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Review article

Quantum technologies in healthcare: A narrative review of foundational innovations, biomedical applications, and regulatory horizons

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Abstract

Quantum technologies are transforming healthcare by enhancing the fields of diagnostics, therapeutics, data security, and clinical decision-making through principles such as superposition, entanglement, and quantum tunneling. This review highlights the foundational concepts, key biomedical applications, and regulatory perspectives regarding the integration of quantum technologies into modern healthcare systems. A narrative literature review was conducted using the PubMed, Scopus, and Web of Science databases. Articles published up to August 2025 on quantum computing, sensing, and cryptography and their healthcare applications were critically analyzed. The search terms included "quantum computing," "quantum sensing," "quantum cryptography," and "quantum machine learning" combined with "healthcare," "drug discovery," and "genomics." Peer-reviewed articles written in English with direct biomedical relevance were included, while conference abstracts and non-peer-reviewed sources were excluded. Quantum computing enables advanced molecular simulations for drug discovery, the efficient analysis of large-scale omics data, and optimized models for personalized medicine. In addition, quantum sensing supports ultra-sensitive biomarker detection, high-resolution imaging, and early disease diagnosis. Moreover, quantum cryptography ensures robust security for medical data and supports compliance with data protection regulations. Its integration with artificial intelligence further accelerates the clinical translation of these innovations. Quantum technologies present substantial opportunities for predictive, personalized, and secure healthcare delivery. However, technical constraints, integration challenges, and regulatory gaps need to be addressed through interdisciplinary collaboration, infrastructure development, and adaptive policy frameworks to realize its full clinical potential.

Keywords: Biomedical simulation, drug discovery, healthcare innovation, personalized medicine, quantum computing, quantum cryptography, quantum machine learning, quantum sensing.

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Quantum technologies have recently evolved rapidly into a revolutionary tool for many industries, including healthcare and biomedical science. In contrast to classical computation, quantum systems employ the phenomena of superposition, entanglement, and quantum tunneling to present previously unknown capabilities in encryption, simulation, and data processing.[1] These abilities make quantum sensing and computation highly attractive for the resolution of complex biological problems, optimization of medical processes, and acceleration of the drug discovery process.

In addition to augmenting theoretical capacity, the emerging domain of quantum sensing and computation is exhibiting initial signs of translational readiness, as elaborated by Shams M, *et al.* (2023).[2] The combination of quantum sciences with clinical sciences has the potential to introduce a paradigm shift in the industry by facilitating improvement in the critical areas of health. This convergence represents a new frontier with the potential to transform multiple aspects of diagnostics, therapeutics, imaging, and patient data management.[3–6]

This shift is also emphasized by Jeyaraman M, *et al*. (2024), who identified weaknesses in the existing infrastructure, algorithmic development, and clinical adaptations[7] and suggested the beneficial application

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of quantum algorithms in drug discovery and disease prediction. Suvvari TK, *et al*. affirmed these views, asserting that the next logical step beyond the current digital health trends is to integrate quantum technologies with artificial intelligence (AI) and biological systems.[8]

The objective of this review is to integrate the latest results from basic research, through translational use, to regulatory anticipation, with a focus on the application of quantum computing, sensing, and cryptography within the medical field. Furthermore, we provide a unified perspective and research agenda that synthesizes these recent advances while addressing the technical opportunities and policy challenges associated with their clinical integration.

Historical roots and biomedical impact of quantum science

The foundations of quantum theory were established in the early 20th century as visionaries such as Max Planck, Albert Einstein, Niels Bohr, and Werner Heisenberg defied classical physics and discovered the discrete nature of energy and matter.[9] Planck's introduction of energy quantization in 1900 revolutionized the concept of continuous energy flow,[10] and Einstein's 1905 description of the photoelectric effect demonstrated light's dual nature as a wave and a particle,[11] laid the foundation for the quantum revolution. At first, insights from quantum mechanics were largely abstract, with scientists hoping to comprehend matter and energy at minute scales. By the mid-20th century, however, those ideas were starting to bear practical fruit, primarily through nuclear magnetic resonance (NMR) spectroscopy, which used the quantum properties of atomic nuclei to interrogate molecular structures with unprecedented resolution.[12] Following NMR, magnetic resonance imaging (MRI) was developed in the latter part of the century, revolutionizing medical diagnostics through the production of high-resolution, non-invasive pictures of the inner anatomy and thus complementing quantum theory with clinical practice.[13]

Milestones in biomedical quantum sensing

Pioneering work at the intersection of quantum technologies and medicine has focused on developing highly sensitive quantum sensors to detect biomarkers at an early stage. These sensors leverage the fundamental quantum effects, such as superposition and entanglement, to achieve unprecedented precision in detecting disease-linked molecular signatures.[14] Quantum dots are tunability-tuned semiconductor nanocrystals with tunable optical qualities that have been used as fluorescent tags in bioimaging, which allows targeted imaging of cancer biomarkers, such as HER2, with unparalleled sensitivity. Nitrogen-vacancy centers in diamonds have also been used as nanoscale magnetic sensors to detect submilligauss magnetic fields associated with neural activity, thereby providing potential for application in neurological disease diagnostics. Together, these advances are landmark achievements in the development of quantum-enhanced diagnostics that enable earlier disease detection and more tailored healthcare treatments.

Quantum computing in medicine

Quantum technologies leverage the principles of quantum mechanics, including superposition, entanglement, and quantum tunneling, to allow computational and sensing capabilities that exponentially exceed those of traditional systems. In the field of healthcare, technologies are being investigated in three main areas: quantum computing, quantum sensing, and quantum communication/ cryptography.

Shams M, *et al.* present a wide-ranging review of how such platforms are being transformed from theoretical concepts to biomedical instruments.[2] They indicated that quantum sensing, which is currently used in technologies such as MRI, is progressing rapidly with utilization in neural interface devices and wearable health monitors.[1] Quantum sensors provide advanced sensitivity and resolution to detect biomolecular interactions or electromagnetic fluctuations at nanoscale resolution.[15]

Quantum computing, however, offers the computational capacity to simulate complex biological systems and large-scale omics datasets. Quantum processors employ quantum bits (qubits), which can exist in many states simultaneously, whereas conventional bits (0 or 1) cannot. This parallelism has the potential to solve computational challenges in drug discovery, genomics, and disease simulation that are currently insoluble using classical hardware. Importantly, this quantum "parallelism" differs fundamentally from central processing unit-based parallel computing, where instead of multiple processors handling independent tasks, a single quantum processor explores an exponential number of states simultaneously within a single coherent system. This is a unique property arising from quantum superposition and interference. Similarly, quantum tunneling, beyond its abstract definition, has direct

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biomedical relevance, as it governs proton transfer reactions in enzyme active sites and influences binding-affinity calculations in ways that classical molecular mechanics often fails to capture accurately.[1, 4, 6, 16–20]

Jeyaraman M, *et al.* (2024) highlighted this transition by listing three key pillars of biomedical utility: molecular simulation and drug–target interaction prediction; high-throughput diagnostics supported by quantum algorithms; and advanced AI integrations for health data modeling based on hybrid quantum–classical systems.[7] In addition, Suvvari TK, *et al.* suggest that these technologies are more than computational improvements and are rather far-reaching disruptors that can reshape clinical workflows, diagnostic timelines, and therapeutic targeting paradigms.[8]

Therefore, this background implies a twofold narrative: quantum technologies as an extension of digital healthcare innovations and a quantum leap beyond conventional bioinformatics, both of which require innovative interdisciplinary models for development and deployment. **Table 1** demonstrates a comparative overview of classical *vs*. quantum technologies in healthcare.

Quantum computing in healthcare research

Quantum computing is set to transform healthcare research by solving computational problems that are problematic for traditional systems. Using the principles of quantum mechanics, this new approach enables more efficient, precise simulations, modeling, and data processing, thereby promoting innovation throughout the healthcare ecosystem.

Biomedical studies typically focus on understanding complex biological systems, and quantum computing may substantially reduce the time required to perform operations such as protein folding, genomic sequencing, and molecular dynamics simulations. For instance, quantum algorithms have been successfully applied to model protein–protein interactions, thus providing critical information required for drug development and understanding disease mechanisms.[43] These computations, which would generally require years to perform using classical computers, are achieved much faster using quantum systems, drastically accelerating the pace of discovery in precision medicine.

Moreover, in genomics, quantum computing enables the rapid scanning of vast genetic databases, thereby facilitating the identification of disease-causing mutations and drug targets.[44] These functions are crucial for unraveling the genetic origins of complex disorders and developing personalized treatment strategies.

Quantum computing also has the potential to revolutionize the planning and carrying out of clinical trials. By simulating patient populations and predicting treatment outcomes, quantum algorithms enable more efficient trial designs. Trial parameters, such as which patients to select and dosing regimens to use, can be optimized by scientists to improve safety, reduce costs,

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Table 1. Comparative overview of classical *vs*. quantum technologies in healthcare.

Features	Classical technologies	Quantum technologies	References
Information unit	Bit (0 or 1)	Qubit (superposition of 0 and 1)	(2, 14)
computational power	Limited for high-dimensional biological problems	Exponentially greater for simulating molecular dynamics and omics datasets	(24, 31)
Drug design	Relies on approximate models; limited by classical simulation capabilities	Enables precise molecular simulations, predicting binding energies and interactions	(21, 27, 28, 42)
Data security	Vulnerable to decryption with future quantum computers	Unbreakable encryption via quantum key distribution (QKD), quantum-secure communication	(52)
Medical imaging	MRI, PET using classical signal processing and reconstruction	Enhanced sensitivity and resolution using quantum magnetometers, gravimeters, and NV centres in diamonds	(13, 15, 35)
Big data handling	Struggles with high-dimensional genomics and clinical datasets	Efficient analysis using QML for clustering, prediction, and classification	(49, 53)
Algorithm scalability	Scales poorly for combinatorially complex problems like protein folding	Quantum algorithms like VQE and QAOA enable scalable optimization and simulation	(45, 54, 55)

MRI, magnetic resonance imaging; PET, positron emission tomography; QAOA, quantum approximate optimization algorithm; QML, quantum machine learning; VQE, variational quantum eigenvalue.

and increase trial success.[45, 46] Quantum algorithms, such as the quantum approximate optimization algorithm (QAOA) and quantum-enhanced machine learning, can facilitate personalized assignment of patients to treatment arms based on their molecular profiles, thereby enabling the development of precision clinical trials.[7, 47]

Furthermore, in health care operations, quantum algorithms are applied to optimize hospital resource management, including scheduling, staffing, and equipment distribution. These optimizations are evident in reduced wait times, streamlined workflows, and improved patient experiences, particularly in time-sensitive environments such as critical care and operating rooms.[48]

Its application is also seen in public health. Quantum-powered analytics can process real-time, large-scale epidemiological data, enabling the early detection of disease outbreaks and rapid response. Its application has been established in research on simulating disease dynamics of spread and in guiding public health responses during crises.[49, 50]

Several case studies have also illustrated the everyday utility of quantum computing in the healthcare industry. Quantum machine learning algorithms have already been used to predict hospital readmission rates, which can be valuable for operations planning and policymaking.[7] In addition, data from wearable devices in patients have been quantified using quantum approaches to determine early signs of cardiovascular disease.[20]

In medical imaging, quantum computing speeds up reconstruction algorithms for computed tomography (CT) and MRI scans. This provides faster, higher-resolution images that improve diagnostic quality and treatment planning.[20]

In addition, landmark initiatives such as the QuPharma Project (University of Strathclyde) and studies by researchers at the University of Sussex have demonstrated the increased uptake of quantum computing in translational research. These projects use quantum technologies to simulate drug–target interactions and analyze brain imaging data, thus enhancing understanding of neurological diseases.

Overall, the application of quantum computing in medicine has the potential to be transformative for enhancing biomedical understanding and drug discovery, as well as for optimizing clinical operations and public health monitoring. As technology advances, it will become an indispensable tool in designing smarter, faster, and more reactive healthcare systems worldwide.

Literature search strategy

A narrative literature review was performed by searching the PubMed, Scopus, and Web of Science databases from January 2000 to August 2025 (with emphasis on 2018 onward). Search terms combined primary quantum descriptors ("quantum computing," "quantum sensing," "quantum cryptography," "quantum machine learning," "qubit," and "quantum algorithm") with biomedical terms ("healthcare," "medicine," "drug discovery," "genomics," "precision medicine," "medical imaging," "data security," and "protein folding") using the Boolean AND/OR operators. Peer-reviewed original articles, systematic reviews, and narrative reviews published in English with direct or translational biomedical relevance were included. Conference abstracts without full-text manuscripts, non-peer-reviewed sources, and studies focused solely on quantum physics without clinical applicability were excluded.

Applications

Transformative power of quantum computing in biomedical research and clinical decision-making

Quantum computing has unparalleled potential to transform biomedical research and clinical practice by enabling the processing of large, high-dimensional datasets at record speeds. Its quantum parallelism enables researchers to model intricate biological systems, such as protein-folding, drug–target interactions, and molecular dynamics, well beyond the capabilities of classical computers. In addition, quantum algorithms are highly adept at multi-objective optimization, thus enhancing clinical decision-making across personalized treatment strategies and predictive diagnostics. The specific domains and examples of such applications are summarized in **Table 2.**

Quantum computing in drug discovery: Accelerating molecular simulation and therapeutic innovation

Quantum computing holds particular promise in drug discovery by offering unprecedented accuracy and efficiency in modeling molecular interactions and accelerating the development of new drugs **(Figure 1)**.[21] Traditional computing methods tend to fail when resolving the complex quantum motion of atoms and electrons and usually rely on approximations that are unable to fully encompass the molecular complexity. Conversely, quantum computers can directly simulate molecular quantum states, thereby enabling precise calculations of ground-state energies, molecular orbitals, and reaction pathways.[22]

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Table 2. Applications of quantum technologies in healthcare.

Domain	Application area	Quantum advantage	Examples	References
Drug discovery	Molecular simulation, target interaction	Accurate quantum modeling of drug–protein complexes, faster hit-to-lead identification	Polaris Quantum Biotech, Google Quantum Lab	(21, 28, 42)
Genomics	High-dimensional omics integration	Rapid analysis of genomic/transcriptomc/proteomic data, enabling personalized therapy	IBM–Cleveland Clinic initiative	(35)
Imaging diagnostics	MRI, PET, bioimaging	Quantum sensors (e.g., NV centers) improve resolution and sensitivity	Quantum-enhanced MRI and neural imaging	(56–58)
Clinical trials	Patient stratification, adaptive design	QAOA enables efficient trial planning based on phenotypes/genotypes	Quantum-enhanced adaptive randomization trials	(56)
Data security	Secure health communication	QKD and QDS ensure unbreakable, tamper-evident data transmission	Quantum links for EHR, IoMT	(52)
Healthcare Operations	Resource optimization	Quantum algorithms optimize scheduling, bed management, and equipment use in hospitals	Hospital logistics via quantum ML	(26, 37)
Disease prediction	Early diagnosis, risk modeling	Combines real-time sensor, clinical, and environmental data using quantum-enhanced AI	Early cardiovascular risk detection	(18, 19)

AI, artificial intelligence; MRI, magnetic resonance imaging; PET, positron emission tomography; QAOA, quantum approximate optimization algorithm; QDS, Quantum dots; QKD, quantum key distribution

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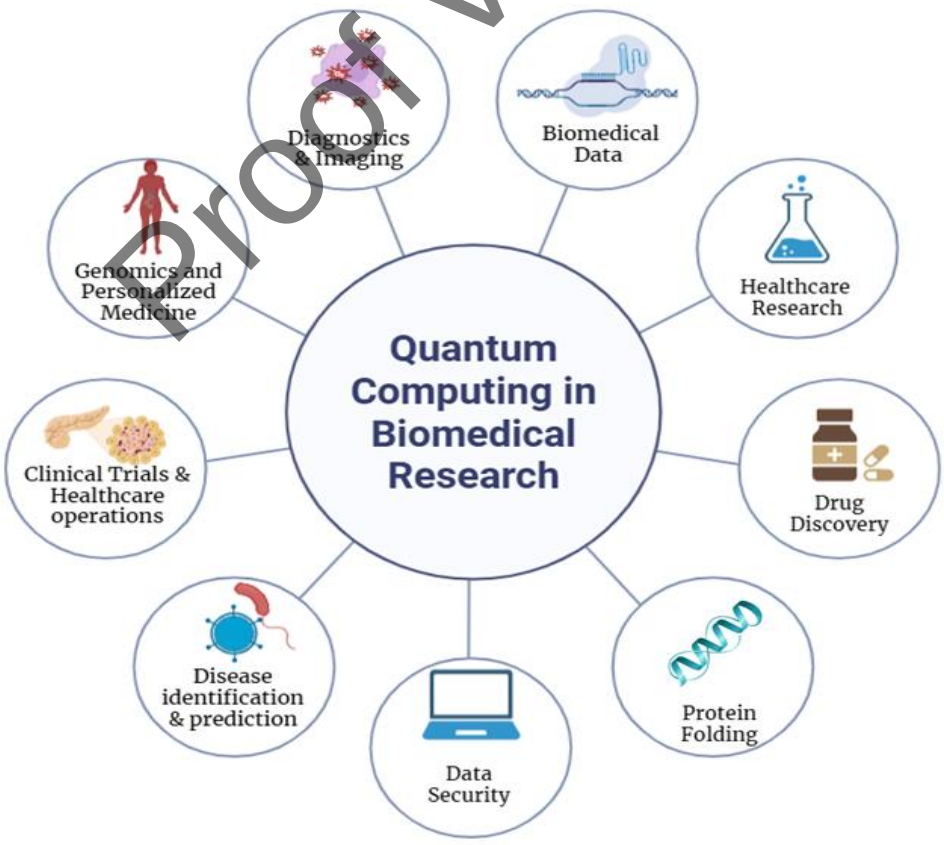

Figure 1. Applications of quantum technologies in biomedical research.

This ability is crucial for determining binding affinities, chemical reactivity, and conformational changes, all of which guide structure-based drug design.[23]

Quantum algorithms such as the variational quantum eigenvalue solver (VQE) and quantum phase estimation have been specifically developed for computing molecular electronic structure, enabling access to their pharmacological potential.[24] The algorithms can surpass conventional high-throughput screening by examining vast chemical libraries in parallel. This quantum parallelism accelerates hit discovery, lead optimization, and toxicity profiling, ultimately reducing the time and expense of pharmaceutical research and development. Quantitative benchmarks support these claims. VQE has demonstrated up to 100-fold reductions in computation time for electronic-structure calculations of small molecules compared with classical density functional theory methods.[24] Moreover, quantum-enhanced virtual screening platforms theoretically enable the parallel exploration of chemical libraries exceeding 10^{12} compounds, greatly exceeding the capacity of classical high-throughput screening.[25]

Real-world applications have also indicated these abilities. For example, Polaris Quantum Biotech applied quantum computing to discover new COVID-19 drugs, while Google's quantum computer has been used to model simple chemical reactions, thereby presenting the possibility of more complex pharmaceutical applications in the near future.[26] Moreover, quantum methodologies have been utilized to maximize the molecular shape of drug molecules, enhancing the effectiveness while reducing side effects.[27, 28]

Furthermore, quantum-boosted models can change how we forecast drug absorption, distribution, metabolism, and excretion, as well as how we assess pharmacokinetics and pharmacodynamics.[29] With the capacity to model biochemical processes *in silico* at an unmatched level of detail, it is possible to considerably enhance the drug safety profile before the initiation of clinical trials. Research by Hossain MS, *et al*. indicated that quantum-aided drug discovery could yield models for treating multicomponent diseases such as cancer and Alzheimer's by identifying new molecular targets.[30]

However, despite its potential, practical issues remain. Quantum computers are hampered by short qubit coherence times and noise sensitivity, which limit their ability to simulate large, biologically relevant molecules.[31] Hybrid quantum–classical models, such as VQE, provide a viable solution by dividing labor between classical and quantum processors, thereby avoiding hardware constraints at the expense of keeping quantum benefits. There is also increased demand for specialists with cross-disciplinary expertise in quantum mechanics and pharmaceutical science. Enterprises such as Zapata Computing are addressing this skills gap through industry-specific training initiatives.[32]

As quantum hardware advances and these hybrid approaches mature, quantum computing is set to become a foundation of data-driven drug discovery. By accelerating simulation, improving molecular modeling, and enhancing compound screening, this technology provides a conceptual framework for streamlined and enhanced therapeutic development.

Diagnostics and imaging

Shams M, *et al*. (2023) indicated that quantum sensing was a strong driver of diagnostic accuracy. They explained how quantum-magnified magnetometers and gravimeters can be used in biomedical instruments to provide ultra-sensitive detection of electrophysiological signals (e.g., brain function or heart rhythm). Moreover, quantum-inspired image processing might greatly enhance the resolution and reduce scan time in modalities such as MRI and positron emission tomography.[2]

Quantum machine learning for biomedical data (big data analysis in healthcare)

Quantum machine learning (QML) is an emerging field with direct applications in precision medicine, as stated by Suvvari TK, *et al*. QML algorithms can handle large-scale omics data, predict disease progression, and classify large clinical datasets. Hybrid quantum–classical systems are already being investigated for the clustering of high-dimensional gene expression profiles and early-stage cancer detection.[8] **Figure 1** illustrates how these advanced computational capabilities can accelerate innovation across the fields of genomics, systems biology, epidemiological modeling, and precision medicine. Such integration has the potential to promote more effective, individual-specific healthcare solutions, thus moving closer to truly personalized medical interventions.

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Genomics and personalized medicine

Quantum computing has the potential to revolutionize personalized medicine by integrating large and diverse biomedical datasets, such as a patient's genome, clinical history, and lifestyle factors, to design individualized therapeutic strategies. Quantum algorithms enable rapid analysis of high-dimensional, multi-omics datasets, such as genomic, transcriptomic, proteomic, and metabolomic profiles, which are often too complex for classical computational methods. This capability supports precision treatment plans, particularly in complex fields such as oncology, neurology, and rare genetic disorders, which marks a shift from reactive to predictive and preventive healthcare.

Moreover, quantum computing enhances drug response prediction by accurately modeling how specific genetic profiles affect individual reactions to therapies, thereby minimizing adverse effects. For instance, Padalhin A, *et al*. and Tarasov VE, *et al*. demonstrated how quantum algorithms can decipher complex genetic markers that influence pharmacogenomics.[33, 34] Similarly, quantum-enhanced imaging and diagnostics that integrate genetic, environmental, and behavioral data improve disease detection and risk assessment.[35]

However, a notable challenge in deploying QML for genomics is the vast size and dimensionality of omics data, which can readily exceed the limits of existing quantum memory and coherence. These restrictions require the design of computationally efficient encoding methods and hybrid classical–quantum processing workflows to make this genomic data analysis feasible.

Practical applications are already emerging. Studies by Shams M, *et al*. and Krzyszczyk P, *et al*. have highlighted how quantum computing-driven models have advanced cancer treatment by predicting tumor responses based on genetic variations.[36] These approaches reduce the trial-and-error nature of treatment planning, thereby improving patient therapeutic outcomes and reducing the associated healthcare costs. Furthermore, Giang V, *et al*. emphasized that quantum algorithms can streamline clinical decision-making to increase the efficiency in treatment design.[37]

Quantum simulations also offer valuable insights into drug–drug interactions, which are particularly beneficial for patients with complex polypharmacy profiles. Research by Solenov D, *et al.* and Flöther FF. has shown that quantum models can predict adverse drug reactions by analyzing molecular interactions with unprecedented accuracy.[38, 39]

Despite these advancements, some challenges remain. Current quantum hardware limitations restrict the scale and complexity of the datasets that can be processed. Efforts such as those at the University of Virginia are bridging this gap by developing quantum-inspired algorithms that run on classical systems. Moreover, integrating quantum computing outputs into clinical workflows is crucial. Collaborative initiatives, such as the IBM–Cleveland Clinic partnership, address this by developing quantum platforms to embed genomic insights into clinical decision support systems.

In conclusion, the integration of quantum computing into personalized medicine holds transformative potential by empowering clinicians with precise, data-driven tools to deliver individualized care while advancing predictive healthcare.

Secure medical data transmission

Quantum cryptography, specifically QKD, is proving to be a breakthrough solution for protecting sensitive medical information from cyberattacks. Unlike classical computational complexity theory-based encryption, QKD employs the principles of quantum mechanics, i.e., the no-cloning theorem and entanglement, to make any attempt at accessing the communication medium traceable. Therefore, QKD guarantees information-theoretic security, which is mathematically unbreakable even for other quantum computers.

QKD allows tamper-evident and non-repudiation communication protocols, which are particularly important to ensure data confidentiality, integrity, and authenticity in the case of healthcare, as stated by Shams M, *et al.*[2] This is also important for telemedicine, remote diagnosis, Internet of Medical Things, and cloud-based electronic health records, where patient data must be transported over potentially unsecure networks. Through secure quantum links among healthcare providers, data centers, and end users, QKD protects against communication interception attacks, data breaches, and ransomware.

In addition, quantum-secured communication enables healthcare organizations to comply with strict data protection laws, such as the United States' Health Insurance Portability and Accountability Act (HIPAA) and the European Union's General Data Protection Regulation (GDPR). Both laws require an extremely high level of security to protect a patient's protected health information, and quantum cryptographic systems provide a secure framework for meeting and exceeding these requirements.[40]

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In addition to QKD, quantum cryptographic methods such as quantum digital signatures and quantum secure direct communication are under consideration for innovative medical data infrastructures.[41] Such technologies hold great promise in enabling the interoperability among digital health platforms, protecting clinical trial data, and maintaining patient confidence in data-centric healthcare settings.

Clinical trials and healthcare operations

Quantum computing also has the potential to revolutionize the design and conduct of clinical trials by optimizing the parameters for complex factors such as patient stratification, treatment order, and adaptive randomization. Quantum algorithms such as the QAOA and quantum-enhanced machine learning enable better matching of patients to trial arms based on their genomic and phenotypic characteristics. This can result in quicker trial closure, improved therapeutic outcomes, and advancement in personalized medicine.[42–44]

In addition to clinical trials, quantum algorithms can optimize hospital operations by enabling real-time optimization of resource use, such as bed and staff assignment and equipment planning. These efficiencies reduce treatment delays, eliminate scheduling conflicts, and maximize overall care delivery efficiency. The result is a more responsive, lower-cost health system that benefits trial participants and the greater patient population.[8]

Disease identification and prediction

Quantum-powered AI algorithms enable the quick and accurate diagnosis of disease from medical images and complex datasets.[40] By correlating data from wearable sensors, electronic health records, and environmental and geospatial information, such as climate trends, disease can be forecast even before it manifests. This enables anticipatory medicine through pre-emptive treatments and facilitates the development of personalized treatment protocols and preventive interventions derived from unique patient health profiles.[41]

Protein folding

Protein-folding information is essential for elucidating diseases caused by protein misfolding, such as Alzheimer's and Parkinson's diseases. Quantum computation enhances the precision and speed of protein-folding simulation and prediction by modeling molecular interactions at the quantum level.[42] Of particular promise are the algorithms of VQE and QAOA. They treat folding as an optimization problem, determining the minimum-energy state among an infinite number of conformations. Such abilities may facilitate real-time simulations of protein dynamics, thereby revealing folding pathways and misfolding mechanisms, ultimately enabling drug discovery and the rational design of therapies.[40]

Limitations and challenges

Technical, ethical, and regulatory challenges

Although quantum technologies have the potential to be transformative, their integration into healthcare is hindered by major technical limitations, ethical ambiguities, and regulatory gaps. Therefore, these need to be overcome to facilitate its safe, scalable, and equitable deployment.

Hardware instability and computational limitations

Jeyaraman M, *et al.* (2024) highlighted that most existing quantum hardware is noisy intermediate-scale quantum computing. They are error-prone and still not scalable for intricate clinical uses. Short coherence times for qubits, high error rates, and the lack of fault-tolerant architectures limit their use in large-scale molecular simulations or genomic analysis. These are distinctly quantum constraints with no classical equivalent. Current superconducting processors require cryogenic temperatures near 15 millikelvin, which are incompatible with standard hospital environments, and two-qubit gate error rates of ~0.1%–1.0% require approximately 1,000 physical qubits per logical qubit for fault-tolerant operation, a scale far exceeding today's available hardware. Furthermore, the advent of fault-tolerant quantum computers will pose a specific threat to classical encryption: Shor's algorithm can factor RSA-2048 keys in polynomial time, thus threatening the security of electronic health record systems and clinical data infrastructure that currently rely on classical cryptography. Transitioning to National Institute of Standards and Technology-approved post-quantum standards (e.g., CRYSTALS-Kyber) should be proactively planned by healthcare institutions.[7] These restrictions require hybrid quantum–classical models, which still require considerable algorithmic optimization.

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Data integration and infrastructure compatibility

The integration of quantum systems with current healthcare infrastructure is formidable. According to Shams M, *et al.* (2023), quantum processors and sensors require cryogenic temperatures, specialized shielding, and isolated environments that are incompatible with current clinical infrastructure.[2] Furthermore, the mapping of quantum outputs to clinical workflows, particularly in the case of radiology, pathology, or electronic health record systems, requires standardized data formats, application programming interfaces, and quantum-sensitive processing interfaces.

Ethical and privacy concerns

Suvvari TK, *et al.* (2025) raised important ethical questions regarding quantum computation in personalized medicine. With the potential to interpret multi-omics data comes risks of genomic discrimination, violation of consent, and re-identification of anonymous patient data. Therefore, quantum computing can ultimately subvert existing encryption practices, thus increasing the pressure to develop post-quantum cryptographic protocols for medical data.[8]

Regulatory and policy readiness

Existing regulatory frameworks, such as those of the FDA, EMA, or CDSCO, are not directly equipped to address quantum-sourced medical products or algorithms. Jeyaraman, *et al.* advocated forward-thinking governance models that assess quantum medical tools using new parameters, including quantum advantage, entanglement fidelity, and algorithmic interpretability.[2]

Shams M, *et al.* suggested a technology readiness assessment and sandbox setup in which quantum solutions would be evaluated for safety and effectiveness in partnership with regulatory agencies.[1] The multiple facets of these challenges indicate the need for a collaborative, proactive strategy. Closing the technical–regulatory gap will be essential to ensure that quantum innovation improves health outcomes rather than complicates them.

Insights from regulatory and policy literature

While quantum technologies for medicine are rapidly developing, current regulatory environments have adapted accordingly. The literature identifies the necessity for anticipatory, flexible, and domain-based governance arrangements that are responsive to the unique nature of quantum systems.

Shams M, *et al.* (2023) highlighted the need for new validation standards and technology readiness assessment for quantum technologies. Classical clinical trial models and software validation workflows may not be suitable for systems that leverage quantum entanglement or hybrid quantum–classical computation. They support regulatory "sandbox" environments, which are tightly regulated, controlled environments where quantum tools are tested with temporary approval, similar to pilot trials for AI-based diagnostics.[1]

Jeyaraman M,*et al.* (2024) suggested that quantum algorithms for biomedical use should be assessed for clinical validity as well as quantum-specific performance metrics, including qubit error rates, coherence times, and scalability potential. Importantly, they highlight that conventional regulatory guidelines, such as ISO 13485 for medical devices or FDA's Software as a Medical Device framework, currently do not cater to the quantum dimension.[2]

Furthermore, Suvvari TK, *et al.* (2025) emphasized the need for international harmonization. As quantum healthcare technologies begin to cross borders via telemedicine or cloud computing platforms, regulations must address data localization, ethical interoperability, and mechanisms for cross-jurisdictional consent. They point to the necessity of post-quantum cryptographic standards in health IT infrastructure to anticipate the eventual obsolescence of classical encryption.[3]

These observations indicate that regulatory systems need to evolve toward modular, evidence-based, and ethics-driven models that are capable of dynamically evaluating quantum innovations as they are translated from the laboratory into the clinic.

Future direction

The use of quantum computing in medicine is rapidly evolving and has the potential to revolutionize how we diagnose and treat disease. Emerging applications of quantum technologies in biomedical science include enhanced diagnostic methods, ultra-precise molecular simulations, and QKD for highly secure cryptographic communication.[3,4] As indicated in the work by Shams M, *et al.* (2023), Jeyaraman M, *et al.* (2024), and Suvvari TK, *et al.* (2025), the potential for transformation of quantum systems is extensive, along with their intricacy as part of real-world clinical and administrative workflows.

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Although quantum computing is very promising, serious challenges remain. The existing hardware quantum limitations, i.e., the need for cryogenic temperatures, error rates, and a lack of scalability, are practical constraints.[31] Beyond this, ethical and regulatory concerns regarding data privacy, algorithmic transparency, and responsibility add complexity to their application. Quantum systems must meet the highest standards of safety, fairness, and reliability, particularly in medicine, where life-or-death decisions are being made.[30, 51]

To realize the potential of quantum computing in medicine, a strategic, phased approach is required. The creation of a quantum-literate workforce is the first step, which includes collaborative academic–industry efforts to develop interdisciplinary training programs that integrate quantum physics, biomedical informatics, and clinical sciences. In addition, creating hybrid quantum–classical frameworks is a viable short-term solution that enables health centers to experiment with quantum technologies within current infrastructure constraints. Pilot studies in applications such as drug discovery, protein folding, and personalized medicine can provide valuable feedback and help validate quantum models for clinical translation.[30]

Furthermore, regulatory bodies must anticipate and establish frameworks for evaluating and approving quantum-based solutions. Policies need to be flexible yet robust enough to address the unique characteristics of quantum technologies without compromising patient safety, data protection, or compliance with global standards such as HIPAA and GDPR.[52] Quantum competency-based open collaboration platforms that integrate quantum specialists, medical advances, policymakers, and ethicists will be vital in harmonizing innovation with pragmatic adoption.

In conclusion, quantum technologies are no longer ideas of tomorrow; they are near-future necessities today. Despite technical and policy challenges, the healthcare sector stands at the threshold of a quantum revolution. Provided that there continues to be interdisciplinary collaboration, investment in infrastructure and human capital, and a forward-looking regulatory vision, quantum computing has the potential to advance predictive, personalized, and highly secure healthcare. The way forward needs to be pursued purposefully, but the potential at stake, including earlier illness detection and more rational therapeutic interventions, makes this transition desirable and necessary.

Conclusion

Quantum technology is no longer the exclusive domain of theoretical physics; it is rapidly becoming an essential tool with the potential to transform the field of medicine. Its applications, ranging from modeling molecular interactions with unparalleled accuracy to encrypting medical records using quantum cryptography, mark a revolutionary step in how disease is diagnosed, treated, and prevented. As illustrated in this review, quantum systems are poised to transform several aspects of the medical industry, including drug discovery, personalized medicine, diagnostics, imaging, clinical trials, hospital operations, and public health surveillance.

To achieve this potential, one must overcome the numerous technical, ethical, and regulatory hurdles. Current quantum technologies, hindered by noise, coherence time, and environmental limitations, are not scalable for standard clinical use. Neither is the incorporation of quantum outputs into standard healthcare processes feasible without extensive adjustments to infrastructure and policy. In addition, ethical issues, especially genomic privacy and algorithmic explainability, need to be anticipated and addressed.

To bridge the gap between innovation and application, a coordinated and multidisciplinary effort is required. Investment is required to create a quantum-ready workforce, support hybrid quantum–classical systems and develop adaptive regulatory structures. There will need to be coordination among technologists, clinicians, regulators, and ethicists to enable responsible healthcare innovation aligned with ethical imperatives and operational realities.

Essentially, quantum technologies are not just incremental innovations; they represent a paradigm shift toward a more intelligent, predictive, and secure healthcare model. Through thoughtful effort and sustained investment, quantum-enabled healthcare may transform the 21st-century standards of care and beyond.

Author contributions

AB contributed substantially to study conception and design, data acquisition, literature review, and data analysis and interpretation; drafted and critically revised the manuscript for important intellectual content; and approved the final version submitted for publication, taking full responsibility for all aspects of the work in accordance with ICMJE criteria.

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Data sharing statement
The present review is based on the cited references. All data generated or analyzed during the present study are included in the published article and the citations herein. Further details, opinions, and interpretations are available from the corresponding author upon reasonable request.

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