

Quantum Computing in Medicine

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ABSTRACT

Quantum computing (QC) is a revolutionary field of computation that leverages the principles of quantum mechanics to process information in ways fundamentally different from classical computers. The relevance of QC to medicine lies in its potential to address computational challenges that are currently insurmountable for classical computers.

Quantum computing represents a transformative force in healthcare, promising faster, more efficient, and more secure medical solutions compared to traditional computing methods. It can process vast amounts of information simultaneously, making it an ideal tool for data-heavy tasks such as genomics, personalized medicine, and predictive analytics. Quantum computing could open up better ways to simulate nature. This paper explores the applications of quantum computing in the medical field.

KEYWORDS: *technology, quantum computing, QC, medicine, healthcare, medical industry, medical professionals.*

INTRODUCTION

With the emergence of ever-improving quantum computers, technology is making its way to revolutionize many fields, and the medical sector is no exception. Quantum computing (QC) has the potential to revolutionize medicine by enabling faster and more accurate data processing, improving drug discovery, enhancing diagnostic methods, and advancing personalized medicine. It offers unique capabilities for addressing complex problems that are infeasible for classical computers. A quantum computer is able to run all the calculations simultaneously that a regular computer has to crunch in a linear order. While supercomputers remain powerful tools for a variety of applications, the unique capabilities of QC open new avenues for solving complex challenges, particularly in fields like medicine.

Recent efforts have explored applications of quantum computing in areas such as drug discovery, patient privacy, and information security. Quantum computing aims to revolutionize areas such as drug development, energy, weather forecasting, cybersecurity, biological sciences, artificial

intelligence, financial modeling, and more. Among the many applications of quantum computing, medical research stands out. Recognizing the immense potential of quantum computing, companies like Google, Microsoft, and IBM are investing billions into quantum research [1].

QUANTUM COMPUTERS

A quantum computer (QC) behaves according to the laws of quantum mechanics. Thus, quantum computers are different from binary digital electronic computers based on transistors. A major difference between classical and quantum computing lies in the way they encode data. While a digital computer requires that the data be encoded into binary digits (0 or 1), quantum computers use quantum bits, which can be in superpositions of states [2]. In other words, instead of storing information in bits as conventional digital computers do, quantum computers use quantum bits, or qubits, to encode information. (Qubits are the basic units of quantum information.) In addition to ones and zeros, qubits have a third state called “superposition” that allows them to represent a one or a zero at the same time. Figure 1 shows the

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comparison between the bit and qubit [3]. The computing power of a QC grows exponentially with the number of qubits it uses.

Quantum computers have the potential to perform certain calculations significantly faster than any digital computers. QC consists of a quantum processor which operates at a very low temperature (a few tens of mK) and an electronic controller which reads out and controls the quantum processors, as shown in Figure 2 [4]. Several forms of physical media (optical fibers and free space) can be used to deliver quantum information. Figure 3 shows a representation of quantum computing [5].

In quantum system, the computational space increases with the size of the system. This enables exponential parallelism which leads to faster quantum algorithms. Unlike classical computer, QC offers massive parallelism within a single piece of hardware.

A typical quantum computer is shown in Figure 4 [6]. The basic building blocks of quantum computers include quantum gates, quantum memories, quantum CPUs, quantum languages, and quantum languages [7,8]:

- *Quantum Gates:* Quantum computers require quantum gates, which are basically different from classical Boolean gates seen in a conventional computer (AND, XOR and so on). A quantum gate acts on superpositions of different basis states of qubits. The quantum gates perform unitary operations on quantum states and lead to quantum circuits. They are particularly important for quantum error correction and experimental quantum information processing. They can be realized by superconductors, linear optic tools, or quantum dots. Common quantum gates are CNOT and SWAP.
- *Quantum Memories:* Quantum memories store the quantum systems in a quantum register for information processing. Quantum memories are formulated by n stationary quantum states. Quantum computers are expected to have limited memory.
- *Quantum CPUs:* These use a quantum bus for the communication between the functional elements of a quantum computer. From a computing perspective, quantum CPUs can be approached through quantum adders.
- *Quantum Languages:* These enable us to create an artificial quantum computer to simulate a quantum computing environment. The programming language should follow a functional programming structure, which can compute the

process as a whole entity with a proper bounded structure.

- *Quantum Algorithms:* Quantum algorithms are significantly faster than any classical algorithm in solving some problem. Most of the successful quantum algorithms use quantum Fourier transforms in them because they require less hardware. Popular quantum algorithms include Shor's algorithm (since integer factorization is faster) and Grover's search algorithm.

In ambitious attempts to realize practical quantum computers, enormous efforts are still being expended both in designing software (quantum algorithms) and hardware development (physical implementation).

QUANTUM COMPUTING IN MEDICINE

Quantum computing was conceived to simulate quantum systems that classical computers cannot efficiently handle. The intersection of quantum computing with medicine began to materialize in the early 21st century, as advancements in both quantum theory and hardware laid the groundwork for practical applications in healthcare. The application of QC in medicine began to take shape with advances in quantum algorithms and hardware during the 2010s. By harnessing quantum principles, researchers aim to develop more precise and efficient diagnostic tools, enhance treatment plans, and unlock deeper insights into disease mechanisms, ultimately advancing the field of medicine. One of the first major milestones occurred when quantum algorithms were successfully applied to simulate molecular interactions for drug discovery. Quantum computers became powerful enough to tackle real-world problems, including those in medical research. Figure 5 show the key applications of QC in medicine [9], while Figure 6 shows some healthcare professionals using quantum computer [10].

For medical quantum computing, the initial focus was on biochemical and computational biology problems. Recently, over 40 studies on medical proof-of-concept quantum computing applications have been conducted, spanning genomics, clinical research and discovery, diagnostics, and treatments/interventions. In particular, quantum machine learning/artificial intelligence has rapidly evolved and shown to be competitive with classical approaches in certain cases [11].

APPLICATIONS OF QUANTUM COMPUTING IN MEDICINE

Currently, quantum computing has advanced various areas in the medical field, including cancer, brain scans, as well as finding drugs. In areas such as drug discovery, genomics, personalized medicine, Monte

Carlo dose calculation, and radiotherapy optimization, QC could significantly accelerate breakthroughs by providing solutions to problems that require massive computational power. QC in medicine has the potential to revolutionize fields such as drug design, genomics, medical diagnostics, AI-enhanced healthcare, and radiotherapy through enhanced computational power and efficiency. Common areas of application of QC in medicine include the following [9,12]:

- *Drug Discovery:* Drug discovery is a complex, data-intensive process, often limited by the computational constraints of classical methods. Developing pharmaceuticals through lengthy and costly clinical trials is definitely passé: scientists and pharma companies started to experiment with alternative ways to speed up the process and make drug discovery and development more cost-effective. One breakthrough that enabled QC's use in the medical field was the development of quantum algorithms for molecular simulation, which are crucial in drug discovery. QC can accelerate the discovery of new drugs by simulating molecular interactions at a scale that classical systems cannot handle efficiently. Pharmaceutical companies began collaborating with QC companies to explore how quantum simulations could accelerate the development of new drugs, particularly for complex diseases like cancer and Alzheimer's. QC has introduced powerful algorithms that have the potential to revolutionize drug discovery by enabling more efficient molecular modeling. Quantum computing might bring supersonic drug design. Figure 7 shows quantum drug design [13].
- *Quantum Machine Learning:* Another milestone in QC's relevance to medicine was the advent of quantum machine learning (QML). QML is a fusion of quantum computations and machine learning approaches to facilitate the processing of big amounts of higher dimensional data more efficiently than possible on traditional computers. It is applicable to the prediction of drug toxicity, analyzing large biological datasets, and by optimization of drug properties in drug discovery. It represents a promising frontier in healthcare by enhancing the capabilities of traditional machine learning models through the power of QC. QML models are proving particularly effective in enhancing diagnostic accuracy. As healthcare data become more complex and voluminous, QML offers the potential to process and analyze these data at unprecedented speed and precision. Practical applications of QML emerged, offering
- powerful tools for medical diagnostics and genomics. QML models can provide deeper insights into individualized healthcare plans, leading to more personalized and effective treatments.
- *Radiotherapy:* The year 2021 saw a significant leap forward with the use of quantum-enhanced algorithms for optimizing radiotherapy treatment plans. Traditional radiotherapy requires complex calculations to determine the optimal radiation dose for a tumor while minimizing damage to surrounding tissues. QC holds great promise in optimizing treatment plans for radiotherapy and personalized medicine by offering unprecedented computational power for complex calculations. QC's ability to process multiple variables simultaneously enabled more precise and efficient treatment plans, potentially reducing treatment times and improving patient outcomes. The Monte Carlo simulation is a powerful computational technique widely used in radiotherapy for accurate dose calculation and treatment planning. It accounts for various physical phenomena, including scattering, absorption, and secondary particle production, making it one of the most reliable methods for calculating radiation doses in heterogeneous tissues.
- *Quantum Imaging:* Quantum principles have the potential to revolutionize medical imaging by enhancing the precision and resolution of imaging technologies like magnetic resonance imaging (MRI). Traditional MRI relies on the interaction of magnetic fields and radio waves to create images of the body's internal structures. Quantum imaging is a form of imaging that uses principles of quantum mechanics to generate highly precise microscopic (or subatomic) level images. QC and quantum sensors show promise in significantly improving the accuracy of these scans. The advancements not only improve the quality of imaging but also reduce the amount of time required for a scan, potentially lowering patient discomfort and exposure to magnetic fields. Figure 8 shows the use of QC in drug discovery and medical imaging [14].
- *Personalized Medicine:* Healthcare is moving toward personalized medicine, where healthcare is customized based on a patient's medical history, lifestyle, and genetic makeup. However, analyzing genomic data at scale poses enormous computational challenges. In the realm of personalized medicine, quantum models offer the ability to optimize treatment plans by processing

vast datasets, such as a patient's genomic information, medical history, and environmental factors, to tailor treatments that are specific to the individual's genetic makeup.

- **Precision Medicine:** Precision medicine aims to tailor disease prevention and management by leveraging an individual's unique biomarker profile, including genetic, molecular, and clinical characteristics. It integrates individual genetic, epigenetic, transcriptomic, proteomic, and clinical data. It relies heavily on early diagnosis and accurate prognosis to guide informed treatment decisions. Unlike traditional "one-size-fits-all" approaches, precision medicine necessitates the seamless integration of diverse patient data, from genetic variants and molecular expression profiles to clinical histories into a coherent framework. However, the scale and complexity of such datasets challenge classical computing approaches. Quantum computing offers a fundamentally new paradigm for accelerating molecular simulations, biomarker discovery, and high-dimensional data analysis. It is poised to transform precision medicine by addressing computational barriers that hinder individualized healthcare. As quantum computing technologies mature, their applications in precision medicine are poised to transform how diagnostics, treatment, and data interpretation are approached. Figure 9 shows QC facilitating precision medicine [14].
- **Medical Diagnostics:** QC is emerging as a powerful tool in medical diagnostics, particularly through its ability to enhance pattern recognition and data analysis for the early detection of diseases. This capability is especially useful in diagnosing diseases like cancer and neurodegenerative disorders, where early detection is critical for successful treatment outcomes. In oncology, quantum algorithms can assist in detecting cancerous cells at earlier stages by recognizing unique patterns in imaging or genomic data.
- **Quantum Genomics:** Genomics is rapidly moving from its initial focus on simple sequencing to include computationally intensive processes that require eventual analysis by quantum computing. The use of quantum computers to handle genomic data is a natural application since genomic data involves gestating huge quantities of complex information and quantum computers are able to effectively and efficiently process this information than conventional computers. Genomic data analysis is a field that involves

processing large datasets, that can be complicated and computationally intensive. Figure 10 shows quantum genomics [15].

BENEFITS

Quantum computing represents a transformative force for the healthcare sector, providing previously uncommon capabilities in operational efficiency, personalized medicine, drug discovery, and diagnostics. It can identify promising drug candidates much faster than conventional methods. In drug discovery, quantum computing offers a transformative leap. Other benefits of QC in medicine include the following [14,16,17]:

- **Speed and Accuracy:** Quantum computing utilizes the principles of quantum mechanics to perform calculations at extraordinary speeds. Quantum computing provides an incremental speedup of disease diagnosis and treatment and, in some use cases, can drastically reduce the computation times from years to minutes. Quantum simulations could mimic complex molecular interactions, accelerating the early stage drug discovery process by allowing researchers to formulate and test a broad array of drug candidates in just a small fraction of the time. By exploiting its ability to perform parallel computations, quantum computing provides an alternative that promises faster data processing and efficient analysis. Quantum algorithms can simulate protein folding processes with more efficiency and accuracy than classical methods can and it can help provide insight into (disease related) proteins.
- **Improving Diagnostics:** Improved imaging quality directly impacts diagnostic accuracy, enabling earlier detection of diseases like tumors, neurological disorders, and cardiovascular conditions. Quantum-assisted machine learning models can analyze imaging data alongside clinical records to support more precise and data-driven diagnostic decisions.
- **Optimizing Healthcare:** QC can enhance management and operations in the healthcare industry. Hospitals face complex optimization problems, such as scheduling staff, managing supply chains, allocating ICU beds, and planning emergency responses. Quantum optimization algorithms can evaluate numerous constraints and variables simultaneously, leading to more efficient and cost-effective decision-making.
- **Complex Systems:** Quantum computers can really revolutionize drug discovery, particularly for complex diseases. Quantum computing has the

potential to process large amounts of data and simulate complex systems in a way that would not be possible with classical computing techniques. It offers great promise in developing realistic simulators for complex tasks that are difficult to predict using traditional methods. Quantum computers can be used to simulate chaotic systems, such as the weather. They can also be used to model the evolution of complex biological systems and social contagions, such as the evolution of an epidemic or a pandemic.

- *Decision-making:* Quantum systems could unlock new frontiers in data-driven clinical decision-making. Quantum algorithms can optimize clinical decision-making processes, leading to more precise diagnoses and treatment recommendations, especially in fields like oncology and cardiology, where individual patient data must be processed in real-time to deliver personalized care.
- *Quantum Supremacy:* This is defined as the ability of a programmable quantum device, which is capable of solving a problem that cannot be solved by classical computers in a feasible amount of time. The behavior of qubits relates directly to the behavior of a spinning electron orbiting an atom's nucleus, which can demonstrate three key quantum properties: quantum superposition, quantum entanglement, and quantum interference.

CHALLENGES

Despite its immense potential, QC faces significant technological barriers that limit its current application in medicine. Challenges in the field include hardware limitations, scalability, regulatory approvals, cost reductions, ethical considerations, and integration within clinical environments. One significant challenge in modern medicine is the sheer volume and complexity of data generated by medical research, clinical trials, and patient records. Currently, the field faces a shortage of expertise, necessitating significant investment in education, training, and skill development. Other challenges include the following [1,9]:

- *High Cost:* One of the major barriers to the widespread adoption of QC in healthcare is the high cost associated with quantum hardware and its maintenance. Quantum computers require highly specialized and expensive components, such as superconducting qubits or trapped ions, which operate in extreme environments. These setups necessitate significant investments in infrastructure, cooling systems, and ongoing operational costs, making QC far more expensive

than classical computing. For healthcare institutions, the cost of installing and maintaining quantum systems is prohibitive.

- *Economic Inequality:* High cost raises concerns about economic inequality, as only well-funded organizations may be able to afford the benefits of QC. Limited availability and high costs restrict access to quantum computers, leading to economic disparities in which only well-funded organizations can benefit.
- *Ethical Concerns:* As QC advances, its powerful data processing capabilities raise significant ethical and data privacy concerns, particularly in the context of healthcare. Ethical concerns arise over data ownership, consent, and the transparency of quantum algorithms in healthcare. Addressing these ethical and privacy concerns is essential to ensuring that QC can be integrated into healthcare in a way that respects patient rights and upholds the highest standards of data security.
- *Data Security:* The security of healthcare data poses a significant challenge in the era of quantum computing. Some attackers employ a "harvest and decrypt" strategy, wherein they acquire data now and decrypt it later when advanced technologies become available. With the advent of quantum computers, medical information could become even more vulnerable. A major challenge posed by quantum computing is the potential to break existing encryption.
- *Hardware Limitations:* One of the primary challenges is the limited hardware capabilities of quantum computers. Current quantum processors, such as those developed by IBM and Google, are still in the noisy intermediate-scale quantum era, where quantum bits, or qubits, are highly susceptible to errors due to decoherence and noise from environmental interactions. Integrating QC into clinical settings poses significant challenges due to the complexity of quantum systems and the existing healthcare infrastructure. Hybrid algorithms are designed to perform quantum computations for specific parts of a problem, while classical computers handle the rest. This approach is particularly beneficial given the current limitations in quantum hardware, as it allows for quantum advantages to be realized without requiring fully fault-tolerant quantum computers.
- *Decoherence:* A key limitation is decoherence, the tendency of quantum states to degrade due to environmental interactions, leading to the collapse of superposition and entanglement. Coherence

refers to the system's ability to preserve quantum states over time; the longer the coherence time, the more reliably computations can be performed. Noise and decoherence may introduce significant errors that limit the scalability and accuracy of current devices. This could be particularly problematic in applications in precision medicine.

- *Integration:* Quantum computers need specialized environments that are not compatible with standard healthcare infrastructure. Quantum algorithms also face challenges integrating with classical healthcare IT systems. Experts predict that QC's integration into mainstream medical research and clinical practice will likely unfold over the next two decades.
- *Scalability:* In classical computing, increasing the number of bits is a straightforward process that directly improves system performance. However, in quantum computing, the process is far more complex. Many promising quantum algorithms assume ideal, low-error hardware. Large-scale medical simulations (e.g., drug discovery, personalized medicine, and radiotherapy) require thousands to millions of fault-tolerant qubits, far beyond current capabilities. The scalability issues extend to the number of qubits required to solve real-world medical problems, as large-scale simulations for drug discovery, personalized medicine, or radiotherapy would require thousands to millions of fault-tolerant qubits—far beyond the capabilities of current hardware.

FUTURE OF QUANTUM COMPUTING IN MEDICINE

Quantum technologies, including computing, communication, security, and sensing, have significantly advanced over the last years. They have become a key enabler for progress towards precision medicine: keeping people healthy through proactive medical care and guidance at the level of an individual. Quantum computing (QC) is poised to become a transformative force in the medical field, offering unprecedented capabilities in data processing, problem-solving, and simulation. The potential of QC to revolutionize medicine lies in its unparalleled ability to solve complex problems that are beyond the reach of classical computers.

One of the key areas driving the future of QC in medicine is the development of quantum error correction and other hardware innovations. Error correction is critical because qubits, the fundamental units of quantum computers, are highly sensitive to noise and decoherence, which lead to errors during computations. As quantum hardware and algorithms continue to improve, particularly with advancements

in error correction, scalability, and quantum-classical hybrid systems, QC's potential to solve complex healthcare problems will become more apparent [9].

Looking ahead, one can envision a future in which quantum computing not only enhances diagnostics and therapeutic design but also democratizes drug discovery. The convergence of quantum computing and AI presents transformative opportunities. Quantum-aware AI models designed to exploit quantum architectures may enable near real-time translation of multi-omic data into clinical insights. The future potential of QC in healthcare is immense. From identifying new therapeutic molecules to enhancing diagnostic precision, quantum computers will allow healthcare professionals to develop more personalized and effective treatments.

CONCLUSION

There is a growing interest in developing quantum technologies to advance research and services in healthcare. However, significant improvements are still needed before the full potential of quantum computing can be realized. The field of quantum computing is expected to require at least a decade or more to achieve widespread commercial application in medicine. The potential of quantum computing to transform medicine is immense, paving the way for breakthroughs that can lead to more precise and efficient medical practices. Major applications of quantum computing in medical sciences demonstrate tremendous potential to transform areas such as pathology, drug discovery, genomics, personalized medicine, and more.

Quantum computing may eventually shorten diagnostic timelines, improve therapeutic precision, and make biomedical innovation more globally accessible. Experts predict that within the next two decades, we will see the first quantum-assisted medical applications, such as quantum-enhanced diagnostic tools or personalized treatment optimization models, begin to appear in specialized healthcare institutions. As this technology moves out of the theoretical realm and into practical application, the world must prepare for a landscape where the rules of data and medicine are rewritten. The transition to a quantum-capable world will require international cooperation and a complete overhaul of how we perceive digital privacy [18]. More information about quantum computing in medicine can be obtained from the books in [19,20].

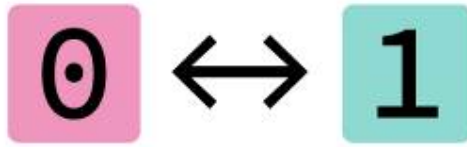
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TRADITIONAL COMPUTERS

Technology based on 'bits'



Bits have two states: 0 or 1

QUANTUM COMPUTERS

Technology based on 'qubits'



Qubits have an infinite number of states between 0 and 1

Figure 1 The bit and the qubit [3].

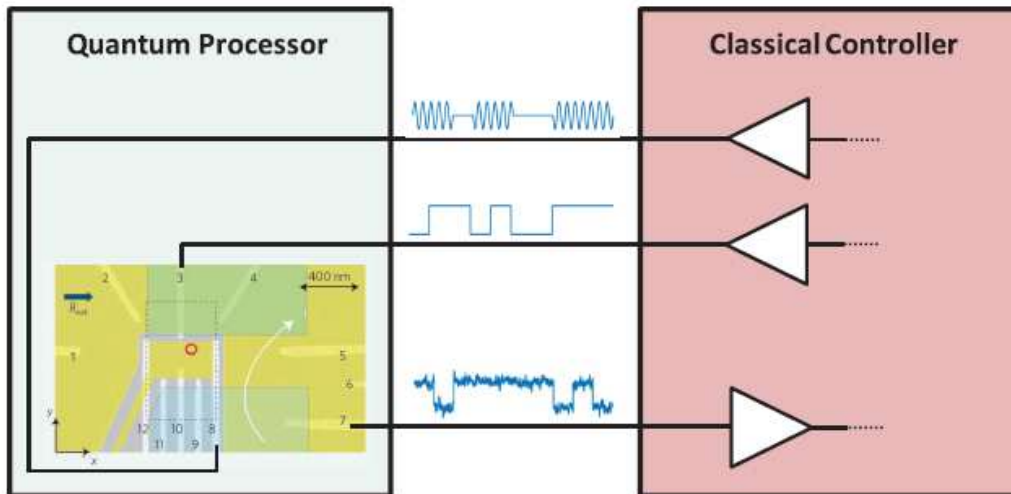


Figure 2 Quantum processor and classical electronic controller [4].



Figure 3 A representation of quantum computing [5].



Figure 4 A typical quantum computer [6].



Figure 5 Key applications of QC in medicine [9]



Figure 6 Some healthcare professionals using quantum computer [10].



Figure 7 Quantum drug design [13].



Figure 8 Use of QC in drug discovery and medical imaging [14].

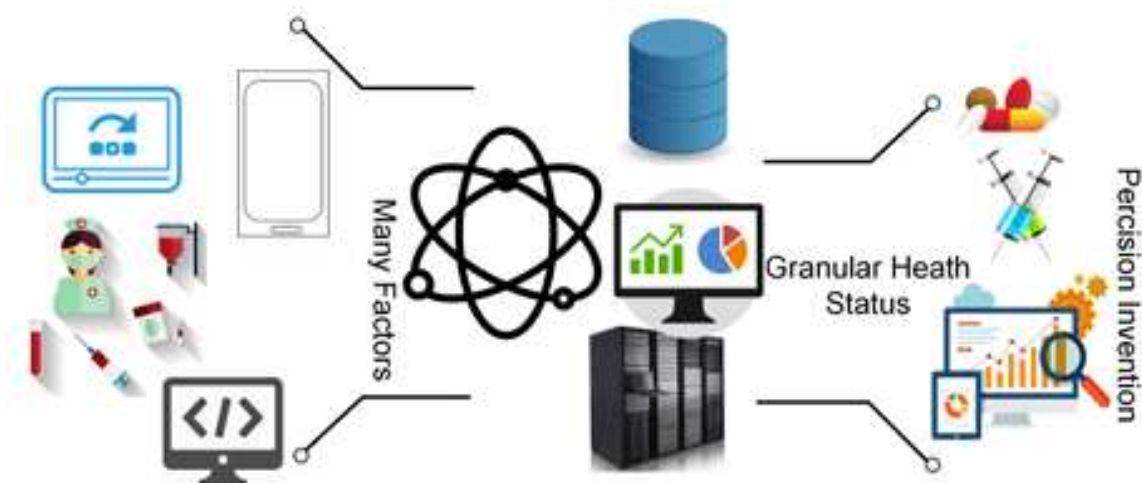


Figure 9 QC facilitating precision medicine [14].

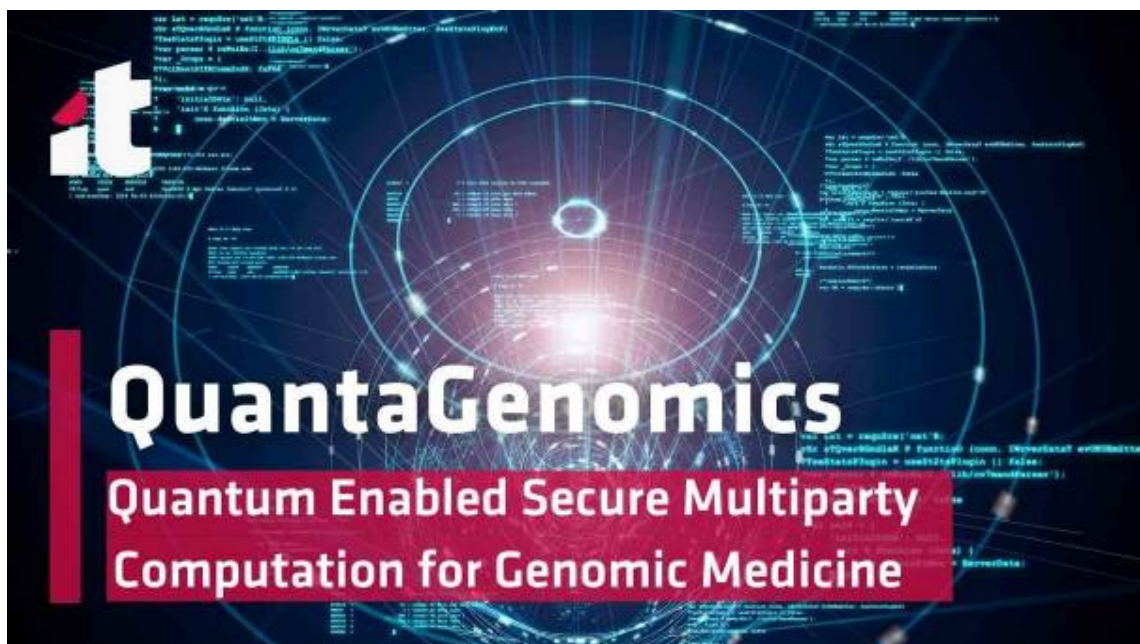


Figure 10 Quantum genomics [15].

