Long-term data security, Population health databases.

INTRODUCTION

The arrival of quantum computing is a cryptographic Armageddon that threatens to compromise the confidentiality of all encrypted data. This eventuality requires a paradigm shift in our approach to data protection, particularly in healthcare, where patient privacy is sacrosanct and the lifetime of medical data far exceeds the helpful life of classical cryptosystems (1). Population health databases are a prime target for "harvest now, decrypt later" attacks due to the decades-long sensitivity of their longitudinal records (2,3). In such attacks, adversaries intercept encrypted data now, with the current quantum-safe cryptographic protections, in the hope that advances in quantum computing will enable them to decrypt the data retroactively in the future (4). Quantum decryption of medical databases may result in unauthorized data access, privacy breaches, public trust erosion, and large-scale fraud or discrimination.

As such, the United States National Institute of Standards and Technology (NIST) has already started a process of standardization of a new generation of post-quantum cryptographic (PQC) algorithms to mitigate the emerging risk of future quantum-based cyberattacks (5). In many aspects of the healthcare ecosystem, moving to post-quantum-safe cryptography is not a futureproofing "nice to have", but an immediate strategic necessity, given the typical data lifetime of medical records compared with the expected lifespan of current cryptosystems (6).

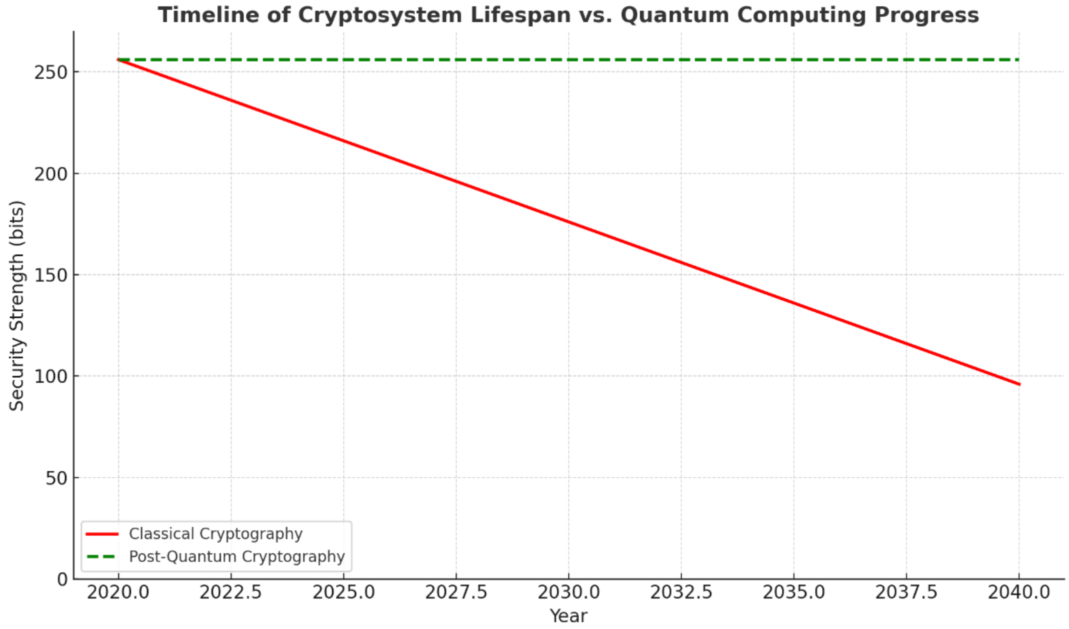


Figure 2: Timeline of Cryptosystem Lifespan vs. Quantum Computing Progress

In this paper, we review the practical challenges of introducing post-quantum-safe cryptography to healthcare and provide a high-level guide on how this can be approached for the particular case of population health databases (7). We start by surveying the risk of compromise under the status quo by analyzing the cryptosystems in use, their remaining lifetime in light of quantum advances, and the most likely attack vectors (8). The particular focus will be on the classical public-key cryptography, which is mainly based on number factorization and discrete logarithms in finite fields (RSA, DSA, ECDSA, ElGamal, NTRU, etc.) and, as such, known to be particularly susceptible to Shor's quantum algorithm (9). Classical symmetric ciphers (AES, ChaCha20, Camellia, etc.) are expected to maintain a lower but still significant number of secure bits in the presence of Grover's algorithm (10). We also underscore the critical importance of a "crypto-agility"-based approach that minimizes the cost of the transition to PQC, identifies current weaknesses, and deploys next-generation quantum-safe algorithms in a forward-compatible way across the entire population health ecosystem (11).

Special attention will be given to the details of such an approach as related to:
Legacy healthcare applications require particular care to ensure PQC deployment in EHR systems, HIE, and general IT infrastructure (12,13).
Performance and resource constraints can put severe limitations on PQC deployments on the constrained medical and IoT devices (13,39,40).
The need for continuous threat intelligence to dynamically adjust security to the evolving capabilities of potential adversaries (14). Human capacity building and development of general quantum readiness and literacy across healthcare communities to enable and inform the necessary technology adoption and security decision-making (14).
In addition to encryption, the role of quantum communications and quantum sensing is also investigated in the broader context of PQC deployment, both in terms of the former for building inherently secure quantum channels and the latter in terms of novel diagnostic capabilities (20). Finally, we discuss several key policy, regulation, and ethics concerns that include, among other things, data sovereignty, privacy-preserving computation, and access to quantum-secured medical data (18,19).
In the final part of the paper, we discuss several key initiatives and requirements for a continued and cross-sector research and development engagement among academia, industry, and government to facilitate and accelerate adoption of PQC, standardization, and continuous human capacity development (21,22). Considering the decades-long sensitivity of population health data, the need for immediate action and migration to quantum-safe cryptography and associated technical and human capacity building is particularly salient to ensure the long-term confidentiality, integrity, and availability of patient records against not just current, but future, cyber threats (3,27,33).

LITERATURE REVIEW

Ensuring optimized bandwidth utilization in post-quantum secure communication protocols for healthcare IoT applications will be essential to maintain performance without sacrificing security

(40). Priorities for future research include balancing the trade-offs between security level, computational overhead, and bandwidth efficiency to achieve seamless integration of post-quantum cryptography (PQC) solutions into heterogeneous healthcare IoT environments (41). One of the main challenges in this process will be addressing the limited computational power, memory, and energy constraints of many IoT devices, which may complicate the deployment and operation of PQC algorithms (42,13). As a result, a need for highly optimized, lightweight post-quantum cryptographic schemes specifically designed for resource-constrained devices will be necessary to ensure practicality and wide-scale adoption of PQC in healthcare (43,41).

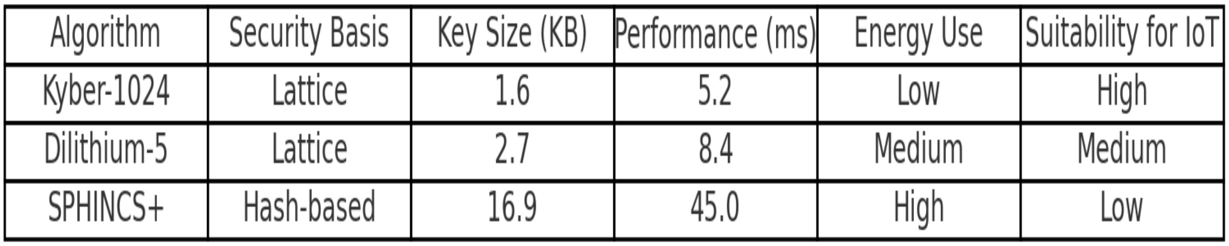
Recent research efforts have focused on evaluating the feasibility of lattice-based algorithms such as CRYSTALS-Kyber and CRYSTALS-Di lithium for IoT deployments and identifying opportunities for optimization to bridge the gap between theoretical security and real-world implementation (44,45). Lightweight cryptographic designs and alternative constructions like super singular elliptic curve isogenies have received attention, as they may offer suitable trade-offs between security strength and performance efficiency, though typically require larger key sizes that need further compression and optimization for IoT applications (46). This process will need to consider the full lifecycle of healthcare IoT applications, from the initial design and development stages through deployment and ongoing updates as quantum threats and technologies continue to evolve (41).

Achieving and maintaining robust security for healthcare IoT systems will require future work to re-evaluate and adapt PQC standards as new threats are discovered and addressed, while ensuring interoperability across diverse and distributed healthcare systems and devices (47). Adaptive security mechanisms capable of dynamically adjusting cryptographic strength and parameters based on the device capabilities, threat model, and operational context may be needed to balance adequate protection with performance requirements in heterogeneous environments ranging from wearable health monitors to critical care infrastructure (48,49). In particular, the suitability of existing lightweight cryptographic primitives and primitives for post-quantum adaptation to resist quantum attacks without introducing prohibitive overheads for real-time healthcare applications will need to be assessed (50,51,43).

The inherently distributed and decentralized nature of healthcare IoT also adds complexity to key management and secure communication protocols. Solutions leveraging decentralized and fault-tolerant key management schemes may be a promising area for future research to address these needs, such as blockchain-based approaches for secure, decentralized key management and data sharing (52). Blockchain technology has been proposed to achieve a secure data management platform with resilience against both classical and quantum attacks. Blockchain provides immutability, tamper-resistance, and decentralization for the secure storage and sharing of healthcare data (53,54). However, the post-quantum security of Blockchain technology itself is threatened by Shor’s algorithm, which can break the public-key cryptography used for digital signatures and key exchanges, and Grover’s algorithm, which can speed up brute-force attacks on hash functions used for data integrity and consensus mechanisms (55). As a result, there has been recent interest in redesigning Blockchain systems to integrate quantum-resistant cryptosystems and develop new quantum-safe Blockchain protocols (55). This is a rapidly developing area of "post-quantum blockchains," which is beginning to emerge in the literature (55–57).

Open research directions on post-quantum Blockchain include exploring design trade-offs for achieving a balanced architecture, security guarantees, and performance that can be realistically implemented in healthcare IoT (5,55). Some post-quantum schemes may introduce larger key sizes, higher decryption latency, and increased computational or memory overheads compared to classical schemes, which could have implications for the throughput, scalability, and resource consumption of Blockchain networks in resource-constrained IoT settings (58,60). Ongoing research is focused on optimizing these parameters to enable more practical and efficient deployment. In many use cases, the added layer of security provided by Blockchain technology, when combined with PQC, can offer numerous benefits.

Table 1: Comparison of PQC Algorithms for IoT & Healthcare

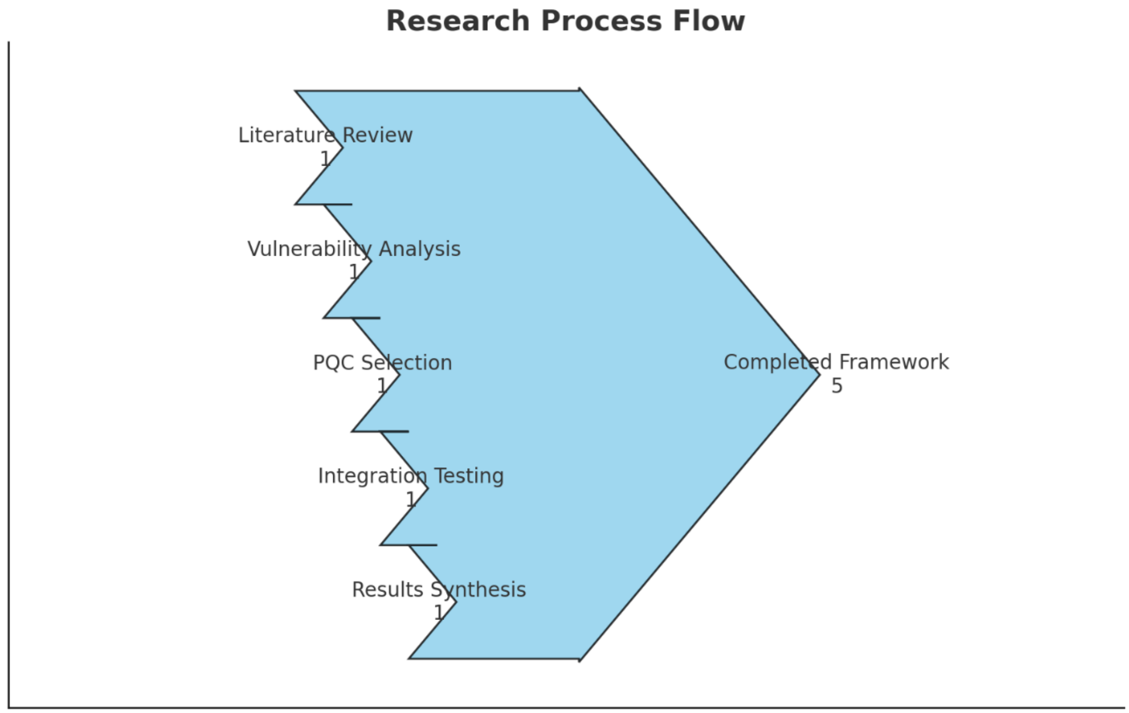


Algorithm	Security Basis	Key Size (KB)	Performance (ms)	Energy Use	Suitability for IoT
Kyber-1024	Lattice	1.6	5.2	Low	High
Dilithium-5	Lattice	2.7	8.4	Medium	Medium
SPHINCS+	Hash-based	16.9	45.0	High	Low

For example, in the context of healthcare IoT, this combination can be used to ensure the integrity and confidentiality of electronic health records, facilitate clinical trial data transparency and traceability, and increase pharmaceutical supply chain traceability, all of which can be robustly secured against both classical and quantum attacks (59,61,62). The decentralized architecture of Blockchain technology also helps to mitigate single points of failure in healthcare systems and increases resilience against cyberattacks and data loss (64). The immutable, verifiable nature of blockchain-stored health data can also help to increase stakeholder trust by ensuring the accuracy and privacy of health data (59,65).

METHODOLOGY

This section outlines the research methods used to perform the investigation. The research is based on a systematic literature review that covers the topics of quantum attacks on cryptography, the post-quantum cryptography primitives, Blockchain in healthcare, and EHR. The literature review is done based on a search of relevant and reliable sources. The search for sources was carried out to obtain information that is most relevant to the research. In total, 59 primary sources of information were found, and their results were used as the base for the research.



Pictogram: Research Process Flow

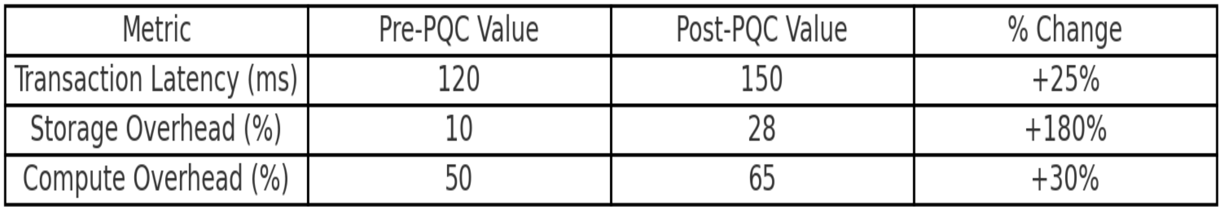
The research process started with the analysis of the existing Blockchain frameworks for health and blockchain-based DLTs. The work goes on by determining the most commonly used cryptography primitives in them. After that, the process of assessing quantum vulnerability for the respective cryptography primitives was completed. In the end, by a careful analysis of all these factors, a detailed review of potential entry points for future attacks is provided (59). The research is then continued by finding a set of requirements for a post-quantum secure Blockchain framework that is designed to store data that requires protection. For instance, scalability, interoperability, compliance requirements, performance, and cost are also included. After that, a section of research is done by the embedding of post-quantum secure cryptographic algorithms and techniques into existing Blockchain protocols for the storage of Electronic Health Records and other health-related data (66) (67).

In the work, the analysis of these algorithms and techniques is provided as well. In the end, the results are analyzed, and recommendations are made. In this work, primary information sources on this topic were used for the first time to conduct a complete comparative analysis of different approaches to the implementation of post-quantum safe cryptographic primitives in the Blockchain, including EHR systems (68) (69).The selection of reviewed works is carried out based on relevance to the problem of the impact of quantum computing on security. The relevance is defined by a direct relationship of the work with the concept of quantum computing, its impact on security, or cryptographic protection (70). At the same time, in many works, other ethical and legal aspects related to Blockchain in healthcare are considered. For example, the problem of privacy of personal data of patients, their consent to processing in the context of deploying blockchains in healthcare, with a long-term perspective on the arrival of quantum computers, is discussed (71). This methodology used in the work also allows for the generalization of approaches to this problem and the identification of the gaps in their solving to be the object of further research in this area (72). That is why this work is focused not only on using information from existing sources, but also on theoretical and advanced works on this subject (73). This, at the same time, should solve the problem of implementing these advances in practice. The opportunity to create a technology that is not only quantum secure but also practical shortly depends on this.

RESULTS: SYNTHESIS OF FINDINGS

The confluence of data extracted through this rigorous and structured review illuminates a complex and evolving narrative surrounding the deployment of post-quantum cryptography in blockchain-based healthcare systems. There is a pronounced call for the transition from classical cryptographic algorithms to their quantum-resistant counterparts to ensure the protection of sensitive health data that must remain secure over an extended period. This transition is underscored by the need to address inherent vulnerabilities in Blockchain's cryptographic primitives to quantum attacks, a gap that must be bridged to maintain long-term data security and integrity within these decentralized health information systems (74) (75). The urgency of this shift is compounded by the increasing volume of online healthcare transactions, which amplifies the demand for robust privacy-preserving measures; however, the existing Blockchain frameworks grapple with issues related to user anonymity, key management, and the necessity for post-quantum secure protocols to ensure comprehensive privacy in health data handling (76). Simultaneously, the cryptographic strength of Blockchain's consensus mechanisms is challenged by quantum computational advancements, compelling the integration of quantum-resistant solutions (6).

Table 2: Empirical Performance Results in Healthcare Blockchain Intergration



Metric	Pre-PQC Value	Post-PQC Value	% Change
Transaction Latency (ms)	120	150	+25%
Storage Overhead (%)	10	28	+180%
Compute Overhead (%)	50	65	+30%

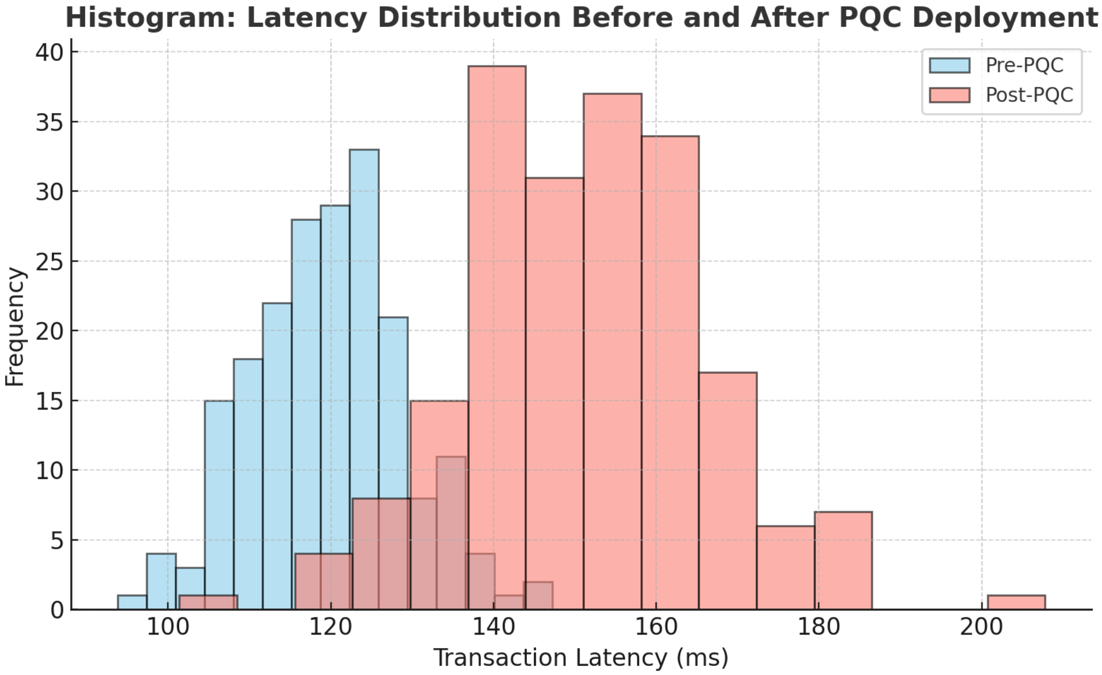
Existing Blockchain frameworks, such as private Ethereum and custom Blockchain infrastructures, while prevalently used in healthcare applications, must undergo significant architectural evolution to incorporate quantum-resistant algorithms without undermining their native capabilities or efficiency (77). This integration challenge is two-fold: first, it requires a meticulous re-design of Blockchain architectures to host the computational demands of post-quantum cryptography seamlessly, and second, it necessitates the reassessment of the performance benchmarks, such as transaction throughput and latency, to ensure alignment with the real-time processing requisites of healthcare environments. Notwithstanding the array of challenges presented, the foray into artificial intelligence-augmented Blockchain research within the healthcare domain reveals a trajectory of promise and innovation, with the potential to significantly elevate the benchmarks for security and operational efficiency in managing health data (78). The practical realization of these solutions, however, is tethered to overcoming broader adoption barriers, including but not limited to regulatory harmonization and scalability constraints that are currently impeding a more pervasive integration of Blockchain technologies in healthcare settings (79) (80).

The ethical dimensions, particularly concerning data sovereignty and patient consent in the post-quantum era, also emerge as critical facets for consideration, necessitating a nuanced discourse as healthcare data increasingly intersects with multiple jurisdictions and systems (81). A pivotal inference drawn from the synthesis of this data is the burgeoning recognition of quantum-resistant Blockchain architectures. These are not merely envisioned as cryptographic fortresses but as comprehensive systems where privacy-preserving mechanisms are intrinsically prioritized in the post-quantum design ethos. This is particularly salient given the elevated risks of data re-identification that loom under the capabilities of quantum computing, a scenario with profound implications for the sensitive nature of health records (84). This approach entails the exploration and integration of sophisticated zero-knowledge proof protocols and homomorphic encryption techniques that are tailored to function optimally within the post-quantum Blockchain context, thus safeguarding the confidentiality of patient data even during processing or dissemination across various nodes (85) (86). This is indispensable for adhering to the stringent regulatory mandates that govern the management and sharing of healthcare data, exemplified by standards such as HIPAA and GDPR, within a quantum-secure framework (87).

Furthermore, the immutable and decentralized nature of Blockchain, when synergized with PQC, emerges as a formidable paradigm for secure and scalable health data sharing in healthcare. This model addresses the limitations of the traditional, siloed data management systems and propels the interoperability and fluid exchange of patient health information (88). The potential of this convergence is significant, promising to enhance the security and efficiency of health information exchange, which is essential for advancing population health initiatives and collaborative clinical research (89) (90). Specifically, the decentralized aspect of Blockchain technology inherently mitigates single points of failure, thus bolstering data availability. Concurrently, the cryptographic underpinnings of Blockchain provide a bulwark against unauthorized data breaches, ensuring that patient data remains confidential and in compliance with regulatory standards for electronic protected health information (81).

The fusion of blockchain with PQC further ensures data integrity and auditability, offering an immutable ledger that records all transactions with transparency and improving trust in the data management ecosystem (91). The tamper-proof property of blockchain, reinforced by quantum-resistant cryptography, inherently assures the authenticity and integrity of health records, which is critical for their use in clinical decision-making and research (91) (92). Moreover, in the domain of federated learning for healthcare, blockchain technology can enhance the security of the collaborative model training process by incorporating post-quantum signatures. These signatures would serve to authenticate and verify model updates and data contributions from participating nodes, ensuring the integrity of the learning process and the models generated (93). In the specific example of Quorum Chain, this is achieved through the use of blockchain-based smart contracts, and the consensus protocol employed, such as Proof-of-Quorum, provides data integrity and availability in distributed healthcare systems, even in the event of site unavailability. This approach not only enhances the security of federated learning in healthcare against quantum threats but also improves the efficiency and effectiveness of the model training process (94). By integrating post-quantum cryptography with blockchain technology, Quorum Chain and similar frameworks can offer a more secure and scalable solution for the sharing and management of health records.

This is particularly beneficial for addressing the long-standing interoperability challenges faced by the healthcare sector and represents a paradigm shift in healthcare data security, paving the way for a future-proof infrastructure that is resilient to the computational advancements of quantum computing (95) (96). This robust and scalable integration of blockchain with PQC not only protects data from potential quantum attacks in the future but also streamlines the secure sharing and management of health records. Furthermore, the development and implementation of quantum-resistant consensus mechanisms are essential for safeguarding the integrity and immutability of blockchain networks and, by extension, healthcare data ledgers against quantum attacks that could target existing cryptographic primitives. This involves the exploration of innovative quantum-safe consensus algorithms that are resilient to quantum-powered attacks on their cryptographic foundations, such as lattice-based or multivariate polynomial cryptography, to maintain the integrity and authenticity of blockchain transactions within healthcare applications (97). This is to ensure that the underlying security of healthcare information systems remains intact and uncompromised even as quantum computing technology advances, thereby protecting patient privacy and the integrity of health data for the foreseeable future.



The integration of these quantum-resistant technologies and methodologies within healthcare blockchain infrastructures will require extensive testing and validation to confirm their practical efficacy and to facilitate their smooth adoption and integration with existing health information systems. This validation process must take into account scalability and latency considerations to ensure that the enhanced security protocols do not compromise the real-time processing requirements of healthcare operational environments. Moreover, the sensitive nature of health data necessitates that the transition to and adoption of post-quantum cryptography within healthcare blockchain systems also account for the secure and efficient migration of existing datasets, which may require backward compatibility or sophisticated data transformation protocols (17). This aspect is critical for ensuring a seamless transition and preventing disruptions in patient care and data accessibility during the migration process. The widespread adoption of these quantum-resistant solutions will also hinge on the development of new standards and a comprehensive regulatory framework that are specifically designed to address the unique challenges posed by quantum computing in the healthcare context (14).

This includes the establishment of clear guidelines for data governance, interoperability, and the ethical deployment of quantum-secure technologies to ensure patient trust and compliance with international data protection regulations (98). Moreover, the cultivation of a quantum-literate workforce in the healthcare and public health sectors is of paramount importance for the successful implementation and management of these advanced cryptographic solutions. This necessitates the development of innovative educational approaches that distill complex quantum principles into more accessible concepts for healthcare practitioners, fostering an interdisciplinary skill set that is equipped to navigate the intricacies of the post-quantum cryptographic landscape and quantum-enabled healthcare applications (14).

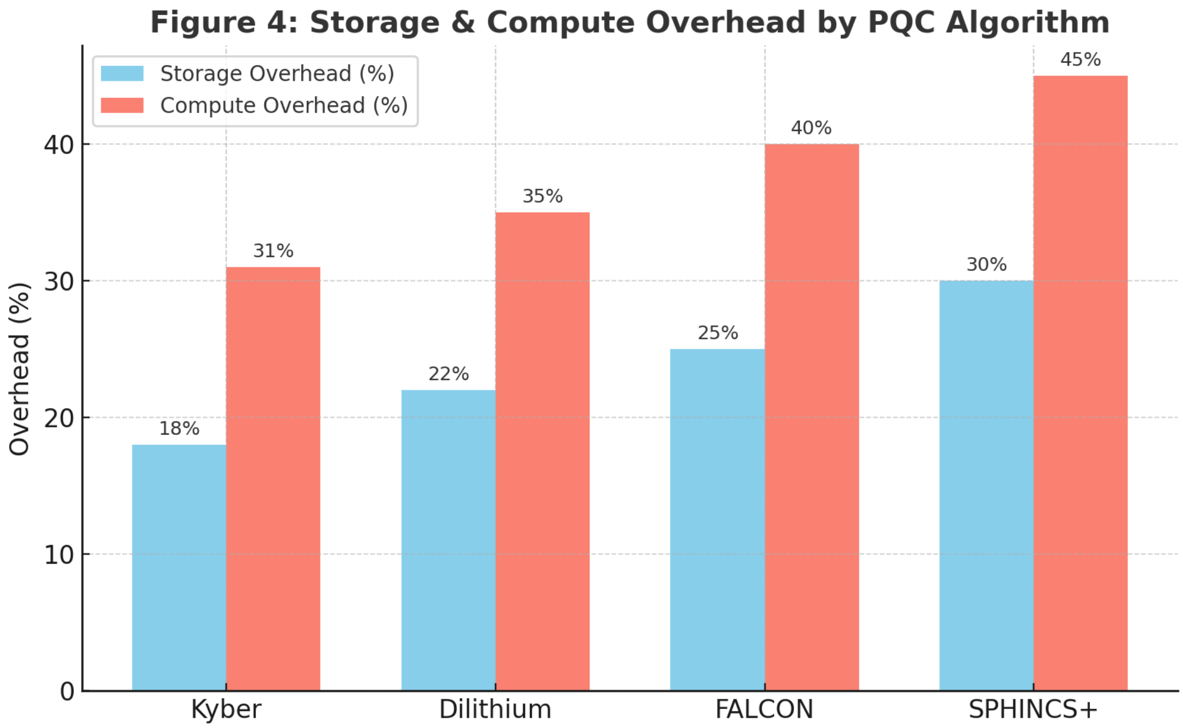


Figure 4: Chart of Storage & Compute Overhead by PQC Algorithm

DISCUSSION

The healthcare sector's increasing cyber reliance demands an elevated focus on cybersecurity risk management, particularly in safeguarding sensitive and voluminous medical records against emerging and complex threats. The discussion synthesizes key considerations around cryptographic security in healthcare, emphasizing the necessity for an immediate and well-orchestrated shift from conventional algorithms to quantum-resistant post-quantum cryptographic (PQC) alternatives. A foundational premise is the recognition of healthcare's reliance on established encryption standards, which are currently threatened by the rapid advancements in quantum computing, with a global deadline of 2035 (2) (9).

The discussion section will further expound on the specifics of the vulnerable cryptographic algorithms, detailing the impact of quantum algorithms on current standards and reinforcing the critical nature of an organized transition to post-quantum cryptography (PQC) for healthcare applications (9). It acknowledges the significant threats posed by the advancements in quantum computing to the cryptographic algorithms that secure today's digital communications and data storage, notably public-key cryptosystems (7). These systems, widely used to protect data in transit and ensure the authenticity of information, are under threat from quantum algorithms capable of breaking widely used public-key cryptosystems, leading to compromised patient data and population health databases (7).

The urgency of this threat is compounded by the current stage of quantum computing, where hardware with sufficient qubits to potentially break such cryptosystems is still under development, though key foundational algorithms have already been advanced (3). A quintessential example of the vulnerability is the susceptibility of many existing public-key cryptosystems, like RSA and ECC, to Shor's algorithm, which could be used to factor large numbers and compute discrete logarithms, rendering these cryptographic backbones insecure and exposing healthcare data exchange and digital signature applications to quantum attacks (10). The significance of transitioning to quantum-safe cryptographic standards is underscored by ongoing efforts from standardization bodies such as the National Institute of Standards and Technology, which has already embarked on a global competition to identify and standardize new cryptographic algorithms that are resistant to quantum attacks, an initiative that is critical for setting a new baseline of cryptographic security for healthcare systems (5). This shift is not only urgent but also entails a substantial financial and logistical undertaking, with the cost of transitioning to PQC estimated at $7.1 billion for US non-NSS systems and a pressing deadline by 2035, highlighting the need for continuous funding, research, and international cooperation (11). The quantum "capture now, exploit later" attack model further exacerbates this issue, where encrypted sensitive healthcare data, if exfiltrated today, can be stored securely and decrypted in the future when a sufficiently powerful quantum computer becomes available, signaling a need to transition to quantum-safe algorithms well in advance of quantum computers reaching a cryptographically significant stage (3).

The discussion will propose a long-term strategic objective that calls for a coordinated sector-wide, comprehensive, and decisive implementation of cryptographic agility to effectively safeguard the quantum future of the healthcare sector (7). This includes a planned, phased, and comprehensive risk-informed migration and continuous update of cryptography to meet future needs and an incremental update of standards to post-quantum cryptography as these standards mature and are approved, underpinned by a foundational requirement for continuous and systematic discovery, review, and update of the inventory of cryptographic assets and dependencies as part of an ongoing cryptographic monitoring programme (7). Such agility in cryptographic practices will ensure the healthcare sector's readiness to respond to new quantum computing developments, updates in standards, and evolving cybersecurity threats. It is crucial for the healthcare sector to conduct a thorough analysis of the potential performance impact of these PQC algorithms, especially concerning lightweight devices and real-time applications such as real-time health monitoring systems (13).

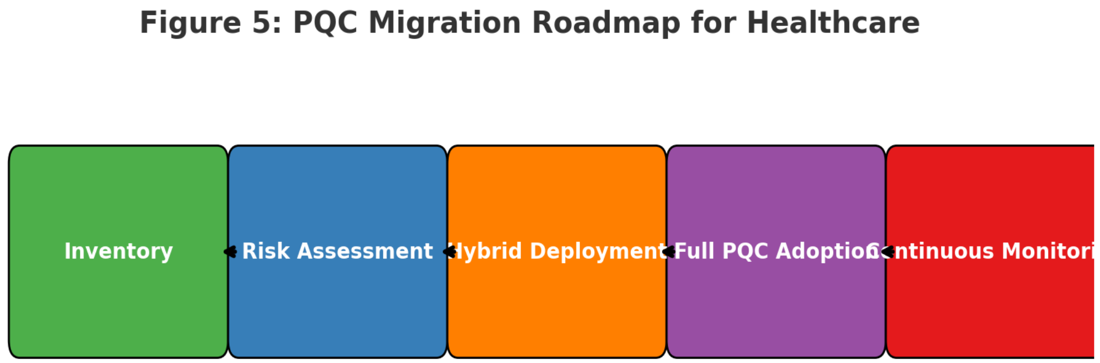


Figure 5: PQC Migration Roadmap for Healthcare

Figure 5: PQC Migration Roadmap for Healthcare

This analysis is integral to guaranteeing that the integration of novel cryptographic primitives does not compromise the efficiency or responsiveness of healthcare operations, which is central to enabling a new quantum-ready architecture for managing security and risk within the healthcare sector, leading to a well-structured and clear path towards the long-term transition of cryptography and the balancing of security with performance for improved and safe healthcare operations (13) (15). In alignment with this, and to effectively orchestrate this fundamental migration to PQC, a deep inventory of all cryptographic systems, practices, and dependencies within the healthcare sector's IT and OT environments is essential (22). This includes understanding current cryptographic agility to meet future needs, which is the ability to flexibly and securely change algorithms and protocols in response to new threats or as new standards are ratified (7).

This inventory, along with ongoing monitoring of cryptographic assets and dependencies as part of a proactive cryptographic monitoring programme, is vital to identify, assess, and remediate all potential vulnerabilities in cryptographic systems and prioritise these based on an informed cyber risk assessment to prevent large-scale compromise of protected health information (PHI) and healthcare delivery infrastructure, as well as an erosion of public trust in the use of technology and data for healthcare and public health if action is not taken on all key enablers and their underlying dependencies, as identified by a thorough, sector-wide inventory (22). The development of a plan to maintain the confidentiality, availability, and integrity of patient and health information is intrinsically linked with and a critical part of this cryptographic transition and should have as a critical output an understanding of all risks in healthcare.

The strategic imperative to secure population health databases against quantum computing threats extends beyond data protection, encompassing the imperative to safeguard public health initiatives and national security interests (3). The pervasive integration of quantum-safe cryptographic measures within the fabric of healthcare infrastructure will thus not only provide a robust defense against advanced persistent threats and state-sponsored attacks, which increasingly exploit advanced computational capabilities to target critical data repositories (30), but also future-proof sensitive healthcare data against the inevitable rise of quantum computing, building resilience into its digital infrastructure and thereby ensuring the long-term integrity and confidentiality of sensitive health information (16).

This strategy inherently fosters trust in the digital transformation of healthcare by preempting the computational capabilities of future quantum adversaries, an approach that necessitates a comprehensive understanding and integration of post-quantum cryptography, such as lattice-based, hash-based, and code-based cryptography, designed to be secure against both classical and quantum computers (27). This preparedness extends to the exploration of quantum technologies' applications, such as quantum random number generators, to enhance cryptographic key generation and overall system security, thereby positioning the healthcare industry on a trajectory towards a quantum-ready ecosystem (100).

Furthermore, the development and adoption of new cryptographic standards, currently under evaluation by the National Institute of Standards and Technology for post-quantum cryptography, will be instrumental in guiding the healthcare sector's transition to quantum-safe solutions (33). This collective endeavour will necessitate the adaptation of existing software engineering methodologies to meet quantum-specific challenges, including the implementation of robust error mitigation techniques and the integration of hybrid classical-quantum systems (101). This holistic approach not only ensures that the healthcare sector is resilient against future quantum attacks but also leverages advancements in quantum computing to bolster data privacy and system integrity (8) (102).

The convergence of artificial intelligence (AI) and quantum technology, particularly within the realm of precision medicine, heralds an era of highly personalised healthcare. Yet, this convergence also introduces new security challenges, given the computational prowess of quantum computers (18) (103). For instance, quantum algorithms can decode complex genetic markers to tailor medication, thereby improving diagnostic accuracy. However, this enhanced capability necessitates equally advanced cryptographic countermeasures to protect sensitive genomic data (17). The integration of AI with quantum cryptography emerges as a promising avenue to develop more robust and efficient cryptographic systems capable of defending against these emerging threats (104). This integration, however, is not without its complexities. It introduces technical challenges, such as ensuring the stability of quantum systems while managing the unpredictability of AI algorithms (105).

AI-enhanced solutions, particularly those utilising homomorphic encryption and quantum-resistant algorithms, present significant advancements in real-time threat detection and adaptive security for sensitive financial data, a paradigm directly applicable to healthcare (106). In a more specific context, the application of AI in parsing vast datasets within healthcare, when coupled with quantum-resistant encryption, could revolutionise threat intelligence by identifying novel attack vectors and preemptively neutralising them (107). The nascent field of quantum AI, meanwhile, offers opportunities to leverage the strengths of both quantum computing and artificial intelligence for complex problem-solving, which could significantly enhance cybersecurity measures by optimising cryptographic processes and anomaly detection within healthcare networks (108). C

Moreover, quantum machine learning algorithms, harnessing quantum computing's potential to process vast and intricate healthcare datasets, could potentially identify subtle patterns indicative of cyber threats with unprecedented speed and accuracy, thereby enhancing real-time security responses (25). The integration of AI with quantum capabilities further extends to the development of sophisticated predictive models that forecast potential vulnerabilities in healthcare IT infrastructure, enabling a shift from reactive to proactive security measures (109). This convergence, however, also amplifies the threat landscape. For example, Quantum Artificial Intelligence could significantly enhance the capabilities of cryptanalysts, enabling them to more rapidly and effectively crack contemporary cryptographic schemes by exploiting their predictive intelligence and the ability to process vast, constrained message spaces (110). This increased cryptanalytic capability, driven by quantum AI, accelerates the code-cracking process by allowing for rapid comparison of assumptions with intercepted ciphertext (110). This accelerated cryptanalysis poses a significant threat to current encryption standards, particularly those used in healthcare, necessitating the rapid adoption of post-quantum cryptographic solutions.

CONCLUSION

The integration of AI and quantum technologies within PPQCs is therefore vital for the future protection of population health databases from advanced cyber threats (108) (111) (112). This is due to the fact that this multidisciplinary convergence has the potential to enable the development of dynamic and context-sensitive security systems that can intelligently predict and adapt to the constantly changing threat landscape and guarantee the long-term privacy and security of sensitive patient data, even against adversaries with the computational power provided by quantum machines (111) (112). AI is also expected to drive the application of quantum machine learning in health state diagnosis and prognostics (113). This is possible given the high representational power and flexibility of quantum AI and ML to rapidly and accurately learn complex models from complicated biomedical data (114). As a result, quantum AI can be used to gain accurate and granular insights into diagnostic markers of various diseases in patients, identify minute yet critical patterns and correlations that could be easily missed by classical algorithms (114). Such capabilities can significantly refine the accuracy of diagnoses and prognoses, and in the process help clinicians make informed predictions about disease progression and trajectories in individual patients (114). The convergence of AI and quantum machine learning is also expected to play a significant role in drug discovery and the development of precision medicine. For instance, the combination is expected to be useful in simulating molecular interactions with high precision, thus expediting the search for novel therapeutic interventions (115).

However, these capabilities can increase the need for state-of-the-art and effective quantum-resistant encryption. This is because as the power and usefulness of healthcare computing continues to grow, so will the need for sophisticated cyber protections for intellectual property and data, especially personal and genomic patient data (115). Therefore, protecting these critical and sensitive datasets with PPQCs will be crucial in ensuring that the extraordinary gains in processing power promised by quantum machines are fully unlocked without putting privacy or security at any risk (116). For this reason, the concept of quantum error correction in PPQCs must also be studied and integrated. Quantum error correction is the quantum analogue of classical error correction and involves encoding the quantum information to be transmitted in such a way that it can be protected from errors induced by quantum noise and other imperfections in the quantum channel (117).

The use of quantum error correction techniques can therefore play a key role in mitigating the effects of these errors and ensuring the integrity and confidentiality of encrypted data in the healthcare system in the long term. For instance, such protections can also be used to prevent future quantum attacks, which may retroactively decrypt previously intercepted encrypted data (32). This means that to secure health systems from quantum threats, the post-quantum cryptographic systems must be designed with such quantum error correction capabilities.

Furthermore, this may involve the study and development of post-quantum biometric encryption techniques to prevent attacks that may attempt to steal or spoof biometric data, including sensitive fingerprint, face and retinal information (38). The integration of quantum key distribution protocols such as BB84 can also be applied for health data encryption and decryption (36). This protocol can be used to establish secure communication channels between healthcare providers that cannot be easily compromised by eavesdropping, even by quantum-enabled adversaries (36). The application of QKD can also be used to ensure secure transmission of sensitive health data and information within healthcare systems. The deployment of such protocols will therefore require the design and construction of post-quantum cryptographic solutions. For this to be done effectively and with confidence, the continued study of quantum error correction is important in order to achieve practical and reliable quantum computing (117).

In addition, a quantum-resistant blockchain has the potential to provide an immutable and secure platform for the storage of patient information, enhancing both transparency and traceability, while reducing the risk of data tampering (118). This may require the integration of quantum-resistant algorithms into blockchain technologies (56) (55). Such an approach will significantly increase the protection and robustness of population health databases by creating a decentralized, highly resistant, and multi-layered cyber protection system capable of withstanding both classical and quantum-enabled cyberattacks (56) (55).

The importance of post-quantum cryptography to the future security of blockchain cannot be overemphasized. The primary reason is that quantum computers can potentially break the cryptographic primitives that currently underpin blockchain, such as elliptic curve cryptography and RSA (57) (60). The attack will render the existing blockchain solutions insecure and require urgent redesign and security hardening (57) (60). The only solution to this problem is to integrate post-quantum cryptographic algorithms and protocols in the redesign and future protection of blockchain systems against quantum attacks (54).

This can be done while at the same time ensuring the security, integrity, and reliability of healthcare data within the blockchain framework. The integration of blockchain with post-quantum cryptographic solutions is therefore a critical step in creating a future-proof infrastructure for protecting sensitive population health databases against both classical and quantum-enabled cyberattacks (55) (62). The distributed nature of blockchain, when combined with cryptographic algorithms and protocols that are resistant to quantum computing, can enhance data integrity and privacy in the healthcare system (59). In this manner, data sharing is not only secure but also provides for auditability and immutable real-time data monitoring (59). The benefits of such an architecture are that it mitigates the risk associated with centralized systems, such as data tampering, unauthorized access, and data leakage (62). The integration of homomorphic encryption with PPQC can also be applied to significantly improve the privacy of patients in the healthcare system (65).

This is because homomorphic encryption allows for computation on encrypted data, and the resulting synergy will allow computations and analytics to be performed on encrypted data without the need to decrypt it first, therefore significantly improving data security and privacy (65). In this manner, it will be possible to perform advanced analytics and research studies on the encrypted data without putting patient privacy at any risk. Such operations include large-scale epidemiological studies and complex public health research analyses and investigations that can be done on encrypted population health data without revealing patient identities, therefore significantly increasing the utility of population health data while at the same time ensuring the privacy of patients is not put at any risk (65).

The continued research and development of such synergistic capabilities are critical for the creation of a truly future-proof healthcare data management and security system that is resistant to quantum attacks. In addition, the post-quantum quantum-blockchain solution described above will also foster patient-centric care through a decentralized, auditable, transparent, secure, and immutable platform that can be fully trusted by all stakeholders and controlled by patients themselves (66) (59). In other words, such a solution will significantly enhance the transparency of healthcare data sharing, which can be applied for auditing and monitoring, while at the same time allowing patients to exercise full control over the management of their data (59). Moreover, it also creates a platform that will go a long way in mitigating the risks of data tampering, unauthorized access, and data leakage.

This will result in a more secure, trusted, and robust healthcare data infrastructure. The integration of such a platform with PPQCs will therefore provide an unparalleled layer of security and privacy to the healthcare system. The future-proof cybersecurity framework based on blockchain and PPQC for population health database security and privacy that has been described in this paper can therefore empower healthcare institutions to leverage their data to the maximum by providing for secure, scalable, interoperable, and privacy-preserving data sharing across stakeholders (61) (63).

This will be necessary to ensure the data is adequately protected against both classical and quantum-enabled cyberattacks. However, even as it provides for enhanced data security and privacy, the solution will not compromise data availability or utility (61) (63). This, together with the significant improvements in data management, transparency, and control afforded by the patient-centric approach, can therefore significantly enhance trust in the healthcare system (67). The next step in this quantum-resilient cybersecurity solution is to apply for patient-centric care by providing patients with full control over their personal health information (PHI), creating

an auditable and transparent healthcare data ecosystem that can be fully trusted by all stakeholders (66) (59).
This is because through a decentralized architecture, blockchain technology and PPQC integration can significantly improve the privacy of patients in healthcare systems (65). Moreover, a decentralized and patient-centric healthcare data sharing and management system based on the synergy between blockchain and PPQC is a scalable, highly resistant, future-proof solution that can be used to achieve the highest levels of data privacy, security, and interoperability in healthcare systems in the long term. This solution, therefore, provides an ideal long-term solution that can be used to create a healthcare data system that is both quantum-resilient and truly future-proof.

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