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Quantum computing revolution in healthcare: a systematic review of applications, issues and future directions

Vamshi Krishna Bukkarayasamudram[1] · Pundru Chandra Shaker Reddy[2] · K Arun Kumar[3] · R. M. Jagadish[4] · Swati Sharma[5] · Mudarakola Lakshmi Prasad[6] · Yadala Sucharitha[7] · Iftikhar Aslam Tayubi[8] · Gopal Kumar Thakur[9]

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Abstract
Conventional treatment methods make even the most basic healthcare issues more complicated, which in turn increases the number of parties involved. Classical computing lacks the speed and accuracy needed for effective stakeholder collaboration in COVID-19 healthcare solutions, such as patients, insurance agents, healthcare practitioners, pharmaceutical suppliers, etc. The research uses organizational information processing theory (OIPT) to examine how quantum computing which is applications of artificial intelligence (AI) could transform the healthcare business, creating a more sustainable and less burdened system. The study of quantum computing (QC) has the potential to bring about "quantum leaps," which might have unforeseen consequences for healthcare. The discovery of new medications, the personalization of medicinal treatments, and the acceleration of DNA sequencing are just a few of the many possible applications of this method. The potential of QC to transform compute-intensive healthcare tasks like drug-discovery, personalized-medicine, DNA-sequencing, medical-imaging, and operational-optimization is the primary focus of this survey paper, which offers the first comprehensive analysis of QCs diverse capabilities in improving healthcare systems. After a thorough literature study, we created taxonomies on the healthcare QC paradigm's history and supporting technologies, applications, needs, architectures, security, outstanding questions, and future research prospects. We hope that by conducting this survey, researchers with varying levels of experience in quantum computing and healthcare will better understand the state of the art, assess opportunities and threats, and make informed decisions as they develop novel architectures and applications for this emerging field.

Keywords Healthcare · Quantum computing · Genetic diseases · Drugs discovery · Artificial intelligence · Quantum machine learning · Quantum annealing · Quantum cryptography

Extended author information available on the last page of the article

1 Introduction

Computing power has increased in recent years, allowing for the practical processing of massive data sets. Compared to classical computers, quantum computers have the ability to solve complicated problems considerably more quickly. The healthcare industry stands to gain the most from QC due to the exponential growth in both the quantity and variety of health data. As an example, new variations of the COVID-19 virus surfaced during the pandemic, posing a challenge to healthcare workers who were utilizing conventional computing systems to sequence the virus's genome (Gupta et al. 2023). In order to effectively manage future pandemic scenarios, it is crucial to investigate innovative methods of accelerating healthcare analysis and monitoring. QC is a game-changer when it comes to healthcare systems (Ur Rasool et al. 2023). By using ground-breaking methods for processing data, QC differentiates itself from conventional computer systems. It makes use of the extraordinary capabilities of subatomic particles, including superposition, entanglement, and interference, and the strength of quantum bits (Ur Rasool et al. 2023). These quantum phenomena allow quantum computers to function at a whole different level, outperforming traditional computers in terms of computing capacity exponentially. Complex problems that are now intractable for ordinary computers may finally have an answer in QC, which manipulates qubits and takes advantage of their quantum states (Kumar 2022). Healthcare is only one of several vital industries that might feel the effects of QC's influence, which goes well beyond its computational capacity. Engineers and scientists are putting in a lot of time and effort to find solutions to the problems and limitations of QC technology. Problems with qubit stability, scalability, noise reduction, and error correction are all part of this category (Srivani et al. 2023).

A new subfield of computer science known as machine learning (ML) is booming thanks to the daily deluge of data sent, collected, and processed (Maheshwari et al. 2022). In practice, ML has several uses and implementations that involve QC. Exciting and applicable to a vast array of fields, QC science is a growing field of study (Bhavin et al. 2021). Recent advances in QC have opened new possibilities for tackling complex computational problems, particularly those involving combinatorial explosion or quantum chemistry, though these benefits are currently limited to a narrow class of tasks and remain largely theoretical or experimental in healthcare contexts (Gill et al. 2022). Using QC techniques has opened up new avenues of inquiry into machine learning and the creation of computer-based systems based on quantum theory (Enad and Mohammed 2023). In quantum theory, QC is a set of interconnected bits that describe the properties and behaviors of energy and matter at the quantum level (Singh and Bhangu 2023). Quantum machine learning is an area that combines conventional ML with quantum mechanics. The use of quantum computers to build ML algorithms with a quantum twist and ML algorithms to analyze quantum systems are complementary processes (Venkatesh and Savadatti Hanumantha 2024). Deep learning and machine learning have experienced rapid development in recent years, and these cutting-edge technologies have discovered widespread use in many different sectors, including aerospace, banking, healthcare, agriculture, and the military. These industries have shown a strong preference for models created using ML-techniques (Behera et al. 2019).

Despite the revolutionary potential of quantum computing and machine learning, their precise use in medical treatment remain unclear. Machine learning improves diagnostics, predictive analytics, and individualized treatment, while quantum computing is great at complex computations like medical imaging, genetic analysis, and drug discovery. It would be helpful to have more clarity on how quantum algorithms enhance machine learning models through faster data processing and healthcare workflow optimization (How and Cheah 2023). To better detect diseases, for example, quantum-enhanced neural networks can process medical data more quickly. Additionally, drug simulations are improved by algorithms influenced by quantum mechanics, which shortens research timelines. In order to demonstrate how quantum computing enhances the influence of machine learning on contemporary healthcare breakthroughs, it is necessary to establish this link. This will allow for a more coherent explanation (Jyothi 2022).

1.1 QC for healthcare

Cloud-based platforms and internet-connected services enable data exchange between Internet of Things (IoT) medical devices and healthcare systems. Quantum computers, with their enormous increase in processing capability, can enable huge advancements in medical services IoT and beyond (Gad et al. 2022). Moving from towards qubits could advance medicinal drug investigation, which contains studying protein collapse, determining the interplay between sub-atomic designs like catalysts and medications, determining the properties of binding connections amid a single biomolecule like DNA or protein &its ligand or inhibitor, and expediting clinical preliminary testing (Ahad et al. 2023). The following is a representation that briefly shows a couple of possible uses. Possibilities for personalized medicine are expanded by the fact that a QC can execute enormously fast DNA-sequencing. It can facilitate the development of new medications and therapies by way of detailed demonstration. Quantum computers may one day provide useful imaging frameworks that gradually offer doctors more granular clarity (Kumar et al. 2022). In addition, it can cope with intricate optimization problems related to creating an optimal radiation plan that kills dangerous cells without damaging surrounding solid tissues. With QC in place, subatomic connection research can begin at the most fundamental level possible, paving the way for tranquilize discovery and clinical study. It takes a lot of time to sequence a complete genome, but with the help of qubits, we can do it in a short amount of time and then analyze it (Zamzami et al. 2022).

The taxonomy encompasses studies that specifically addressed healthcare-related topics via quantum computing or hybrid quantum-classical techniques. Studies that did not meet the inclusion requirements have no bearing on healthcare applications from an empirical, theoretical, or architectural standpoint. Two separate reviewers coded the data, and when they found inconsistencies, they discussed and reached a consensus to fix them, guaranteeing consistency and replicability. Figure 1 shows the final structure that was formed after the taxonomy was further refined and validated through expert comments.

The existing medical services correspondence network is depicted in Fig. 1as having three layers: discernment, web, &cell organization. The primary function of structure is to provide quality of service to healthcare applications via clinical devices. Healthcare infrastructure, clinical sensors, hardware, patients, professionals, and health care workers are all examples of clinical devices that go into the discernment layer (Awan et al. 2022). The required processing power of these devices can be satisfied by connecting them to advanced framework stages, such as a distributed computing environment or a cell organization.

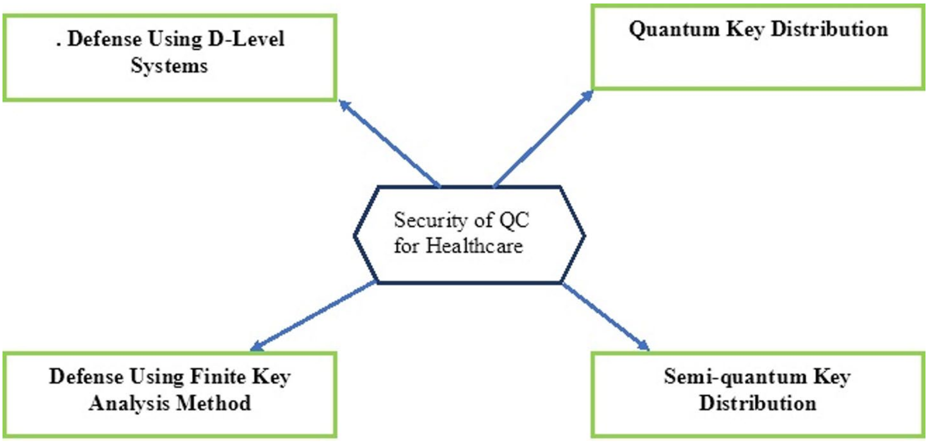

Fig. 1 Healthcare Communiqué quantum Network. (Source: Optical and Quantum Electronics)

Supersonic medicine, rapid genome sequencing and analysis, in silico clinical trials with pretend patients brought back to life, cloud-based emergency clinics, and the predictive security of patient data through quantum vulnerabilities are all possible outcomes of QC. The QC's role in medicine is unclear (Cherbal et al. 2024). Quality considerations are increasingly placing a premium on rapid diagnosis and precise treatment, while QC promises unmatched processing speed &power. Thanks to this new development, patient-centered care can be enabled by analyzing massive volumes of data related to healthcare services. Using QC, experts may be able to spot patterns and suggest studies or accessible medications. Super meds, highly transdermal patches, and very symptomatic technology can all benefit from using qubit innovation (Wenhua et al. 2023).

The use of qubits, which are entanglement-enabled and exist in superposition, allows for parallel computations beyond classical capabilities, setting QC apart from traditional computing. Quality Control uses quantum gates to function probabilistically, as opposed to the binary processing used by desktops or HPC clusters (Bonab et al. 2023). While QC still has a ways to go before it can compete with lab desktops for everyday activities, it's showing great potential in optimization and molecular simulations, two highly specialized fields. Prime factorization, quantum simulations, and combinatorial problems are areas where QC surpasses HPC Tier-1/2 clusters in theory. However, in practice, QC is not as dominant because to hardware limitations such as qubit instability and error correction. For data-heavy workloads, large-scale numerical simulations, and HPC, hybrid quantum-classical methods are becoming more popular, but for specialized applications, HPC is still the way to go (Gill et al. 2022). Improvements in the stability and scalability of qubits may allow QC to outperform classical supercomputers in some fields, however it is still not a replacement.

When we talk about "classical computing," we're referring to both desktop computers and HPC clusters, which include both Tier-1 and Tier-2 facilities. For some types of problems, where speedups of exponential or quadratic magnitude are conceivable, QC offers theoretical benefits over classical computers. These include probabilistic inference, quantum chemical simulations, combinatorial optimization, and data-heavy and parallelizable jobs. Qubit count, coherence, and error rate limitations mean that existing QC capabilities are restricted. This means that hybrid quantum-classical models will likely be the norm for most upcoming applications; in these models, classical HPC takes care of massive data management while QC is used for specific, computationally heavy subroutines.

With the help of QC, the clinical field is undergoing a transformation as new innovations reduce the burden of questionable treatments. Using quantum imaging technologies, one may see individual particles in stunning detail (Möller and Vuik 2017). A doctor can get help understanding the effects of medications via AI calculations powered by QC. Quantum calculations may be used to evaluate the efficacy of treatments, and artificial intelligence can aid in the detection of anomalies in the human body. In addition to requiring evaluation by a radiologist, standard X-rays can distinguish between bright and dark regions. However, quantitative imaging techniques can be tailored to different types of tissues, allowing for more accurate and precise imaging. Accurate medical diagnosis is now possible thanks to the QC architecture (Casino et al. 2019). Taking into account patient characteristics such as age, race, orientation, and genetics, they can use this data to provide therapies that are generally effective. In (Sáez-Ortuño et al. 2024), authors state that one area where these clever ideas could find utility is in drug discovery. Compared to current quantum techniques, subatomic frameworks made by quantum reenactment will be faster and more accurate. In addition, quantum AI algorithmic advancements provide exciting alternatives to traditional machine learning methods, which can also subsidize to the initial stages of drug-discovery.

Presented in a methodical fashion, this overview traces the development of QC and the technologies that have made it possible. It delves into the fundamental areas of use, sorts the needs for implementing it in high-performance healthcare systems, and emphasizes the security implications. To summarize, this survey primarily offers the following contributions:

- Including its drivers, prerequisites, uses, obstacles, designs, and unanswered questions, this is the first all-encompassing study of healthcare-related QC technologies.
- We go over the fundamentals of QC that will be necessary to establish quantum healthcare service providing.
- We evaluated the crucial role that QC plays in healthcare systems and spoke about the main areas of application for QC.
- Here, we take a look at the current research on QC and how it could help build healthcare systems of the future.
- The security concerns and essential requirements of QC systems for implementing healthcare service delivery on a big scale are discussed.
- We go over the present problems, what's causing them, and where the research has to go to solve them so that quantum healthcare systems may be implemented efficiently.

An outline of the article's structure is as follows. In Sect. 2, we reviewed the relevant literature and examined the works' contributions, as well as their pros and cons, with an emphasis on the core technology they used. In Sect. 3, the essential conditions for QC to be used to the delivery of healthcare services on a wide scale are discussed. In Sect. 4, we present a taxonomy and outline various approaches to healthcare architectures that include QC. The present state of QC systems' security designs is covered in Sect. 5. The present state of open questions, their origins, and potential avenues for further investigation are covered in Sect. 6. Section 7 serves as the paper's last section.

2 Related works

This field has been the subject of substantial inquiry by a large number of scholars. There is a large amount of prior research on QC (Saeed et al. 2022). In order to give a thorough understanding of the vast groundwork done in the area of QC for drug development &discovery, this section tries to give brief descriptions of important previous publications and research articles.

2.1 QC in drug discovery

For a high-level summary of what goes into developing and designing a medication in (Pal 2023)Quantitative structure-activity relationships(QSAR), molecular-docking, and quantum modeling are some of the processes in their research. Their study delves into the ways in which quantum computers can integrate medicinal chemistry, bioinformatics, and cheminformatics in a clear and accurate manner (Osama 2023). One unique aspect of this strategy that distinguishes it from more conventional approaches to drug development is the focus on quantum simulations for molecular system identification, as pointed out by (Kumar et al. 2024). In addition, they back the idea that quantum simulation &machines should use a hybrid quantum-classical method to create a fault-tolerant system that can overcome the constraints of existing quantum computers' development stage. According to (Brijwani 2023), the QC's evolutionary iterations greatly improve genetic algorithm development. An examination of the complementary nature of quantum theory and genetic programming is presented in this work. Quantum computers, on the one hand, provide more computational power, while genetic programming adds a genuine random component (Shaker 2023). Combining the two areas paves the way for more sophisticated and effective approaches to tackling problems. In the review of QC to focus on its architecture, applications, and the potential effects on privacy and security, as well as its quantum needs and the machine learning components of healthcare (Imran et al. 2021). We should talk about other polls that take into account some of these variables but not all of them. This study's findings are compared to those of various surveys in Table1.

2.2 QC in machine learning

In order to address the computational limits of conventional systems, in (Yagi et al. 2023), authors examine methods based on superposition and quantum entanglement. On the other hand, the survey covers complicated quantum physics without delving into the societal consequences of this field in general. They also examine the Internet of Things (IoT) resource constraints and propose a quantum cryptography-based solution. To address security vulnerabilities in the Internet of Things (IoT), they create a solution based on edge computing and management software. The problem is that this study is narrowly focused on security issues. In order to facilitate the application of QC to the processing of information capabilities. This method uses quantum channel capabilities to accomplish traditional information processing (Egger et al. 2020). These include theories of quantum learning, works on quantum information security, works on QML, and works on quantum data-analytics (Coccia 2024). QC applications are under-researched in these surveys. The effects of implementing QC have been the subject of some of the previously published works. In their analysis of quantum cryptography systems, authors of (Williamson and Prybutok 2024)focus on the execution vulnerabilities. Regarding wireless communication, they drive into quantum search techniques. In order to address the difficulties associated with communication, in (Srirama 2024) authors suggested a layered abstraction and reviewed the current state of quantum distributed solutions. A large number of these surveys either completely ignore healthcare or just touch on it in passing.

2.3 QC in healthcare security

Conventional IT infrastructures are ill-equipped to handle the deluge of healthcare data generated by various sources (e.g., patient records, medical devices, service applications, studies, etc.). When applied to the healthcare industry's massive data and operations, QC seems to be a game-changing, innovative technology (Ahmad et al. 2023). Various diverse systems carry out separate but interdependent tasks within the healthcare business as a whole (Sood et al. 2022). Scientific, clinical, and commercial groups often interact in complex ways to produce new theories and information. The four main parts of a healthcare ecosystem, according to (Mbunge et al. 2021), are delivery, financing, policymaking, and innovation. The government as a policymaker, payers, service providers, and patients are the four main groups with vested interests in the healthcare industry. According to the available literature (Hassija et al. 2020), the innovation and spread of new technical foundations in the healthcare business are greatly influenced by institutional regulation and policymaking.

Healthcare expenditure in rapidly developing nations is expected to surge by a factor of 2.2, according to the World Health Organization (Gezimati and Singh 2023). Typically, private companies are the ones that come up with models for technical innovation. But when it comes to medical innovation, there are a lot of players, and the outcome usually hinges on lawmakers, user feedback, and scientific testing (Chen 2022). The policies of each country's government will also have an impact on this development. For example, research has shown that blockchain technology can be used to store and transfer data among various healthcare providers, including hospitals, clinics, labs, pharmacies, and insurance companies, all with the goal of improving patient care and satisfaction. To go a step further, research (Kumar et al. 2021)shows that healthcare app purchases and service consumption are value drivers. The majority of the available literature has concentrated on the many facets of healthcare component interactions. A rapid and accurate care system is required because of the intricacy of the human body and the complexity and unpredictability of the healthcare industry (Olatunji 2021). Consequently, we're going to talk about the function of technology integration in the healthcare industry and its interconnected ecosystem.

2.4 Limitations of the QC in healthcare

First and foremost, there are technical limits to healthcare QC, such as the need for extremely low temperatures and complicated error correction, which in turn make the technology costly and difficult to maintain. Computational mistakes can occur due to noisy qubits' propensity for decoherence (Chaudhary et al. 2022). Most healthcare models are built for traditional systems, which makes algorithm creation a difficulty. Managing massive medical datasets efficiently is hindered by the scarcity of qubits. The potential for QC to circumvent current encryption systems raises concerns about data security. Dependence on classical

Table 1 Summary of the works related to QC in healthcare

Title of the work	Description of the work	Dataset Used	Methodology	Outcomes of the work
Quantum Computing for Drug Discovery (Shuford 2024)	An overview of how quantum computing is revolutionizing drug discovery processes.	Drug molecule databases	Utilizes quantum algorithms to model molecular interactions and predict drug efficacy.	Improved accuracy in drug efficacy predictions and faster identification of potential drug candidates.
Advancements in Quantum Machine Learning for Genomics (Dedeturk et al. 2021)	Exploration of quantum machine learning techniques applied to genomics.	Genomic sequences from public repositories	Implements quantum neural networks to analyze large genomic datasets.	Enhanced ability to identify genetic mutations and disease markers.
Quantum Algorithms for Optimizing Radiotherapy (Olorunsogo et al. 2024)	Development of quantum algorithms aimed at optimizing radiotherapy treatments.	Patient treatment plans and radiotherapy outcomes	Designs quantum optimization algorithms to enhance treatment planning.	More efficient and effective radiotherapy treatment plans.
Quantum Computing in Medical Imaging (Gill et al. 2024)	Innovative applications of quantum computing in enhancing medical imaging techniques.	Medical imaging datasets (CT, MRI, etc.)	Applies quantum image processing techniques to improve image resolution.	Higher resolution medical images, leading to better diagnosis.
Applications of Quantum Computing in Bioinformatics (Padhi and Charrua-Santos 2021)	Analysis of the impact of quantum computing on bioinformatics research.	Biological data from bioinformatics databases	Uses quantum algorithms to analyze biological data and identify patterns.	Improved pattern recognition in biological data, leading to new discoveries.
Quantum-enhanced MRI Techniques (Coccia and Roshani 2024)	Enhancements in MRI techniques through the application of quantum computing.	MRI scans from clinical trials	Develops quantum-based techniques to improve MRI signal-to-noise ratios.	Clearer MRI images with reduced noise, improving diagnostic accuracy.
Quantum Computing for Personalized Medicine (Ullah et al. 2023)	Application of quantum computing in developing personalized medicine strategies.	Patient health records and genetic profiles	Uses patient data to model personalized treatment plans via quantum simulations.	More tailored and effective treatment plans for patients.
Quantum Cryptography for Healthcare Data Security (Alfa et al. 2021)	Utilization of quantum cryptography to ensure healthcare data security.	Healthcare data archives	Implements quantum key distribution to secure sensitive medical data.	Enhanced security of healthcare data, reducing the risk of data breaches.
Quantum Machine Learning in Predicting Disease Outcomes (Singh 2024)	Quantum machine learning models used to predict disease outcomes.	Electronic health records (EHRs)	Employs quantum support vector machines to predict patient outcomes.	Increased accuracy in disease outcome predictions, aiding in treatment planning.
Quantum Computing for Genomic Data Analysis (Farouk et al. 2020)	Application of quantum computing for analyzing large genomic datasets.	Large-scale genomic datasets	Uses quantum algorithms to process and analyze genomic sequences.	Faster and more accurate genomic data analysis.

Table 1 (continued)

Title of the work	Description of the work	Dataset Used	Methodology	Outcomes of the work
Quantum Computing in Protein Folding Simulations (Adnan et al. 2022)	Simulating protein folding processes using quantum computing.	Protein structure databases	Models protein folding pathways using quantum Monte Carlo simulations.	Better understanding of protein folding mechanisms, potentially aiding in disease research.
Quantum Computing for Accelerated Drug Design (Lakshminarayanan et al. 2023)	Accelerating the drug design process with quantum computing technologies.	Chemical compound libraries	Utilizes quantum chemistry to accelerate the drug discovery process.	Reduction in the time required to design new drugs.
Quantum Computing in Health Data Analytics (Zaman 2022)	Analyzing healthcare data with the power of quantum computing.	Healthcare analytics datasets	Applies quantum machine learning to extract insights from health data.	Improved insights from healthcare data, leading to better patient outcomes.
Quantum Computing for Complex Biological Systems (Nawaz et al. 2019)	Modeling complex biological systems using quantum computing.	Biological systems simulation data	Uses quantum simulations to model and analyze complex biological interactions.	Enhanced understanding of complex biological systems.
Quantum Neural Networks in Healthcare (De Alwis et al. 2021)	Development of quantum neural networks for healthcare applications.	Medical imaging and patient records	Develops quantum neural networks for enhanced predictive analytics in healthcare.	Improved predictive analytics, leading to better diagnosis and treatment plans.
Quantum Computing for Big Data in Healthcare (Munjal and Bhatia 2023)	Handling big data challenges in healthcare using quantum computing.	Healthcare big data repositories	Utilizes quantum computing to process and analyze large healthcare datasets.	More efficient processing of large healthcare datasets, leading to better insights.
Quantum-assisted Diagnosis Systems (Lu et al. 2023)	Quantum-assisted systems to improve diagnosis accuracy.	Diagnostic test results	Implements quantum algorithms to enhance diagnostic accuracy and speed.	More accurate and faster diagnoses.
Quantum Computing in Biomedical Research (Ali et al. 2023)	Broad applications of quantum computing in biomedical research.	Biomedical research data repositories	Applies quantum techniques across various biomedical research areas.	Wide range of improvements in biomedical research methodologies.
Quantum Algorithms for Precision Medicine (Veena 2023)	Creating precise medical treatments through quantum algorithms.	Precision medicine datasets	Develops quantum algorithms to tailor treatments to individual patient profiles.	More precise medical treatments tailored to individual patients.
Quantum Computing for Healthcare Logistics (Yagi et al. 2023)	Optimizing healthcare logistics with quantum computing.	Healthcare logistics data	Uses quantum optimization algorithms to improve healthcare supply chain efficiency.	More efficient healthcare logistics and supply chain management.

infrastructure creates integration issues. Both acceptance and scalability are hindered by the absence of standards. Medical apps face hurdles in approval due to ethical and regulatory concerns. The use of QC is restricted to prestigious universities due to its high cost and limited accessibility. Finally, the practical benefits are still up in the air, so any real-world healthcare applications are still in the realm of theory (Admass 2023).

In theory, quantum algorithms can speed up some issues by an exponential or quadratic factor; nevertheless, the actual benefits of these algorithms vary depending on the problem and the surrounding circumstances. For example, Grover's algorithm offers a quadratic speedup for unstructured search problems, and Shor's approach brings integer factorization down from sub-exponential classical time to polynomial time on a fault-tolerant quantum computer. To simulate tiny molecules like hydrogen (H_k) with less computing complexity than complete configuration interaction approaches on classical systems, Variational Quantum Eigensolver (VQE) has been investigated in the healthcare setting. Low qubit counts, short coherence times, and noise make it difficult to exploit these speedups at scale today, so these advantages remain essentially theoretical. The use of quantum algorithms in clinical or large-scale biomedical contexts is still in the future, despite its promising future.

2.5 Taxonomy development process

QC for healthcare taxonomy development entails grouping concepts to classify advances in this interdisciplinary field. First, domain identification defines medication discovery, diagnostics, genetic analysis, and hospital optimization. To uncover key concepts, data collection collects literature, research, and expert insights (Zhao et al. 2024). Quantum techniques (e.g., quantum machine learning, variational quantum eigensolvers) and healthcare applications (e.g., oncology, neurology, customized medicine) are then hierarchically categorized (Chavhan 2022). Consistent classification rules prevent overlaps. Professional evaluations and iterative changes validate and improve the taxonomy before implementation and documentation for research and policymaking. A good taxonomy improves systematic analysis, research organization, and quantum-driven healthcare solution scalability (Rejeb et al. 2023).

3 Methodology

Having a search strategy that is well stated, having specified inclusion and exclusion criteria, having a screening procedure that is transparent, and having a study design that is well-justified are all components of a solid research methodology. This guarantees that the study is targeted, thoroughly conducted, and generates results that can be relied upon. The methodology section should provide specifics regarding the process of identifying the relevant literature, the categories of research that were deemed eligible, and the procedures that were followed in order to choose the studies.

3.1 Search strategy

A comprehensive search was conducted in PubMed, Scopus, IEEE Xplore, and Web of Science using keywords such as “Quantum Computing”, “Healthcare”, “Applications”, “Challenges”, and “Systematic Review”, limited to articles published between 2015 and 2025.

3.1.1 Inclusion criteria May include

- Peer-reviewed articles.
- Studies focusing on applications of quantum computing in healthcare.
- Articles published in English.
- Research articles, reviews, and conference papers.

3.1.2 Exclusion criteria May include

- Non-English papers.
- Abstracts without full-text.
- Opinion papers, editorials, or white papers without empirical data.

3.2 Screening process

Part one of the screening process involved looking over the titles and abstracts, and part two involved reading the entire texts. Following the established inclusion and exclusion criteria, two separate reviewers determined whether or not each of the included studies met the inclusion and exclusion criteria. When two reviewers couldn’t agree on anything throughout the selection process, they talked it out and, if that didn’t work, they brought in a third party to help them settle it. The accuracy of the final dataset was guaranteed by utilizing reference management software to detect and eliminate duplicate records. This methodical procedure helps filter out studies that didn’t have much to do with the area where quantum computing and healthcare meet.

3.3 Study selection and PRISMA flow diagram

The PRISMA 2020 framework influenced study selection. To demonstrate study selection, the manuscript includes a thorough PRISMA flow diagram (Fig. 2). This graphic shows the number of database searches, duplication removal, studies eliminated following title and abstract screening, and full-text publications reviewed for eligibility. The number of studies in the review is clearly stated, exhibiting methodological rigor and transparency in the selection process.

3.4 Data extraction and synthesis

This review used a standardized data extraction form to extract data from chosen research. Publication details, study aims, quantum computing approach or model, healthcare applica-

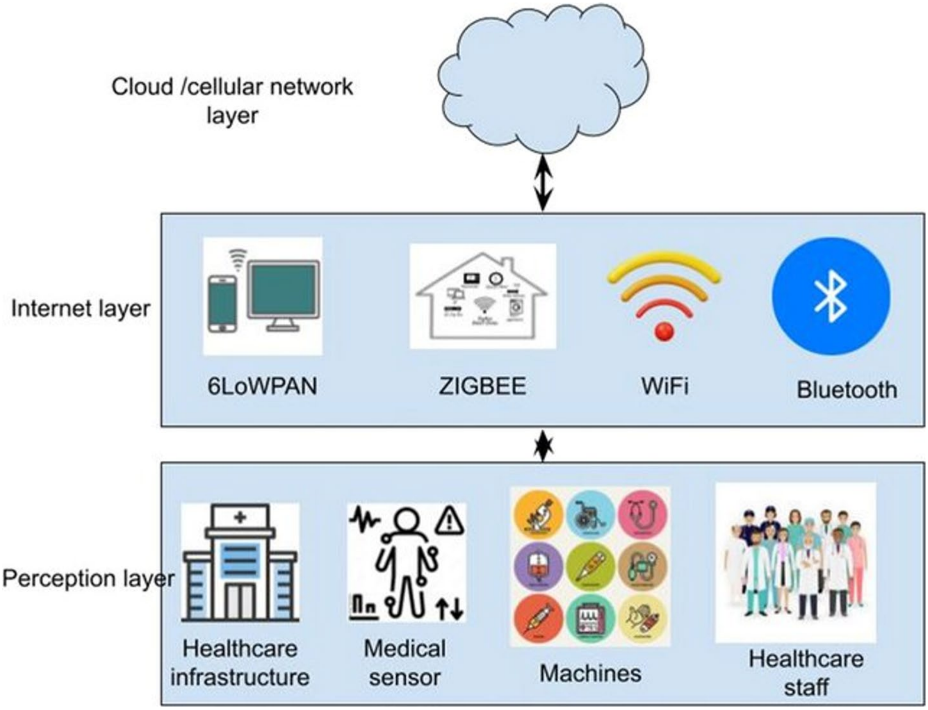

Fig. 2 PRISMA flow diagram on the literature review strategy (Haddaway 2022)

tion, main findings, limitations, and future directions were collected. Themes and patterns from the selected papers were categorized and analysed using a qualitative synthesis. This narrative synthesis led to an integrated view of current research and identified research gaps and potential for future study in this interdisciplinary field.

3.5 Justification of study design

Because quantum computing applications in healthcare need a detailed and methodical examination, this work used a systematic review design. The topic is novel and interdisciplinary, therefore investigations differ in focus, scope, and methodology. A systematic approach aggregates and synthesizes scattered facts to provide a cohesive perspective of technological advances, practical implementations, and obstacles. This architecture is ideal for identifying trends, consolidating knowledge, and identifying opportunities for additional research in quantum computing and healthcare innovation.

PRISMA flowchart represented in Fig. 2, which visually outlines the study selection process for a systematic review, detailing records identified, screened, excluded, and included. It ensures transparency and reproducibility by documenting the inclusion/exclusion criteria and the number of studies at each stage.

While assumptions and simulations might help us anticipate the future, unforeseen events like pandemics are notoriously difficult, if not impossible, to foretell. Nevertheless, healthcare providers are anticipating that QC may provide answers to issues that are now intractable for computers (Alzoubi et al. 2022). These include, but are not limited to, genome sequencing, the discovery of novel pharmaceuticals and materials, and the rapid development of vaccines and treatments. In addition, healthcare systems with complicated information management and clinical operations generate massive amounts of data, which in turn spurs technical advancements in the healthcare sector (Prateek et al. 2023). According to the research (Dadhich 2022), healthcare executives have already done a lot of testing with DARQ technologies, which are going to have a huge revolutionary effect on the business in the next years. Biogen, Accenture, and 1QBIT are working together to build a cutting-edge quantum-enabled molecular comparison application. The goal is to enhance advanced molecular design and accelerate the discovery of drugs for complex neurological disorders (Yulianti and Surendro 2022).

4 Necessities of QC for healthcare

There are a number of medical applications where quantum-enhanced computing has the potential to reduce processing time. Nevertheless, the needs of healthcare-related QC cannot be applied universally. To illustrate the point, systems for vaccine development and drug discovery are distinct. Consequently, there are a lot of things to think about when implementing QC in healthcare.

4.1 Computational power

A crucial need for any healthcare application is a low computational time. When it comes to complicated healthcare concerns, like molecular structure simulation, traditional computers with CPUs and GPUs just can't cut it. Because of this, QC, which can model enormous problems utilizing massive quantities of multidimensional spaces, is essential. Searching through a list of objects is made easier with Grover's-search-algorithm, which is a well-known example of the capabilities of QC. If we wish to pursuit through a ton's objects, and each piece takes one ms to check, then a quantum computer will only need one second (Ray et al. 2019).

4.2 High-speed connectivity

One of the most important technologies for linking smart medical devices is fifth-generation (5G) connectivity. In addition to a massive capacity, it offers very low latency, increased bandwidth, and very durable integrity. Data transfers to edge/cloud infrastructure are essential to the operation of IoT objects (Pal 2023). New concerns about data availability integrity and secrecy have arisen as a result of cloud storage's security flaws which impact users directly. With the help of 5G/6G networks QC can offer new services. For effective healthcare paradigmShifts, quantum walks provide a universal processing model with built-in cryptography capabilities. To create new quantum algorithms and protocols that function on top of ultra-fast 5 G/6G networks, researchers have turned to mechanical versions of classic random walks called quantum walks (Soni 2020).

4.3 Quantum communications networks

One aspect of quantum technologies, known as quantum communication, focuses on how to use different quantum states of light to complete specific communication tasks. In recent times, there has been a rise in interest in the possible commercial uses of QC. Together, these features hold the potential to enable the ideal secrecy protocol that can withstand external attacks, and QKD makes private communication possible by letting distant entities share a secret key. In order to achieve network security, synchronization, and computing with quantum enhancements. The standardization of the quantum Internet is being overseen by Qirg, an IETF research group dedicated to the topic (Rejeb et al. 2024).

4.4 Higher-dimensional quantum communication

Contemporary trends in technology have had a significant impact on quantum information. There has been a recent uptick in research on high-dimensional quantum states, particularly as they relate to quantum communication. A huge amount of information may be stored in Hilbert space, and it is also resistant to noise. A combination of integrated photonics &bulk optics was also utilized by the authors to investigate "multiple photonic degrees of freedom for generating high-dimensional quantum states" in (Behera et al. 2019). To facilitate the transmission of the quantum states, many channels were constructed, including single-mode, free-space links, underwater channels, multicore, and multimode-fibers.

4.5 Fault tolerance

Given the delicate entangled nature of the components' connections, fault tolerance is of the utmost importance in quantum computers. This results in highly accurate quantum calculations by making quantum computers resilient and introducing methods to address quantum problems. Because of this, quantum computers can handle calculations that were previously too difficult for classical computers to handle (Kamalov et al. 2023). But systems relying on those calculations are very vulnerable to processing errors, whether they occur in the qubit itself or in the technique used to measure it. There are serious problems with the mechanism of error correction. Using auxiliary qubits to monitor qubits—which continuously evaluate logical flaws for rectification and detection—is a possible technique to monitor these systems (Khan 2023). Although auxiliary qubits have demonstrated encouraging results thus far, mistakes in these components could cause qubit faults, which in turn could cause even more operational defects. It is possible to insert error correction code among the qubits, which would enable the system to fix the code in the event that any bits are incorrect (Nguyen et al. 2023).

4.6 Quantum obtainability of the healthcare systems

Close closeness to the equipment is required for computation in conventional systems. Nevertheless, quantum computers are situated at a considerable distance from the actual users. Because of the difficulty in accessing virtual machines hosted on quantum-computers, it is imperative to address the availability requirements of these machines with caution when considering sharing virtual machines (Srivani et al. 2023).

4.7 Deployment of quantum gates

The utilize of quantum gates is necessary for multilayer QC. Every quantum gate in this scenario is responsible for carrying out a unique operation on the quantum systems. Hardware limitations, make it difficult for a particular quantum system to synchronize with multiple gates at the same time (Shaikh 2024), which is why quantum gates are used in various QC applications. In this model, coupling topology is necessary; for instance, qubit-to-qubit coupling based on the reliability of the gates intricate to determine the depth of the circuit (Fateh 2024).

4.8 Use of distributed topologies

Because quantum states are physically far apart, dispersed topologies could allow for the realization of large-scale quantum computers. In a distributed topology, quantum algorithms (such as error correction) are executed by quantum computers and communicated across a quantum bus. In order to implement quantum error correction, distributed computation, and communication, a unified infrastructure and communication protocol are necessary (Kassab et al. 2019). Any arbitrary quantum hardware can be managed using communication protocols with the help of a system area networks paradigm (Shamshad et al. 2022).

4.9 Quantum machine learning

Given the novelty of quantum artificial intelligence and QML, it is important to conduct needs assessments in these areas from the vantage point of experimental quantum information processing. The use of superconducting quantum circuits for the execution of fundamental protocols was investigated in (Durant et al. 2024). Computing and quantum information processing are made possible through the use of superconducting quantum circuits. Utilizing DL for low-dimensional binary data is their suggested method. This method is mostly for training unsupervised models and works well with small-scale quantum processors. The other forms of quantum machine learning are further discussed in this study when applied to actual clinical data (Nagpal et al. 2024).

Here, we lay forth some new criteria for implementing QC in healthcare settings. The use of QC in healthcare necessitates taking into account the varied needs of various infrastructures. In order for quantum healthcare systems to work, existing healthcare infrastructure needs to be modernized to accommodate the enormous processing capacity offered by quantum computers (Ghosh et al. 2023).

5 QC architectures for healthcare

This part provides a synopsis of the research that has gone into designing QC architecture with healthcare in mind. To kick off this section, we will first give a high-level summary of the overall architecture of quantum computers.

5.1 Quantum algorithm design for healthcare applications

If there aren't enough algorithms tailored to quantum computers for healthcare applications, scientists won't be able to take advantage of their fast development in this area to create treatments that save lives. Using a combination of classical and QC, most modern quantum algorithms are hybrids (Umapathy 2023). It is critically important to develop hybrid algorithms for use in healthcare applications. They enable these applications to take advantage of quantum hardware, which is computationally superior, first and foremost. Pure quantum algorithms will be the end result of a gradual evolution of hybrid and quantum-inspired methods as the science progresses. Pure quantum procedures are the ultimate goal, while hybrid and quantum-inspired approaches are only natural progressions along that path (Asghar et al. 2022).

A quantum algorithm was created in (Kumar 2022)to expedite the clinical extrapolative investigation of COVID19 patients. They made use of the expanding family of algorithms known as QML, which originated in the theory of QC. To take advantage of resolution parallelism and optimum constraint cracking with Moore's law, the plan is to use QC for machine learning jobs. In order to address the issue of healthcare deadline scheduling, authors of (Alauddin et al. 2021), developed a multi-objective QC genetic-algorithm. The reason behind this is because serious problems, like patient harm or death, could arise if healthcare applications were to be late. Directed cyclic graphs (DAGs) are used to describe healthcare applications in the suggested algorithm. To ensure QoS, each step of the workflow is a deadline in and of itself (Sanka et al. 2021).

Several major projects are underway with the goal of developing healthcare-related software based on quantum algorithmic research. Pharmaceutical research and development have received GBP8.4 B from the UK to build a QC-platform (Akhai and Kumar 2024). Numerous medicinal companies are teaming up with QC research groups to use QC-algorithms in drug-discovery. To combat brain diseases like Alzheimer's, for example, the biotech firm Biogen (Suhail et al. 2020) is employing the skill to create new potential treatments.

5.2 QC frameworks for healthcare

In the literature, one can find several approaches that are based on QC. One example is the logistic regression health assessment model put out in (Ezugwu et al. 2023)that makes use of quantum optimum swarm optimization in order to identify various diseases in their early stages. In order to come up with a visualization, reviewed previous work (Arshad et al. 2023)that used 3D methods for quantum-imaging in photon-starved environments. A project was suggested in (Gupta et al. 2023)that would use cloud-based quantum computers to analyze electronic healthcare data using natural language processing. The authors of (Pattnaik 2020) came up with the idea of "Aptamers for Detection and Diagnostics (ADD)" and created a smartphone app that could detect SARS-CoV-2 by analyzing optical data collected by conjugated quantum nanodots.

5.3 Secure QC for healthcare

For telehealth systems, authors of (Batista 2023), suggested using quantum blocks for encryption and scrambling; their method has two layers of safety that are activated by choosing a preliminary seed value for encryption. Protected more effectively from differential and statistical attacks is the suggested system (Paul et al. 2021). On the other hand, while performing complicated quantum cryptography computations, the suggested system generates a tremendous amount of overhead. For the purpose of controlling who has access to crucial data within the Big Data paradigm (Omolara et al. 2022), a quantum digital signature that incorporates all three parties involved in the signing process: the sender, the recipient, and the arbitrator. The authors of (Kumar et al. 2019), didn't suggest a brand-new quantum computer; instead, they put a quantum protocol into action that doesn't increase network overhead. But this plan doesn't account for private information that travels from sender to receiver as part of the planned quantum computer deployment (Mysore 2022).

A recent study (Awan et al. 2022)suggested a blockchain-QC hybrid framework for the security of electronic health records, with blockchain serving to authenticate users and grant them permission to access data in a controlled manner. However, because to the massive network overhead created by QC and blockchain infrastructure, the suggested system's performance degrades (Batista 2023). Hence, prior to the system's real deployment, its performance should be intuitively evaluated. In their work (Batista 2023), authors introduced two unique methods for concealing quantum information: quantum picture watermarking and quantum steganography. A system for managing quantum keys with almost no overhead has been proposed (How and Cheah 2024). But there's no way to tell how effective this plan is without comparing it to other methods.

6 Security of QC for healthcare

It is of the utmost importance to guarantee the security of healthcare applications since they are basically life-critical. However, healthcare institutions' inherent silos prevent innovation, data sharing, and systematic advancement, which poses a significant barrier to healthcare researchers (Nguyen and Voznak 2024). Additionally, prominent cybersecurity expert and Quantum Security Alliance chair Chuck Brooks argues that successful security implementation should enable productive collaboration among governments, businesses, academics, and researchers (Bhavin et al. 2021). Given that QC has the potential to provide exponential improvements in computing capacity, putting present cryptographic-based systems at risk, ensuring the security of such a system is of the utmost importance. QC with cryptography takes advantage of classical-cryptography and quantum mechanics to provide unrestricted security for both ends of healthcare communiqué, while cryptography has been thought of as the theoretical foundation for healthcare information security (Lu 2019). One of the earliest commercially available applications of QC is quantum-cryptography. Instead of relying on complicated computing assumptions that have not been verified, quantum cryptography relies on the basic principles of mechanics. Figure3 is showed an overview of the healthcare information security taxonomy.

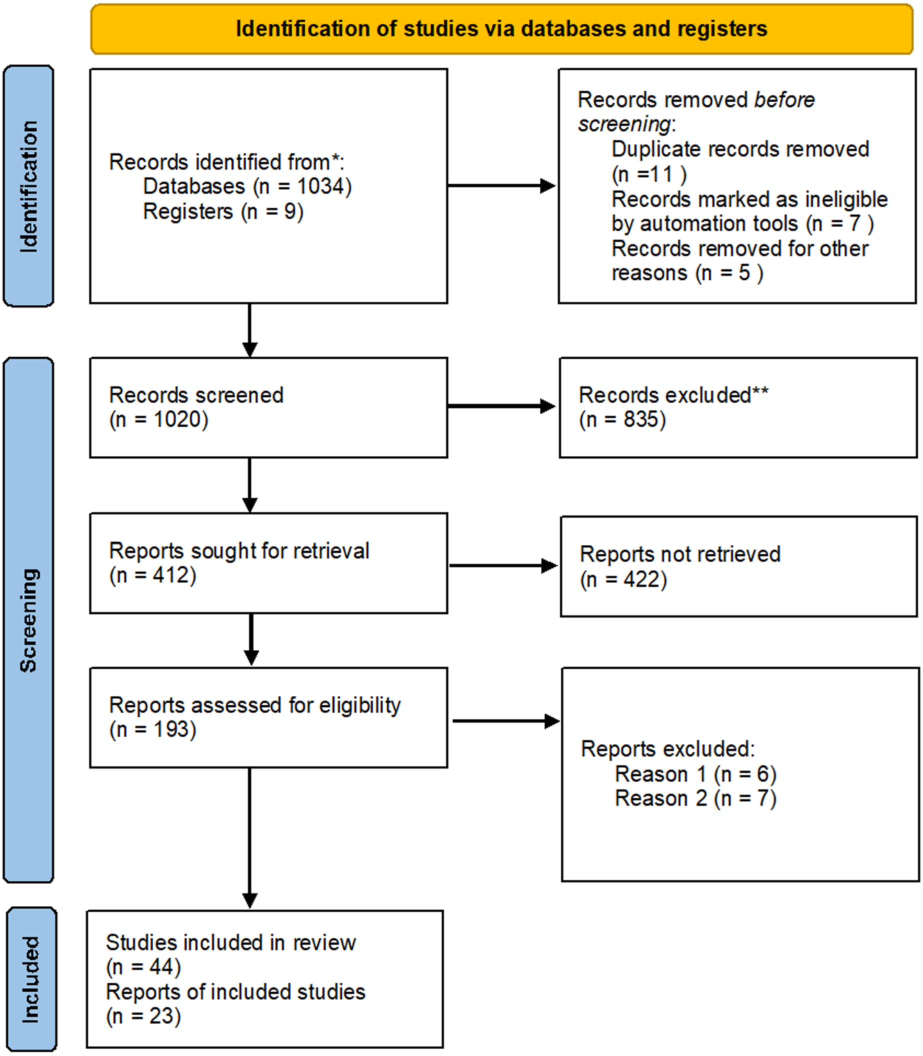

Fig. 3 Security taxonomy of healthcare systems

6.1 Quantum key distribution

To authorize two components, a mechanism called quantum-key-distribution(QKD) distributes a key that both parties agree upon, ensuring safe transfer. In order to identify attacks that attempt to extract sensitive information, the QKD protocol makes use of specific quantum rules, which are typically derived from the intricate features of QC (Shaikh et al. 2023). To be more precise, QKD uses the traces that an attacker leaves behind when they try to steal the data to identify attacks. QKD permits the creation of keys of any length and will halt the operation upon detection of an attack. It devised the first QKD technique, BB84, and it is most utilized method in hypothetical QC-research (Banerjee 2020). When it comes to addressing critical distribution and management restrictions in traditional algorithms, QKD shows tremendous promise. By connecting the security to the quantum error correction code and the entanglement purification protocol, authors of (Trenfield et al. 2022) demonstrated the BB84 method. In order to facilitate key sharing between communicating entities in wireless body sensor networks used for remote patient health monitoring, authors (Patil et al. 2020)proposed QKD based on an improved version of the BB84 protocol. Their findings show that the method aids in protecting the detected data when it is sent from the sensor network to the doctor. For diverse medical equipment, developed an improved QKD method. An authorized third party sets up a quantum channel for communication, and the key-server sends out an encryption-key in qubit form over the channel (Jawad et al. 2023). The QKD security protocol has been the subject of much study in the academic literature, leading to various innovative enhancements to the QC security paradigm.

A real-world application of Quantum Key Distribution (QKD) in healthcare is its implementation in secure medical data transmission. In 2020, China's Anhui Medical University piloted a QKD-based telemedicine system, ensuring ultra-secure communication between hospitals for patient data sharing and remote diagnostics (Tanwar et al. 2019). Using quantum-entangled photons, the system prevented eavesdropping and cyberattacks on sensitive medical records. This enhanced security framework was crucial for protecting patient confidentiality while enabling seamless collaboration between specialists across different locations. Such implementations demonstrate the potential of QKD to revolutionize healthcare cybersecurity, safeguarding medical data against quantum-era threats (Gardašević et al. 2020).

6.2 Defense using D-level systems

Due to its greater data transfer rates, which are necessary for next-generation medicinal sensors, quantum D-level devices are appealing to the healthcare industry. Take implanted brain-machine interface devices as an example; these send massive amounts of neural data by way of thousands of cathodes that track brain tissue in various cortical levels (De Felice and Petrillo 2021). Improving error resistance and increasing the transmitted key rate are two goals of the d-level protocols in relation to QKD. To prevent both simultaneous and individual attacks, the authors of (Al-Ghuraybi et al. 2024)used d-level systems. Both systems were presented, one using $d+1$ concurrently unbiased basis and the other using two mutually unbiased bases. Protocols using entangled photons have shown proof of security against individual attacks (Rani et al. 2023). The problem with this method, though, was the higher mistake rate it introduced. For BB84 in situations with a high loss rate, the authors suggested using the decoy pulse technique in (Arif et al. 2023). Instead of signal pulses, a privileged user uses multiphoton pulses. In (Usmani 2022), the security proof of the coherent-state protocol is given, which uses homodyne detection and Gaussian-modulated coherent state to protect it from arbitrary coherent assaults. Protecting quantum channels from common assaults that eavesdroppers with high computing power could launch is the goal of the authors of (Thomson and Beale 2021). The more generalized version of this analysis was later expanded upon in (Purohit et al. 2024). In (Pulicharla 2023), we see an example of a passive security method that successfully separates each input pulse by means of a beam splitter.

Numerous security vulnerabilities exist in a system that depends on QC for processing &security in healthcare. Some examples of these attacks are protocol, denial of service, authentication, exchange, man-in-the-middle, and interception. To protect QC systems against various broad-spectrum assaults, we detail current defensive strategies in this section. For example, in their defense plan for BB84 (Rodríguez-Mazahua et al. 2016). A protective approach for more quantum protocols with key generation by independent measurements was proposed in (Adel 2022). In (Yang et al. 2022), we see a comparison of secret keys that break Bell inequality. The authors argued that eavesdroppers should only have access to information that complies with the nonsignaling criterion.

Regarding "the security of Gaussian continuous variable QKD with coherent states against arbitrary attacks in the finite-size scheme," In (Vaissnave 2024), authors conducted an evaluation. Similarly, in (Valdez and Melin 2023), they have up a procedure for assessing the safety features of an applicable distributed-phase-reference QKD in the face of generic assaults. In (Vásquez-Iturralde 2024), an orthogonal frequency division multiplexing system is proposed as a foundation for the continuous variable QKD. A technique "to prove the security of two-way QKD protocols against the most general quantum attack on an eavesdropper, which is based on an entropic uncertainty" relation was proposed by the authors in (Ibegbulam et al. 2023). The authors of (Hassija et al. 2020) provided a detailed description of Eckert's initial entanglement protocol's stance with respect to a broad category of assaults.

6.3 Defense using finite key analysis method

Incorporating the finite key analysis method into the composable unrestricted security proof, QKD has recently gained popularity as a security scheme. In several real-world BB84 contexts, such as those involving entanglement-based methods and prepare-and-measure implementations without decoy states, the authors of (Al-Saggaf et al. 2023) try to solve the security restrictions of finite-length keys. Likewise, in order to achieve a key rate higher than that of a full-device-independent QKD, the finite-key analysis of MDI QKD as described in (Agrawal 2023) first has to exclude the main detector channels. Presented in (Alamri et al. 2022) is the security proof for the finite-key regime against the general form of assaults. Within a certain time, constraint for signal transmission, the authors demonstrate the practicability of MDI QKD implementations over vast distances. In (Tuli et al. 2020), we see a realistic, resource-constrained, somewhat device-independent BB84 protocol for preparation and measurement. In (Pashazadeh and Navimipour 2018), we see the results of a security analysis that was run in response to the potential exposure of confidential information through preparation-related communications.

By ignoring the inner workings of the quantum device, DI QKD (Porambage et al. 2021) hopes to bridge the gap between theoretical and actual QKD implementations. It can offer more security than classical systems while reducing security assumptions. On the other hand, it is necessary for the receivers of the information on either end to detect the violation of Bell inequality. The fact that gathering data about the underlying hardware is unnecessary is what DI is all about (Ahmad et al. 2023). Here, the gadget may stand in for enemies. Consequently, element identification is more important than thinking about the implementation of quantum security (Valle-Cruz 2024). Here, DI QKD can protect against a variety of security flaws. Furthermore, the method described in (Chen et al. 2014) can be used to protect security vulnerability identification that is produced by quantum communication channels.

The goal of proposed work (Trivedi et al. 2023), for key sharing between two valid remote operators by proposing a device-independent measuring scheme. When contrasted with DI-QKD, MDI-QKD offers a number of additional benefits. Due to the successful elimination of detector channel weaknesses, MDI-QKD achieves a higher real key rate compared to DI-QKD. In addition, in order for the communication to work, neither party needs to do any form of measurement; all that is required is the transmission of quantifiable signals (Lu 2021). Here, it is not necessary to regard the two ends of the communication as black boxes in order to conduct measurements. This has the potential to make the QKD standardization procedure more efficient by removing the need to validate detectors. Since detectors are not available, the bit strings intended for mutual connection cannot be protected from the channels (Aboy et al. 2022). However, in a secure paradigm, they must describe the quantum states they transfer over channels. As long as the attacker doesn't concentrate on polarization maintenance, this paradigm is safe from attacks that target the encoding and decoding modules. The authors (Singh et al. 2024), put out a continuous-variable MDI protocol for the purpose of detecting attacks from untrusted third parties (Madhav 2022). The use of Gaussian-modulated coherent states was also suggested by (Moujahid 2023)in their MDI-based method. A decoy-state protocol was suggested by the writers in (Hang et al. 2022). Using an optimal technique, this scheme achieves a finite secret key rate by selecting a measurement basis with a biased probability and intensities of different sorts of states. Phase locking and converting the normal encoding pulses of the BB84 into polarization modes are two of the phase encoding strategies suggested in (Aithal and Aithal 2024). Through the use of virtual photon subtraction, enhanced the functionality of a protocol. To make the continuous-variable MDI technique more efficient, the authors of a related work (Maheshwari et al. 2022) employed photon subtraction.

6.4 Semi-quantum key distribution

SQKD takes advantage of unique quantum capabilities of one or more communicating parties. It reduces computing cost and removes computational overhead. With SQKD, you can be guaranteed that you'll reach QKD on both ends of the connection. For this technique to work, the sender needs quantum capabilities but the recipient can have classical ones. The transmitter carries out a number of tasks, including as preparing quantum-states, taking quantum-measurements, and storing quantum-states (Gupta et al. 2018). According to this model, the receiver is responsible for a number of tasks, such as preparing new qubits, measuring them, sorting them in order, and sending them without interfering with quantum channels (Meena et al. 2022). The, authors of (Rathod et al. 2022)put forward the initial SQKD. They tested the protocol's robustness using single photons in this scheme. They generalized the fundamental conditions in the latter state, expanding this work. Complete heftiness could only be accomplished by transmitting the qubits discretely while attacking them collectively, according to their analysis of these conditions. A practical procedure based on four-level systems was also suggested (Miller 2019).

Key bits can be sent by the sender in an encoded format on a Z-base. A strong SQKD scheme with less than four quantum state transfers was suggested (Sharma et al. 2024). A two-way eavesdropping strategy was examined in (Khang 2023)in relation to a SQKD protocol. A method for two traditional users to secretly share keys was suggested in (Bashir et al. 2023). By avoiding the sender's measurement capabilities and making sure it's resilient against joint attacks, the authors of (Sharma et al. 2020)shown that classical users' measurement skills are not necessary for SQKD to work. In their attempt to steal session keys, utilized an untrusted quantum-server. New protocols are being developed at the moment using a variety of quantum states and technology (Nagaraj et al. 2018). The security flaws in SQKD have also been examined by a small number of researchers (De Alwis et al. 2023).

7 Open issues and future research directions

The many unanswered questions of healthcare-related QC are covered in this section. We lay out a taxonomy of these problems, explain what causes them, and suggest some avenues for further study that could lead to solutions.

7.1 QC for big data processing

QC's inherent capacity to enhance computational processing makes it an ideal match for big data analytics. Personalized services, improved diagnostics, and prognoses are just a few ways in which big data has the potential to transform healthcare, according to previous studies (Maraveas et al. 2024). In instance, descriptive, predictive, and prescriptive analytics can be made possible by big data in healthcare by utilizing data-science and improvements in ML/DL. For effective healthcare predictive analytics, for example, ensemble approaches built from multimodal data can be utilized (Nguyen et al. 2021). Research into the potential synergies between QC and semantic technologies is also necessary for the development of cutting-edge methods of processing medical big data for improved classification and comprehension. In addition, it can be useful for mining massive multimodal medical databases for hidden correlations (Nasralla et al. 2023). One example is the quantum machine learning method that uses semantic knowledge graphs, which was created in (Niazi and Mariam 2023). Similarly, taking into account three essential criteria—minimalism, efficiency, and accuracy—a quantum semantic communications framework is offered in (Bhukya et al. 2023) for the purpose of creating future reasoning-based communication systems. Additionally, they used unsupervised quantum clustering to glean semantic and contextual information from the intended messages.

7.2 Quantum AI/ML applications

More powerful artificial intelligence and machine learning models, made possible by QC's promised increased processing power, have the potential to bring forth game-changing innovations in healthcare (Tahir et al. 2020). With its extensive list of potential uses, quantum-enhanced AI/ML stands out among the many types of quantum algorithms with healthcare implications. Machine learning methods are a good fit for QC because they rely on operations with huge matrices, which are much improved by QC (Abd 2020). A wide range of applications can be supported by AI/ML because of its capability and diversity.

Many classic learning techniques rely on antiquated hardware accelerators; one such model is the conjugate gradient method. In order to improve the inference model as a whole, QC could lend a hand with AI/ML activities during machine construction. An early example is a well-known design that makes use of the Boltzmann machine (Hiwale et al. 2023). A Boltzmann machine is a network of hidden artificial neurons connected by weighted edges. The energy function of neurons is defined by the way they interact with their neighboring neurons. Accordingly, quantum AI has the potential to both enhance the accuracy of training models and shorten the time it takes to train ML (Burhanuddin 2023).

Driving a car, picking stocks to exploit a portfolio, or using suggestions to choose the correct product are all examples of real-time decision-making tasks handled by these systems. In order to make educated decisions, the majority of AI applications build an inference model. Pattern recognition, rule-based analysis, and sequence identification are the foundations upon which these inference models rest (Park et al. 2019). In the system's design, rule-based inference models go hand in hand with predefined answers. But the creativity of the app maker is crucial to these apps. Patterns and correlations drawn from a mountain of preexisting data provide an alternate approach. Reduced prediction accuracy may result from even a little inaccuracy in the inference models. Inference model error reduction is like a search problem in that it requires precision (Manjunath 2022).

7.3 Large-scale optimization

A wide range of industries frequently employ optimization methods. When dealing with many cases, many optimization problems become intractable and experience a combinatorial explosion. Consider the well-known Traveling Salesman Problem (TSP), an optimization issue that seeks to determine the shortest path between cities by visiting each city once and then going back to the starting location (Almusaed et al. 2023). When the number of cities gets very large, the optimal solution to the NP-Hard TSP problem becomes intractable. Since tackling such problems on conventional computer systems requires an excessive amount of time, heuristics are used in these situations (Muhammad et al. 2021). Two possible answers to these issues are provided by QC, namely universal quantum computers and quantum annealing. In addition, when tackling optimization issues, quantum annealing—an optimization heuristic—can outperform conventional computing systems. An easier alternative to building a universal quantum computer would be to use specialized quantum annealers (Chen and Zhang 2014). It has not been investigated, however, how effective they are compared to conventional computers. One way to achieve cost-effective solutions is by using lightweight digital annealers. These can mimic the properties of quantum annealers on conventional computer platforms. Although universal annealers can solve QC difficulties, they are rarely used in commercial settings (Shi et al. 2022).

7.4 Quantum computers for simulation

"If you wish to create a model of the natural world, you'd better make it based on quantum mechanics," allegedly stated Richard Feynman. When it comes to creating realistic emulators for complicated tasks that are hard to forecast utilizing standard models, QC shows a lot of potential (Mohsan 2020). The weather is just one example of a chaotic system that quantum computers can model. Additionally, they can be employed to simulate the development of social contagions and intricate biological systems, such the progression of a pandemic or epidemic. In addition, quantum computers show potential for studying medication interactions on a molecular and cellular level and for metabolic simulations within a call (Mahmood et al. 2022). This has the potential to pave the way for the creation of innovative vaccinations and pharmaceuticals. A digital twin of a human cell or organ can be created using a quantum computer. It is important to think about and deal with the different ethical concerns that can arise because QC will also allow for fine-grained and possibly invasive applications (Taj and Zaman 2022).

7.5 Quantum web and cloud services

The increased functionality offered by QC can only be realized if the issue of bringing QC-services to service hardware is met. QC is difficult to access for general-purpose problem-solving because of the huge quantity of resources needed for implementations (Lamnabhi-Lagarrigue et al. 2017). One initiative that aims to overcome the constraints of providing quantum healthcare services on commodity technology (Iakovidis et al. 2021). A cloud-based platform called “RXN” will be developed as part of this project. It will use AI models to anticipate chemical reactions in order to optimize synthesis processes and generate chemical procedures automatically for usage in remotely accessible labs. You can use Amazon Web Services as an example of a situation to develop quantum web services. The use of quantum web services is demonstrated, for instance, by Amazon Braket (Bharany et al. 2022). It offers a great place for professionals and researchers to test QC models in real time and see how they perform. An experimental environment for designing, testing, and evaluating QC algorithms using simulated quantum hardware is provided by Amazon Braket (Asim et al. 2022). Hidden behind the scenes, it employs D-wave’s quantum annealing and hardware based on gates. Systems constructed on superconducting qubits by Rigetti and ion-trap devices by IonQ are examples of these gate-based quantum computers (Zheng et al. 2019). In order to offer users quantum web services, additional QC technologies are needed, in addition to the Amazon Web Services environment. The created QC algorithm can be tested with software development kits (SDKs) (Yang et al. 2020).

Quantum web services have interesting healthcare applications but need examples to prove them. Quantum Key Distribution (QKD) encrypts video consultations and protects patient data in quantum-secure telemedicine. Cloud computing technologies like IBM Quantum and AWS Braket help speed up genomic analysis, DNA sequencing, and individualized treatment regimens. By enhancing molecular simulations, quantum-powered AI can speed up drug discovery (Quy et al. 2023). How quantum cryptography secures healthcare data transmission, hybrid quantum-classical models enhance AI-driven diagnostics, and quantum cloud services manage hospital resources are key research concerns. Answering these questions can improve hospital security, efficiency, and predictive analytics.

7.6 Quantum security applications

More and more cybercriminals pose a continual threat to the security of cyberspace. Cyberspace can now be protected from these types of attacks thanks to the development of essential security frameworks. Nevertheless, traditional computer systems find this procedure to be somewhat intimidating. When applied to classical computer systems, QC with ML aids in the creation of security protocols (Abdel-Basset 2024). When it comes to protecting sensitive information from intrusion, quantum cryptography—made possible by QC—offers effective answers. Nevertheless, conventional encryption methods are rendered ineffective by the unparalleled computational capabilities of QC, which in turn pose security concerns. In light of this, methods of encryption that are resistant to QC are urgently needed (Laxminarayana et al. 2022). An answer to the issues with encryption is being worked on by the National Institute of Standards and Technology (NIST). To make sure encryption methods are ready for QC, they should be built with care. In addition, the quantum environment may render conventional password management techniques inadequate (Nair 2024). Applications of QC can, for instance, guess passwords that would otherwise take a long time to decrypt in a shorter amount of time. Due to its persistence over time, postquantum encryption poses a unique threat to personally identifiable health information (PHI). Picture this: a patient's encrypted medical record details the fact that they underwent bone surgery after suffering a school-related accident. A person's record does not expire and continues to be valid until their death. If hackers were to steal such records today, they could store them until QC is a reality, at which point they could decode them and use them in attacks (Praveen and Srinivasan 2022). In order to safeguard complex data, new methods are required to implement robust encryption strategies. There are a number of security vulnerabilities associated with cloud computing that must be recognized and addressed, particularly in the case of quantum machine learning services provided through the cloud (Abd-El-Atty et al. 2020). In addition, quantum services are now available through the cloud.

7.7 Developing a quantum market place

Quantum service pricing and resource distribution to users is a critical issue in quantum computer deployments. An online marketplace for QC may be created, offering a platform where users could subscribe to the service and pay for it as they go. The pricing should be established depending on the utilized services, and workers can subscribe to the facilities they wish. These cloud-based services would be available to customers, including healthcare providers, on a pay-as-you-go basis (Vijay 2023). To build pricing models and disseminate quantum services, however, a coordinated quantum strategy is necessary for the establishment of such a distributed quantum marketplace. Financial models, mechanisms for the distribution of services, and control strategies for the allocation of quantum resources can all be developed by domain specialists with experience in quantum systems, which is essential for this type of system (Abdulbaqi et al. 2023). Just recently, D-Wave made an announcement about their plans to launch their quantum cloud service, Leap, on the Amazon Web Services (Ur Rasool et al. 2023).

7.8 Ethical implications and regulatory challenges

Concerns about data privacy, security, and equal access are at the heart of the ethical and regulatory issues raised by the use of QC in healthcare. Questions of informed consent, possible biases, and abuse of decision-making power arise when considering the capacity to analyze large volumes of sensitive patient data. While Quantum Key Distribution (QKD) does improve security, new regulatory frameworks are needed to make sure it complies with data protection standards like GDPR and HIPAA (Haddaway 2022). Also, there can be gaps in healthcare innovation due to the prohibitive cost and limited availability of quantum technologies. To ensure the responsible integration of QC into healthcare while retaining patient confidence and data integrity, it is important to establish worldwide standards, ethical guidelines, and supervision systems.

7.9 Computational considerations and the role of quantum advantage

Computing profiles of healthcare workloads differ substantially. Genomic alignment and electronic health record processing are examples of memory-bound tasks that depend on fast data access rather than computational power. On the other hand, quantum acceleration could be useful for computationally heavy and combinatorially complicated applications such as protein folding, molecular optimization, and quantum chemistry.

Keep in mind that there is no such thing as a universal speedup promised by quantum computing. The algorithms developed by Grover and Shor deal with the limited set of circumstances in which quantum advantage can materialize. Optimization, simulation, and specific areas of quantum machine learning are the subject areas of this review that have demonstrated theoretical or practical potential in applying quantum approaches to solve problems.

Quantum computing is anticipated to augment the existing strengths of classical HPC systems, which are capable of managing large-scale simulations, deep learning on medical pictures, and real-time diagnostics. It opens up new avenues for drug development, personalised medicine, and biomolecular modeling by tackling edge instances where classical methods scale poorly.

7.10 Challenges in data ingestion and memory architecture

Potentially accelerated variant calling and probabilistic modeling are two areas of genomic study that can benefit from quantum computing. But applications like sequence alignment still need a lot of memory and efficient access to big datasets, which are challenges for present quantum systems. Massive obstacles include the expense of converting classical data into quantum states and the absence of scalable quantum random access memory (qRAM). Therefore, at these junctures, quantum computing may not be very useful. The use of quantum computers selectively in areas with computational bottlenecks and classical systems to handle data-heavy activities might be a more practical hybrid architecture.

7.11 Implementation challenges and technological debt

Technological debt refers to the long-term challenges arising from integrating quantum components into existing classical healthcare systems. These include interoperability issues due to mismatched data standards and communication protocols, reliance on immature software abstraction layers, and the risk of poor long-term maintainability as platforms and frameworks evolve. Without careful design, such integrations may require costly refactoring and hinder scalability in future healthcare applications.

8 Conclusions

With its unprecedented scalability, efficiency, and dependability, QC has utterly transformed conventional computer systems. Applications in healthcare can benefit from the computational efficiency that QC offers by taking use of its essential properties. With that goal in mind, this study offers a thorough literature review on the topic of using QC to create healthcare solutions. Our focus here was on the many ways in which QC could improve healthcare. We also offered a taxonomy of current healthcare system QC architectures and outlined the essential criteria for developing healthcare applications powered by QC. In addition, we covered various quantum technologies that can guarantee the security of healthcare apps that use QC, as well as other security aspects of such systems. Lastly, we covered the present problems, what's causing them, and where research could go from here with QC offering huge benefits. Researchers interested in exploring the potential of QC in healthcare applications will find this groundbreaking work to be an indispensable resource, since it lays out all the major points about the implications of QC on the healthcare paradigm.

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Declarations

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Authors and Affiliations

Vamshi Krishna Bukkarayasamudram[1] · Pundru Chandra Shaker Reddy[2] · K Arun Kumar[3] · R. M. Jagadish[4] · Swati Sharma[5] · Mudarakola Lakshmi Prasad[6] · Yadala Sucharitha[7] · Iftikhar Aslam Tayubi[8] · Gopal Kumar Thakur[9]

✉ Vamshi Krishna Bukkarayasamudram
vamshi.b@manipal.edu

✉ Pundru Chandra Shaker Reddy
chandu.pundru@gmail.com

✉ Yadala Sucharitha
suchi.yadala@gmail.com

K Arun Kumar
akanagan@gitam.edu

R. M. Jagadish
rm.jagadish@gmail.com

Swati Sharma
swati.sharma@presidencyuniversity.in

Mudarakola Lakshmi Prasad
prasad.hinduniv@gmail.com

Iftikhar Aslam Tayubi
iftikhar.tayubi@gmail.com

Gopal Kumar Thakur
send2gopal@gmail.com

[1] Manipal Institute of Technology Bengaluru, Manipal Academy of Higher Education, Manipal, India

[2] Amity School of Engineering and Technology, Department of Computer Science Engineering, Amity University, Noida, Uttar Pradesh, India

[3] GITAM School of Technology, Department of Computer Science and Engineering, GITAM University, Bengaluru, India

[4] Department of CSE (Data Science), Ballari Institute of Technology & Management, Ballari, Karnataka, India

[5] Presidency School of CSE, Presidency University, Bengaluru, Karnataka, India

[6] Computer Science and Engineering, Institute of Aeronautical Engineering, Dundigal, Telangana, India

[7] Sharda School of Computing Sciences and Engineering, Department of Computer Science and Engineering, Sharda University, Greater Noida, Uttar Pradesh, India

[8] Department of Computer Science, Faculty of Computing and Information Technology, Rabigh (FCITR), King Abdulaziz University, Jeddah-21589, Saudi Arabia

[9] Department of Data Sciences, Harrisburg University of Science & Technology, Harrisburg, Pennsylvania, USA