Fundación
InstitutoRoche 20
aniversario

Anticipating reports

QUANTUM TECHNOLOGIES

IN THE MEDICINE OF THE FUTURE

Observatorio
de Tendencias
EN LA MEDICINA
DEL FUTURO

Anticipating report coordinated by:

Miguel Ángel Martín-Delgado
Professor of Theoretical Physics at Complutense University of Madrid. General Coordinator of the scientific consrtium QUantum Information TEchnologies MADrid (QUITEMAD).

Collaborating experts:

Javier Prior
Director of the Quantum Tecnologies Group at the University of Murcia.

Vicente Martín
Professor of Computer Science at the Polytechnic University of Madrid. Coordinator of the Quantum Information Research Group. Debuty Director of the Computational Simulation Center.

Advisory committee at the Observatory of Trends in the Medicine of the Future:

Joaquín Arenas
Director of the 12 October University Hospital Reasearch Institute (i+12).

Ángel Carracedo
Director of the Galician Public Foundation in Genomic Medicine (Galicial Health Department) and Gorup Coordinator of Genomic Medicine at Santiago de Compostela University (CIBERER).

Pablo Lapunzina
Full Professor of Human Genetics and Head of Reaearch Group at Medicine and Molecular Genetics Institute (INGEMM) at La Paz University Hospital (IdiPaz) and Scientific Director of CIBERER.

Fernando Martín-Sánchez
Deputy Manager of the Medical Informatics, Digital Strategy and Innovation Area at La Paz University Hospital.

www.institutoroche.es

How to reference this report: *Fundación Instituto Roche. Anticipating report Quantum Technologies in the Medicine of the Future. 2024.*

With the collaboration of Ascendo Sanidad&Farma

Content

PRESENTATION

The Anticipating Reports, elaborated within the framework of the Observatory of Trends in the Medicine of the Future fostered by Roche Institute Foundation, are intended to contribute to the generation and sharing of advances in areas of emerging knowledge related to Personalized Precision Medicine and that will be part of the Medicine of the Future.

The Observatory has an Advisory Committee of experts formed by Dr. Ángel Carracedo, Dr. Joaquín Arenas, Dr. Pablo Lapunzina, and Dr. Fernando Martín-Sánchez. Their functions include the selection of the topics addressed in these reports, the identification of experts, and the validation of content.

This report on "***Quantum Technologies in the medicine of the future***", is coordinated by **Prof. Miguel Ángel Martín-Delgado**, and has been elaborated with the participation of experts Prof. Javier Prior and el Prof. Vicente Martín.

Prof. Miguel Ángel Martín-Delgado is a Full Professor of Theoretical Physics at the Complutense University of Madrid (UCM), holding a PhD in Physical Sciences. He is a Member of the Board of Directors of the Spanish Center for Metrology, Fellow of the ELLIS Society (European Laboratory for Learning and Intelligent Systems), Visiting Research Fellow at Princeton University, and has been an invited visitor at numerous prestigious international institutions. He has directed the Quantum Information and Computation Group at UCM since its establishment in 2003. Additionally, he coordinates the Quantum Information module of the Master's in Theoretical Physics at UCM. He is also the General Coordinator of the scientific consortium QUITEMAD (Quantum Information Technologies Madrid in the Community of Madrid), Scientific Editor of the journal Scientific Reports (Quantum Physics area) of the Nature Publishing Group, and Corresponding Member of the Royal Academy of Sciences. His scientific achievements in quantum computing include: the first quantum algorithms developed in Spain; the formulation of new, more versatile and higher computational capacity topological quantum computer models known as 'topological color codes,' which enabled the first complete quantum error correction in an experimental quantum memory; pioneering the study of the properties of topological insulators and superconductors with applications in quantum computing; the formulation of the first quantum agent of AI (quantum robotics) with mathematically proven quantum advantage; and the development of new algorithms with Bayesian inference for quantum AI.

Prof. Javier Prior holds a Bachelor's degree in Physical Sciences from the University of Valencia and a PhD from the University of Murcia, having worked for over

10 years in the field of quantum technologies. Prof. Prior has been a researcher at the University of Oxford and Imperial College (England) for more than three years, and subsequently joined the Polytechnic University of Cartagena as a professor, where he combined his position with that of a visiting professor at the University of Ulm (Germany) for more than 10 years. Since 2021, he has been a professor in the Department of Physics at the University of Murcia, where he leads the research group in quantum technologies along with the quantum sensors laboratory. Additionally, he is a co-founder and organizer of the biennial conference series “New Trends in Complex Quantum Systems Dynamics” and an editor of the journal Scientific Reports. He has been the principal investigator of 11 research projects, including two ERAnet actions (QuanERA) and a Horizon Europe project. His research has had a significant impact on the fields of quantum biology, through his interpretation of the role of quantum physics in photosynthesis, and quantum sensors, exploring the nature of Nitrogen-Vacancy detectors implanted in diamonds, where he has developed new measurement protocols with applications in the medical field.

Prof. Vicente Martín is a Full Professor of Computer Science at the Technical University of Madrid, Deputy Director of the Center for Computational Simulation, and Coordinator of the Research Group on Quantum Information. He is also the coordinator of the DIANA NATO Quantum Communications Test Center and the Quantum Communications Infrastructure of Madrid. He has been the Principal Investigator in more than 30 Quantum Communications projects, notably his participation in the European Quantum Flagship program, where he led work related to quantum networks. He has also coordinated the National Quantum Communications Program (complementary actions) at the national level. He has worked on standards for QKD (Quantum Key Distribution), mainly at ETSI (European Telecommunications Standards Institute) where he was a founder of the Industry Specification Group on Quantum Key Distribution and is currently vice-chair, and at CEN (*Comité Européen de Normalisation*), where he is the coordinator of the Working Group on Quantum Cryptography and Communications. His main research interest is the integration of Quantum Communications for new applications in Telecommunication Networks and critical infrastructures.

EXECUTIVE SUMMARY

Quantum technologies are transforming numerous sectors, including healthcare. Although their use in the medical field already includes established applications such as lasers and nuclear magnetic resonance, recent advances have positioned quantum technologies as one of the emerging areas with the greatest potential to revolutionize healthcare. In this context, three quantum technologies stand out: quantum sensors, quantum computing, and quantum cryptography.

These technologies promise significant improvements in clinical research. **Quantum sensors** will enable more precise detection of biomarkers and other molecular markers, facilitating the development of new diagnostic techniques. **Quantum computing**, with its ability to process large volumes of data at unprecedented speeds, will enhance the design of innovative drugs and optimize clinical trials.

On the other hand, in clinical practice, these technologies have the potential to transform disease prevention, prediction, and early diagnosis. They could also improve patient monitoring and personalized treatment, contributing to more effective health care tailored to the individual needs of each person. **Quantum cryptography**, for its part, will offer absolute security in data protection, a critical aspect in an increasingly digitalized healthcare environment.

However, the development of quantum technologies is still in its early stages, and their integration into the healthcare system requires the generation of solid evidence and the creation of adequate infrastructures. Additionally, it will be necessary to address a series of technical, implementation, and training challenges to ensure effective integration, aiming to fully leverage their potential and translate their innovations into the medicine of the future.

INTRODUCTION

Quantum technologies are those based on the properties and characteristics that matter acquires at a microscopic scale, studied by quantum physics. The application of quantum technologies in medicine has well-established precedents, such as, the use of lasers or nuclear magnetic resonance imaging (MRI). However, with the advances in recent years in this field, they have positioned themselves as one of the emerging technologies with the greatest potential and impact in the medicine of the future. In this regard, it is worth noting that the United Nations have chosen the ***year 2025 as the International Year of Quantum Science and Technology****,* in commemoration of the 100th anniversary of the discovery of one of the fundamental principles of quantum physics, Heisenberg's Uncertainty Principle.[1–3]

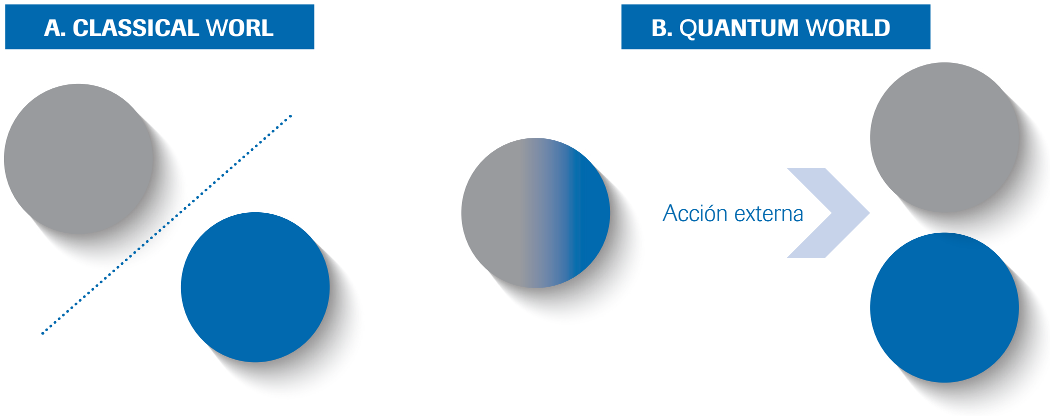
In fact, in recent years, significant advances have been made in the field of quantum technologies, enabling the development of new methods for studying, predicting, diagnosing, treating, or monitoring diseases tailored to the needs of each individual, which will promote the implementation of Personalized Precision Medicine. Thus, and thanks to the availability of computer tools capable of performing massive analyses and exchanging health data quickly, efficiently, and securely, applications derived from quantum technologies are expected to revolutionize the medicine of the future.

QUANTUM PHYSICS PROPERTIES AND PRINCIPLES

Quantum physics is a branch of physics that emerged in 1900 and developed during the first quarter of the 20th century. It studies phenomena that occur at the atomic and subatomic scales. The particles found at these scales, also known as quantum particles, such as atoms, electrons, or photons, exhibit properties that differ from microorganisms and structures observable at a macroscopic scale. These **properties of quantum particles** give them distinct behavior, which are described as follows:

- **Superposition or coherence:** a quantum particle can exist in multiple states simultaneously, constantly oscillating between them. However, if a particle is affected by an external signal or disturbance, it loses its "coherence" and collapses into a single state. This prevents knowing exactly what state a quantum particle is in at any given moment. It is, at the moment of observation, that the particle is disturbed and adopts one of its possible states. [4–8]

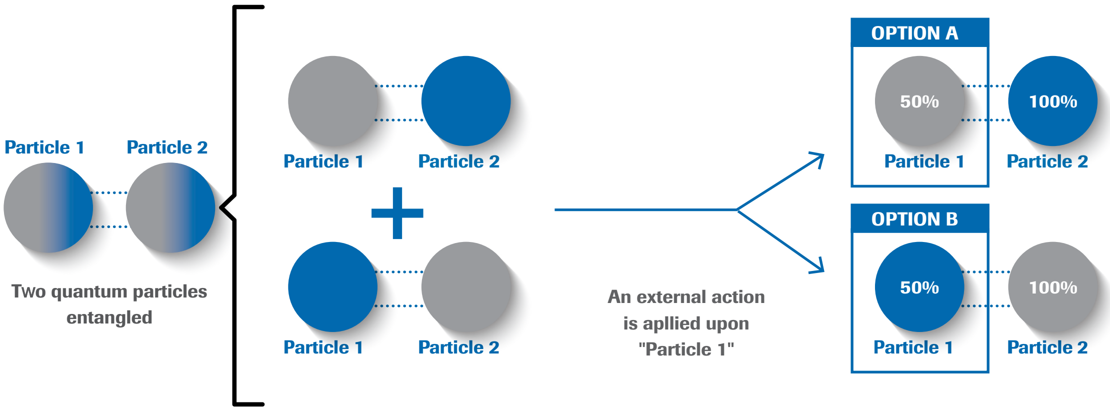
Figure 1. Quantum superposition or coherence.



In the classical world, particles an only be found in ones state (grey or blue). According to quantum principles, particles oscillate between both states (grey and blue), and only take on one of the states when an external action is applied.

- **Entanglement:** Two or more quantum particles in a system[a] are strongly correlated with each other. This means that the quantum state of one particle is so closely linked to the state of the others that it cannot be described independently. Thus, even if the particles are separated, measuring the state of one particle instantaneously reveals the state of the other. [4–8]

Figura 2. Entrelazamiento cuántico.



In a quantum system of two entangled particles, both particles exist initially in a superposition of states, oscillating between grey and blue. However, when applying an external action and measuring the state, for example, of particle 1, it takes one of the two possible states (grey or blue), with a probability of 50% for each case. If, upon measurment, particle 1 is found to be in the grey state, particle 2 will instantly take the opposite state, blue. Similarly, if particle 1 is measured in the blue state, particle 2 will automatically be in the grey state. This correlation occurs regardless of the distance between particles.

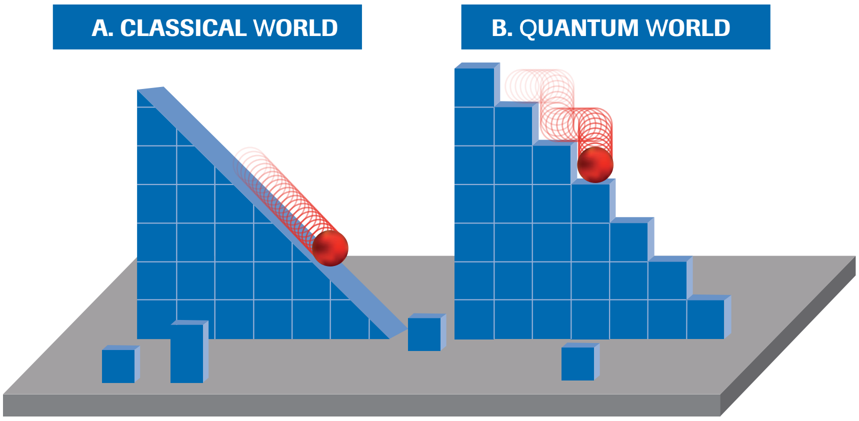
Furthermore, the **principles governing quantum physics**, and therefore quantum particles, differ significantly from those of classical physics, which describes phenomena occurring at a macroscopic scale:

---

[a] *Set of particles correlated with each other.*

- **Energy Quantizatin Principle**: In quantum systems, energy can generally only take discrete values. This means that energy the energy of a particle cannot vary continuously but only in discrete increments or energy packets called "quanta”.[4-8]

Figure 3. Energy Quantization.

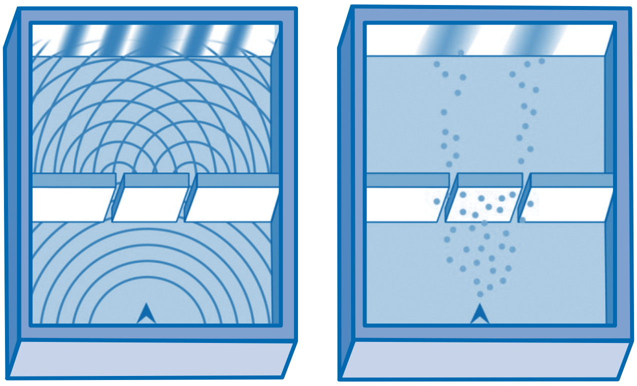


In a classical system, energy varies gradually or continiously and, therefore, can take any value. However, in a quantum system, energy can only take discrete values, varying in a "stepped" manner in what is known as "quanta". Adapted from (9)

- **Heisenberg's Uncertainty Principle**: It states that it is not possible to simultaneously and precisely measure certain properties of a particle, such as its position and velocity, for example. Measuring a particle's position with great precision makes its velocity indeterminable, and vice versa. This implies that, instead of describing the exact trajectory of a particle, quantum physics provides a probability of finding the particle in a particular location and with a certain velocity. These probabilities (amplitudes) are described by the **Schrödinger equation**, which allows the study of how a particle's properties change over time in a mathematical way. [4–8]

- **Interference Principle:** Derived from the fact that quantum particles can behave as probability waves, when two or more waves interact or overlap, a phenomenon known as "interference" occurs. [4–8]

Figure 4. Interference Principle.



The double-slit experiment demonstrates that quantum particles have a dual nature: they can behave like particles or like waves. When electrons or photons are directed at a barrier with two slits, an interference pattern is observed on the screen behind the barrier (left). This pattern indicates that the particles pass through both slits simultaneously and behave like waves. However, if an attempt is made to observe which slit a particle passed through, its behaviour changes: it acts like a classical particle, passing through only one slit, and the ineterference pattern disappears (right). Adapted from (10)

It is worth noting that although the **quantum physics principles** are intrinsic to the atomic scale, they **can be applied at the macroscopic scale, expanding the potential of many technologies.** Specifically, in the field of health, quantum technologies will allow the detection and measurement of small variations in substances with great sensitivity, enable rapid and precise calculations, and improve the processing and handling of large volumes of data. Additionally, they will enable the creation of coding and encryption systems that will make communications much more secure than they currently are.

NEW QUANTUM TECNOLOGIES IN THE FIELD OF HEATLH

As previously mentioned, many of the devices currently used in clinical practice have a quantum origin, such as MRI for medical imaging or lasers used in various medical applications. However, in recent years, significant advances have allowed the development of new quantum technologies that can be applied in the field of health. These quantum technologies can be categorized into **quantum sensors, quantum computing, and quantum cryptography**.

Quantum sensors

A sensor is a device that detects a specific external action, such as temperature, pressure, etc., and transmits it accordingly. **Quantum sensors enable highly sensitive measurement of changes in quantum properties due to an external action**, be it in the energy quanta of a particle, entanglement between different systems, or quantum coherence. Currently, quantum sensors are the most developed quantum technologies, allowing the detection and measurement of minimal variations in substances that go unnoticed by traditional sensors, with great sensitivity, in small samples. Additionally, thanks to the high precision of quantum sensors, it is not necessary to repeat measurements to obtain consistent results.

Different platforms[b] are being developed for the application of quantum sensors in the field of health, and the results are promising, such as, for example:

- **Sensors based on Nitrogen-Vacancy (NV) Centers implanted in diamonds (NV diamonds or NV centers in diamonds)**. These are crystalline structures of diamond in which one of the carbon atoms is replaced by a nitrogen atom, leaving an adjacent vacant position and creating a "defect" or irregularity at the atomic level.[12] NV centers are highly sensitive to physical changes in their environment, such as heat, light, pressure, electromagnetic fields, or the chemical composition of their surroundings, among others. Additionally, these NV diamond-based sensors are **biocompatible**[c] and the only ones that can operate at room temperature, properties that currently make them the main potential quantum sensors in the field of medicine.[12]
- **Sensors based on SQUIDs (Superconducting Quantum Interference Devices).** These consist of devices made of superconducting materials shaped like a ring, separated by a thin layer of insulating material. SQUID-based sensors are capable of measuring changes in magnetic fields with high sensitivity and precision. Unlike NV diamond-based sensors, SQUID-based sensors are not biocompatible and need to remain at cryogenic temperatures (between -150°C and -195°C).[13]

Quantum computing

Classical computing refers to the use of computers and systems based on the principles of classical physics for data processing. In contrast, quantum computing is a branch of computing that **uses the quantum physics principles to process information.** It is characterized by having a much **greater computational potential than classical computing, being able to solve complex problems much more quickly and efficiently**.[14–16]

---

[b] *System or set of technologies that serve as basis for the design, development, and implementation of, in this case, quantum technolgies*

[c] *They don't produce allergic, inmunological, etc., reactions when coming into contact with the body's tissues*

The main difference between the two is the **basic unit of information** they use. In conventional computing, the unit of information is the bit, which can take on two values, 0 or 1. Information is generated through combinations of bits, which can then be stored or processed by the computer. In contrast, in quantum computing, the unit of information is the **qubit**, which can be in a superposition of both states, 0 and 1, simultaneously.[14–16] Additionally, thanks to the quantum properties of entanglement and interference, qubits can exponentially increase the amount of information generated and perform multiple calculations in parallel with great precision. This significantly contributes to solving more complex problems in a shorter amount of time.

Quantum computing requires the use of quantum computers capable of processing qubits of information. These are very complex and sensitive systems that must be kept in stable conditions, with temperatures close to absolute zero (-273°C) in some current prototypes, and isolated from external noise (electric fields, magnetic fields, etc.). In fact, any alteration in these conditions can affect the capabilities of quantum computers, leading to the generation of errors in their calculations.[14–17] This makes it challenging to make quantum computers available and usable in various applications, and specially in current clinical practice.

Currently, there are numerous quantum platforms in development representing different approaches in the field of quantum technologies. The diversity in the types of qubits and their characteristics is crucial for finding the most suitable solutions for various quantum applications in the future. Among the main platforms are:

- **Trapped Ion Qubits**: A platform based on the use of charged atoms (ions) that are held in devices called ion traps[d]. These ions exhibit quantum properties such as state superposition and entanglement. This platform is used to construct quantum computers, **allowing for multiple precise calculations to be performed simultaneously.** Additionally, thanks to the design of these ion traps, multiple quantum systems can be connected, enhancing their scalability and processing potential.[18–20]

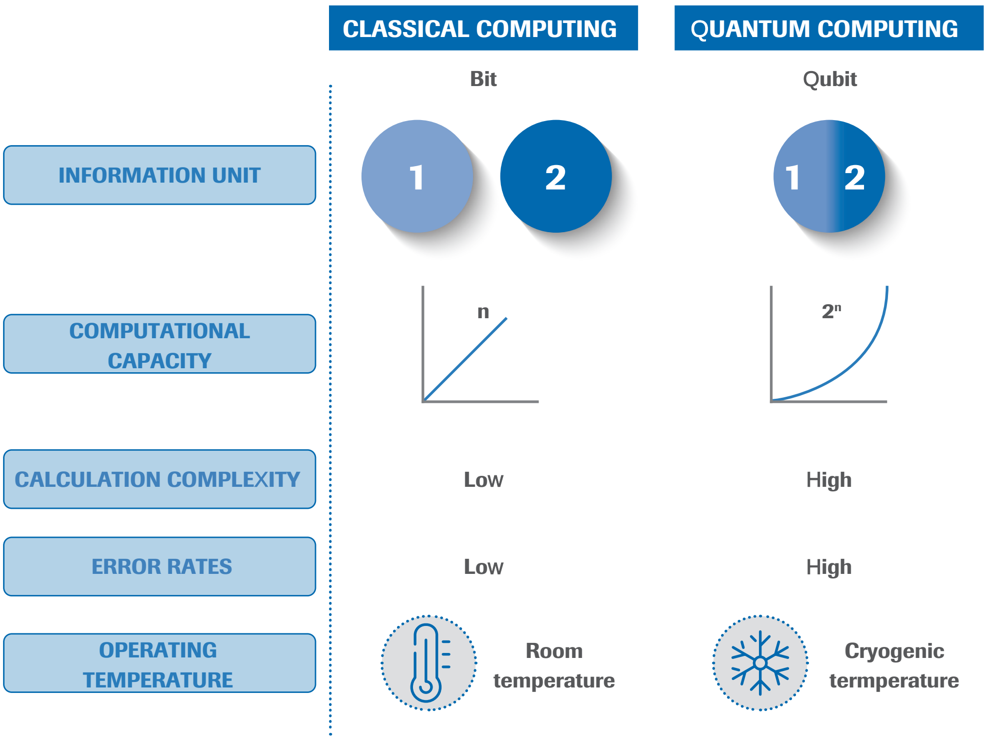
---

[d] *Device that uses electromagnetic fields to trap ions.*

- **Superconducting qubits:** A platform that uses circuits based on superconducting materials, such as lead or aluminum, to efficiently transmit electric current. This platform significantly increases the transmission of electric current compared to other conventional materials, thereby **enhancing the efficiency, speed, and scalability of information processing.**[21–23]
- **Qubits in Optical Lattices**: A platform based on the use of neutral atoms that are trapped in optical lattices[e]. Neutral atoms exhibit quantum properties and can be manipulated to model their quantum state and **perform various fast and precise operations.**[24,25]

Other notable platforms include silicon spin qubits, photonic qubits, single electrons in diamond (nitrogen-vacancy centers), topological qubits, spin qubits in molecules, among others.

Figure 5. Main differences between classical computing and quantum computing.



	CLASSICAL COMPUTING	QUANTUM COMPUTING
	Bit	Qubit
INFORMATION UNIT	1 2	1 2
COMPUTATIONAL CAPACITY	n	2^n
CALCULATION COMPLEXITY	Low	High
ERROR RATES	Low	High
OPERATING TEMPERATURE	Room temperature	Cryogenic termperature

Classical and quantum computing differ in several jey aspects. In classical computing, the basic unit of information is the bit, which can be = or 1, whereas in quantum computing it is the qubit, which can simultaneously represent both 0 and 1. This allows a quantum computer, with n qubits, to perform parallel calculations on 2^n possible combinations, increasing greatly the computational capacity of these computers and enabling them to solve mucho more complez calculations than classical computers. However, due to the sensitivity and nature of qubits, quantu, computers have much higher error rates than classical computers, which tend to be more reliables. Additionally, to function correctly, quantum computers must be maintained under exterme conditions, while classical computers operate under normal conditions. Adapted form (16).

Quantum computing is expected to be the quantum technology with the greatest potential impact on the medicine of the future, due to its ability to perform rapid and precise calculations, enhancing the processing and handling of large volumes of data and the improvement of quantum simulation models.

Quantum cryptography

Cryptography involves **encoding or encrypting information using complex algorithms and mathematical problems**, such as the factorization[f] of large integers to **establish keys and protect information.**[26] It is a very secure systembecause current computers do not have the computational capacity to decode these keys. In fact, today's most powerful computers would take billions of years (3.31 x 10^{56} years) to crack a 256-bit key.[26] However, in 1994, Peter Shor mathematically demonstrated that quantum computing, with its ability to process a tremendous amount of data and perform calculations simultaneously, could indeed break conventional cryptographic keys in a much shorter time, in a matter of minutes or seconds.[26–28]

Quantum cryptography is based on the **quantum properties of coherence and entanglement to generate keys and protect information**. Therefore, **regardless of advances in computational capacity, quantum keys could not be deciphered**. Thus, quantum cryptography positions itself as a revolutionary technology for information protection and security, enabling the creation of more secure communication systems.[27,28]

The main platform developed for the application of cryptography in the health field is **waveguide-based photons**[g].[29] This platform consists of a structure that confines and directs photons in a specific direction, capable of transmitting signals at high speed and over long distances. Based on this platform, the main quantum cryptography system developed is **Quantum Key Distribution** (QKD), designed by Bennett and Brassard in 1984. It is based on sending photons through an optical fiber cable between the system agents, sender and receiver, who previously establish a secure key to encode the information. The sender is capable of defining the specific physical orientation of the photons, thus “forcing” each particle to adopt a unique value (0 or 1), generating a key through the optical fiber cable simulta-

---

[f] It involves decomposing a number, a polynomial, a matrix, or other mathematical entities into a product of simpler ones.
[g] Light particle with the smallest unit of energy in a light wave. Photons cannot be divided and oscillate in two perpendicular directions at the same time.

neously at both the sender and the receiver. The receiver reads the state of each photon received and compares them with the states of the sent photons, collaboratively generating the key. Once this key is established, both the sender and the receiver can use it to encrypt and decrypt messages through classical cryptographic algorithms. Since it is not possible to observe the quantum state of the photons without modifying it, any attempt to break the key by an external agent (neither the sender nor the receiver) would disturb the system, thus disabling access to the information.[26–28]

Given the nature and sensitivity of health-related information, and the significant advancement in the digitalization of the health sector, quantum cryptographypositions itself as a potential tool to protect information and enable data exchange between healthcare professionals, researchers, and patients securely.

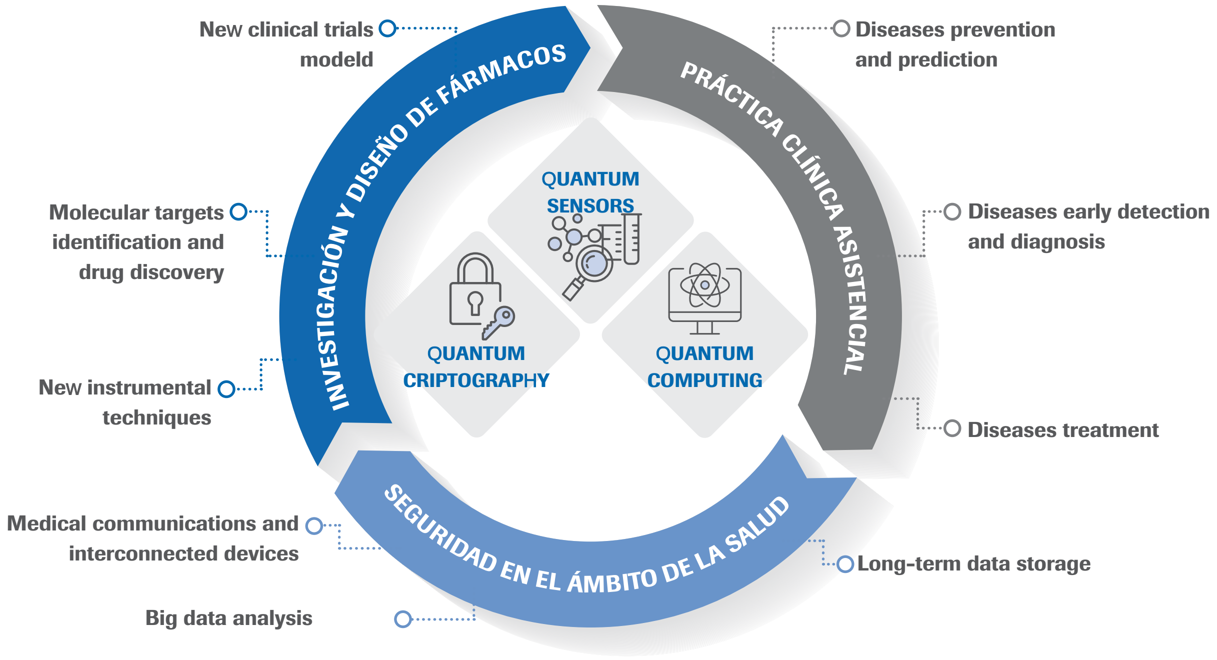
At the national level, it is worth highlighting the MadQCI project (Madrid Quantum Communications Infrastructure), initiated in 2009, which aims to build a quantum communications infrastructure covering the metropolitan area of Madrid and connecting with the future European Quantum Communication Infrastructure (EuroQCI). The project is not only focused on improving cybersecurity but also on promoting technological innovation through collaboration between public and private institutions. Key participants include the Technical University of Madrid, Telefónica, and RedIMadrid. Currently, the network extends within a 30 km radius, and it is expected that in the future, hospitals and health centers in Madrid will be integrated into this network to ensure the security of clinical information exchange.[28, 30]

For all these reasons, **quantum sensors, quantum computing, and quantum cryptography** are positioned as emerging technologies with great potential in the medicine of the future. Their development and implementation will enable a **paradigm shift in healthcare research and in the security and privacy of data in an increasingly digitalized healthcare environment, as well as contribute to Precision Personalized Medicine by enhancing the capacity for disease prevention, prediction, and early diagnosis, and the development of innovative and personalized treatment**.

QUANTUM TECHONOLOGIES APPLICATIONS IN HEALTH

The main objectives pursued by quantum technologies in the field of medicine, and specially in Personalized Precision Medicine, focus on the **development of new research techniques and drug design, the improvement of clinical practice and patient care, and the support of healthcare professionals in decision-making, as well as the security in the collection, storage, and handling of health data.**

Figure 6. Main quantum technologies applications in Personalized Precision Medicine.



QUANTUM TECHNOLOGIES APPLICATION IN DRUG REASEARCH AND DESIGN

In the field of biomedical and clinical research, **the application of quantum technologies, particularly of sensors and quantum computing, is expected to have a greater impact.** These technologies will allow for a deeper knowledge and better understanding of diseases and their causes through the **development of new advanced instrumental techniques**[h] **and the massive analysis of data**. Additionally, they will enable the **redesign of the way new drugs are researched through quantum simulation models, contributing to the optimization and reduction of the time needed in the different phases of health research.**

---

[h] *Scientific processes used to provide information about the composition of substances. There are three main types that encompass the majority of instrumental techniques: spectroscopy, electrochemistry, and chromatography.*

New instrumental techniques development

Microfluidics

One of the main lines of development with diamond NV quantum sensors focuses on the field of microfluidic[i], given **quantum sensors high sensitivity for the analysis of samples chemical composition and precise measurement in microvolumes**. NV diamond-based quantum sensors can be integrated into **microfluidic devices** known as **lab-on-a-chip**[j], integrating one or several laboratory functions on a single platform, such as DNA sequencing, chemical analysis in biological samples, the study of chemical or enzymatic reactions, among others. Furthermore, quantum sensors have been included in **microfluidic chips** known as **organ-on-a-chip**[k] to study human pathophysiology or the therapeutic effect of drugs on the organism. [31,32]

Nano-Nuclear Magnetic Resonance Spectroscopy (nanoNMR)

Another of the most promising lines of work with NV diamond quantum sensors is what is known as nano-nuclear magnetic resonance spectroscopy (nanoNMR).[33–35] NanoNMR allows to study systems formed by few molecules and to detect of the presence of free radicals[l], achieving **a sensitivity that can detect variations at a nanometric scale (10^{-6} mm) with much higher resolution than conventional NMR spectroscopy techniques**[m]. Its applications are being developed for the study of molecular interactions in complex biological environments, and the analysis of molecular structures and chemical compositions of materials and biological systems that cannot be detected with traditional NMR spectroscopy techniques. [33–35]

Molecular targets identification and drug discovery

The study and understanding of the biological processes that give rise to various diseases are fundamental to comprehending the causes and risk factors for the development of pathologies, as well as to developing different preventive, diagnostic, and therapeutic strategies.

Molecular targets

In the field of **omics sciences** (for more information, see the Anticipating Report on *Omic Sciences*), there are currently **applications of quantum sensors and quantum computing that will allow their full potential to be exploited, promoting a holistic and personalized approach based on the individual characteristics of each person**,

---

[i] *Field of study of the behavior of fluids at the micrometric scale.*

[j] *Instrument or microfluidic device that uses very small amounts of body fluids or solutions containing cells or other substances to perform some laboratory tests.*

[k] *Systems that contain natural or artificial tissues cultured in microfluidic chips to simulate the microenvironment and key functional aspects of organs.*

[l] *Atom or group of atoms, generally highly reactive and short-lived, that possesses one or more unpaired electrons.*

[m] *Type of medical imaging that uses a strong magnetic field and radiofrequency waves to produce highly detailed images.*

In the field of genomics, quantum computing can be used to study patterns and molecular interactions derived from large DNA sequences, facilitating the understanding of genetic diseases and the rapid and accurate identification of relevant mutations.[36] Additionally, large volumes of data can be compared, optimizing, for example, the reconstruction of phylogenetic trees that show the evolutionary relationships between different species, providing more information about genetic evolution. This field is especially important for the understanding and study of hereditary diseases.[36] Furthermore, through quantum machine learning algorithms (QML), it will be possible to classify genetic diseases from large genetic data sets. This enhanced processing capability can aid in the early detection of diseases and the development of personalized treatments, paving the way for genetic research and Precision Personalized Medicine.[36,37]

Similarly, in the field of proteomics, quantum technologies will enhance the understanding of protein interactions in various biological processes that trigger numerous diseases, for which there are currently no tools or devices available to study them in detail. Additionally, thanks to the inherent properties of quantum sensors, biological processes occurring at the intracellular level can be studied. Specifically, NV center quantum sensors implanted in nanodiamonds have been developed for studying inflammatory processes through the measurement of local thermal changes in the cells that trigger inflammation. These sensors will enable physiological studies to generate scientific evidence on the origin of various diseases and pathologies, such as cardiac disorders, diabetes, or autoimmune diseases, which are believed to be closely related to inflammation and overactivation of the immune system.[38,39] Through quantum algorithms, it will also be possible to predict how proteins interact during these biological processes, with the aim of identifying new therapeutic targets and guiding the development of new treatments. [36]

Quantum computing also plays a fundamental role in the study and determination of protein spatial folding. The correct spatial folding of proteins determines their function in the organism. However, currently, the structure of less than 10% of the proteins, whose sequences are available, is known experimentally. In this context, QFold has been developed, a quantum computing tool that combines the AlphaFold[n] prediction system based on deep learning techniques with the Metropolis-Hastings quantum computing algorithm.[40] With algorithms like QFold, it will be possible to perform molecular simulations and modeling of complex interactions at the atomic level to predict protein folding quickly and accurately, and therefore their three-dimensional structure, with

---

[n] *Artificial Intelligence program that predicts the structure of proteins using a deep learning system.*

greater accuracy than conventional techniques and with less time and resource consumption.[36,37]

Drug discovery and design

The **advances in computational chemistry and bioinformatics, along with the vast availability of health data, have improved the identification of molecules that can serve as therapeutic targets for drug design and development.** Given the large availability of data and the dependence on high-potential and high-performance computational resources needed for the discovery of new drugs, it is expected that advances in quantum computing could revolutionize biomedical research and the development of much more effective targeted treatments and therapies. Through quantum algorithms, it will be possible to explore a wide variety of chemical compositions and identify potential candidates with greater accuracy. Additionally, their implementation will favor the optimization of processes, reducing costs and time required in pharmaceutical research. The development of quantum simulation methods will allow faster and more accurate characterizations of molecular systems than current computational chemistry methods.[41,42]

Development of new clinical trial models

Quantum technologies can be applied to the design of new clinical trial models, reducing the required time and improving health outcomes. For example, quantum sensors applied in organ-on-a-chip systems allow for the creation of a biological environment that simulates the natural behavior of human organs to conduct toxicology studies without the need for animal models. The high sensitivity of these sensors, along with the requirement for very small samples, enables more efficient and cost-effective clinical trials, improving data quality and accelerating the development of new treatments and medications. [31,32,43]

On the other hand, new advances in systems and computational tools with great computing potential have improved the estimation of research outcomes. In recent years, there has been an increase in the use of tools based on the probabilistic method of Bayesian inference in research[o]. Bayesian methods allow the continuous updating of the probability of treatment success as new data is collected during the trial for decision-making based on probability. In turn, they allow real-time adjustments to the study, modifying aspects such as sample size or dosage, among others, with the aim of improving efficiency and reducing the time and costs associated with the trial. The application of quantum computing to existing Bayesian analysis tools can help accelerate information processing and increase efficiency in the search for solutions.

---

[o] *Bayesian interference is a stadistical method that allows the probability of a hiyothesis to be updated as new evidence becomes available.*

These capabilities not only optimize the time and resources employed but also provide a faster and more accurate estimation of significant clinical outcomes and benefits. [44–48]

QUANTUM TECHNOLOGIES APPLICATION IN CLINCAL PRACTICE

Diseases prevention and prediction

The **development of new tools and predictive models using quantum computing will open up new possibilities in Preventive Medicine and Precision Public Health**. For example, thanks to quantum algorithms, large volumes of viral genomic data can be analyzed to better understand how viruses evolve and spread. This analysis will allow researchers to study and construct viral phylogenetic trees using advanced information theory techniques[p]. The information derived from the analysis will facilitate the study of evolutionary relationships between viruses and their hosts, identifying patterns of mutations and genetic recombination that give rise to new strains. Understanding and comprehending these processes provide crucial information for establishing strategies for the development of prevention plans.[36,37]

Diseases early detection and diagnosis

Early diagnosis and timely management of diseases are essential for improving health outcomes and the quality of life of patients. **Technological advances and the identification of biomarkers have enabled the development of diagnostic tools that are crucial in defining the most appropriate therapeutic approach for each patient**. In this context, various quantum technologies are being developed to offer more precise and early diagnoses.[38,39]

Biomarkers detection

The application of diamond NV-based quantum sensors is being developed for the detection of biomarkers in cancerous cells, such as the oncological biomarkers SKBR3 or HER2, or in blood cells infected by the parasite *Plasmodium falciparum*, the cause of malaria. This involves labeling with magnetic nanoparticles that specifically bind to the biomarkers, allowing them to be detected with high resolution.[49,50]

In this regard, it is expected that, in future medicine, these sensors will be integrated into the previously mentioned lab-on-chip devices and could be available at various healthcare points of care or even in people's homes (ponit-of-care testing[q]).

---

[p] Computational and mathematical tools that are used to analyse and understand complex data, like DNA and RNA sequences, to find patterns and relationships btween them.

q Clinical laboratories located near patient healthcare spaces where patients can go to undergo laboratory tests

This will enable faster and more accurate diagnostics as well as real-time disease monitoring. [31,32]

Medical imaging

On the other hand, in the field of applying quantum sensors in medical imaging, NV diamond-based sensors and SQUID sensors can be used to improve both resolution and accuracy. This **increased resolution allows for a more detailed visualization of tissues and organs, facilitating a more accurate interpretation of images and aiding in the early detection of pathologies**. Additionally, due to their ability to provide real-time results, these sensors can be particularly useful in image-guided surgeries or disease monitoring.

In this vein, there have been significant advances in developing NV diamond-based sensors for diagnosing cardiac pathologies through magnetic cardiology, which allows for the study of the origin and evolution of cardiac arrhythmias, fibrillation, and tachycardia, among others.[51] Another example is SQUID-based sensors, which can measure the electrical activity of the gastrointestinal tract through a diagnostic technique called **magnetogastrography**, thereby enabling early detection of possible gastric and intestinal pathologies, such as motility disorders or intestinal obstruction..[13]

Additionally, in the field of **Neurology**, quantum sensors are emerging as highly relevant tools for understanding and early detection of diseases such as Parkinson's or Alzheimer's, which require more detailed analysis. For example, a technique called **magnetoencephalography**, based on SQUID sensors, is being developed. This technique can identify electrical activity generated between neurons and observe the brain's dynamic processes with high resolution and in real-time.[52] On the other hand, non-invasive techniques using NV diamond-based sensors are being developed to detect and measure the magnetic fields produced by electrical changes generated by neurons during information transmission. [53] Although these tools are being tested in animals, they have the potential to offer non-invasive and highly accurate methods for identifying brain electrical activity. This line of research could be useful for understanding neuronal behavior and, therefore, for the development of early diagnostic techniques for some neurological and psychiatric disorders.[13,53]

In the field of **Oncology**, significant advancements have been made with the introduction of improved diagnostic techniques that allow for early cancer detection and more precise real-time monitoring and follow-up. One of these techniques is based on the hyperpolarization of contrast agents to enhance current Magnetic Resonance Imaging (MRI) scans, enabling the examination of tumors at a metabolic level. This technique enhances the magnetic properties of certain metabolites, such as pyruvate, which play a crucial role in the glycolysis of cells. Cancer cells typically have a higher glycolytic rate than healthy cells, so by amplifying the signal of these metabolites, an increase in metabolic activity can be detected, facilitating the identification and characterization of tumors.

This technique offers significant advantages over traditional diagnostic techniques as it measures metabolic changes in tumors, which occur much earlier than anatomical changes, allowing for early tumor diagnosis. Additionally, it enables real-time metabolic imaging, promoting better tracking and monitoring of tumor progression.[54]

Decision-making support in health

Bayesian inference emerges as an innovative support tool for healthcare professionals in decision-making. It enhances the interpretation of medical test results and allows for more accurate disease prediction. Additionally, it helps define personalized and more efficient treatments for each patient based on the probability of treatment success according to the patient's genetic and clinical profile and medical history.[44–47] In this sense, quantum computing will improve the estimates made by prediction and diagnostic tools based on Bayesian inference, offering greater precision and accuracy in results. The application of quantum Bayesian inference in critical medicine will allow for the analysis and comparison of a vast amount of health data (genomic, transcriptomic, epigenomic, clinical, and other health determinants) in a very short period. This will help healthcare professionals make quick decisions and reduce errors, thereby improving patient care. [44–47,55]

Diseases treatment

In addition to improving the study of new molecular targets and the design and development of new personalized therapies and pharmacological treatments, one of the treatments that will be most impacted by quantum technologies is **radiotherapy**. Radiotherapy uses computers with great computational capacity capable of analyzing information obtained from medical images, such as Computed Tomography (CT) or MRI, and the location and extent of the tumor to precisely define the tumor's positio.[56] All of this requires numerous precise and complex simulations. In this regard, quantum computing will allow for multiple parallel simulations, enabling the formulation of a much more precise therapeutic plan and optimizing the radiation dose delivered in an optimal time. Progress to date has focused on applying quantum computing to the design of machine learning algorithms, such as the Quantum Tunneling Algorithm (QTA), which will optimize therapeutic planning and treatment precision, improving their adaptation to patient needs.[57,58]

QUANTUM TECHONOLOGIES APPLICATION IN HEALTHCARE SECURITY

Thanks to technological advancements in the healthcare sector, it has become increasingly possible to incorporate data from various sources, providing information that can be of great interest to healthcare professionals, researchers, and especially patients (for more information, see the Anticipating Report on *Data in the Era of Personalized Precision Medicine*).

Due to the nature of health data, it is **essential to have protection mechanisms and systems that guarantee the anonymity of individuals, ensuring confidentiality, protection, and privacy at all times**. Therefore, in an increasingly automated and digitized healthcare environment, it is vital to ensure that information, especially that related to patients or healthcare actions directed at patients, is accurate and has not been compromised. In recent years, new cryptographic mechanisms have been developed to safeguard the security of health data concerning its storage, sharing, and analysis. In this regard, quantum cryptography offers security mechanisms whose implementation and integration into existing protection systems could ensure a completely secure data environment.

Long-term data storage

Technological and computational advancements have transformed the way information is stored, moving from physical records stored on paper to digital records, where information is stored in large electronic data repositories. Additionally, in recent years, due to the advent of big data and advancements in Information and Communication Technologies (ICTs), there has been a growing trend in using cloud-based databases and data repositories. The **massive generation of health data necessitates ensuring the security of its storage over long periods, as well as establishing mechanisms that allow for the exchange of information without being compromised by external agents**, thereby **safeguarding the integrity and accuracy of the information**. Quantum Key Distribution (QKD) technologies will enable the development of distributed databases[r] in different locations, interconnected by a network, ensuring "absolute" security in the access and exchange of information. Through this quantum infrastructure and key generation, the confidentiality of clinical data is ensured, allowing access or

---

[r] *A type of database consisting of multiple databases interconnected by a network, allowing any user to access the data from any part of that network.*

modifications only by parties integrated into the network.[28] Additionally, one of the significant advantages of this technology is that, in the event of data loss due to a failure or cyber-attack, it can reconstruct itself, recovering and restoring the lost information.

Big data analysis

In the healthcare sector, the **collection, generation, and analysis of data can be highly relevant to researchers, healthcare professionals, and patients**. The availability and analysis of these data have significantly contributed to the implementation of Personalized Precision Medicine. In this context, Quantum Key Distribution (QKD) presents significant potential in the field of big data analysis. Through this technique, comprehensive information about a dataset can be obtained, aggregating partial datasets without the owners of those partial datasets having to disclose information about them. This allows for the creation of, for example, genomic trees in a collaborative manner, without each participating party having to reveal their data, thereby preserving the privacy of their sources or maintaining the intellectual property of their data. This approach not only facilitates collaborative research and data sharing but also ensures that sensitive information remains secure, fostering trust among data owners and promoting a more integrated and comprehensive analysis of healthcare data.[59]

Medical communications and interconnected devices

In recent decades, advancements in medical technologies and the widespread use of ICT systems and tools have transformed the healthcare field. Support technologies based on Artificial Intelligence (AI) and the automation of some clinical tasks are increasingly being used in clinical practice, offering more precise and effective solutions tailored to the needs of individuals. Additionally, the use of participatory digital health technologies, such as health apps and wearables, along with Internet of Things (IoT) technology, has increased, allowing users to access health-related information in real-time.

Similarly, the development of telemedicine and telemonitoring has enabled healthcare professionals to offer services to users regardless of their location, improving access to healthcare and reducing geographical barriers. **All these technologies and new healthcare models require the constant generation of data and information flows**. However, **the transmitted data may be susceptible to interception by various external agents**. In this regard, through quantum cryptography technologies, quantum communication protocols are being developed in the healthcare field that can verify the identity of a user or device before allowing access to data or systems, preventing external agents from gaining access. Additionally, it is worth noting that these protocols can be integrated into current medical technologies without the need for the technology itself to be of a quantum type. Specifically, the application of a previously mentioned quantum protocol, known as the BB84 protocol, is being studied in a wireless body sensor network[s] used for remote health monitoring. The results demonstrate that this approach helps protect against attacks on the detected data transmitted through the sensor network to the healthcare professional.[60]

---

[s] *Wireless Body Sensor Networks (WBSN) are systems of sensors located on or near the human body that monitor and transmit physiological data in real-time. These sensors can measure parameters such as heart rate, blood pressure, glucose levels, physical activity, among others.*

CHALLENGES

The **significant advancements in quantum technologies in recent years highlight their great potential in the future of Medicine. However, they are still in the early stages of development**, and the impact of their application in the healthcare field will not be observable for several years. Specifically, it is estimated that the implementation of quantum sensors, which are among the most developed quantum technologies, will occur in the short term, and in the case of quantum cryptography, in the medium term. As for quantum computing, its adoption in clinical practice still faces challenges, as the technology is susceptible to external noise during information processing, making its implementation expected in the long term. Presented below is a series of technical, implementation, and professional training challenges that must be addressed in the coming years to integrate these advancements into clinical practice.

TECHNICAL CHALLENGES

Despite the significant ongoing investments and rapid evolution observed so far, quantum technologies still do not possess the necessary capacity and technological level required for their proper implementation. To fully leverage the potential of quantum technologies, it is essential to address some technical challenges inherent to their quantum properties.

- **The outcome of computational errors due to the alteration of quantum properties** such as the loss of coherence, inaccurate use of qubits, or environmental interference, among others. However, error correction algorithms and mechanisms are being developed and are already available, designed to mitigate and correct alterations in quantum properties, ensuring greater accuracy in the calculations performed by quantum computers.
- **The High sensitivity of quantum technologies to changes in the environment.** Quantum technologies require conditions, such as cryogenic temperatures or temperatures close to absolute zero, ultra-low levels of electromagnetic interference, and the avoidance of any interference that could alter the properties of quantum, particles and components. This high sensitivity necessitates complex infrastructures and specialized facilities to ensure the proper functioning of quantum, technologies. However, significant advancements are being made in the development of quantum, computing platforms capable of operating at room temperature.

- **The difficulty in scaling quantum technologies. Quantum technologies are highly sensitive and require specific and adequate conditions to maintain quantum coherence and error correction.** Therefore, expanding quantum systems without losing quantum properties is a complex and costly task. This challenge specifically affects quantum computing, due to the limitations in constructing quantum systems capable of handling large amounts of qubits. This limits the capability to perform complex calculations in a reasonable period and, therefore, to address complex problems in areas such as molecular simulation and machine learning. These difficulties are currently under study and continue to lead to ongoing innovations.

IMPLEMENTATION AND TRANSLATION CHALLENGES TO CLINCAL PRACTICE

Based on the state of the art and technological advancements in the field of quantum technologies, it is anticipated that their implementation in clinical practice will be gradual with an extended timeline.

- **The necessity of conducting clinical trials in humans to demonstrate the efficacy and safety of using quantum technologies.** For the translation of this technology, or any other, into clinical practice, it is essential to demonstrate minimum levels of safety and efficacy. In the case of quantum technologies, since they are in the early stages of development, there are still no results demonstrating their efficacy, feasibility, and safety in humans. Most clinical trials and validations conducted thus far have been performed on animals, although the first human clinical trials for the development of certain quantum sensors have begun.
- **The high economic investment in infrastructure required for the development and implementation of quantum technologies in healthcare.** The maintenance and current infrastructure needs of quantum technologies imply associated costs that can be substantial. This hinders the adoption of quantum technologies in clinical practice and often leads to the prioritization of other available alternative technologies. However, it is expected that as progress is made in the development of some quantum therapies, interest and funding for these technologies will increase, facilitating their translation into clinical practice.

TRAINIING AND EDUCATION CHALLENGES

Quantum technologies are expected to significantly impact the way healthcare is delivered in the future. However, to ensure their proper implementation and appropriate use, it is crucial to address several challenges related to the training and education of healthcare professionals.

- **The need to incorporate specialized professionals in the field of quantum health technologies within medical teams.** To achieve successful implementation of quantum technologies in the future of Medicine, it is essential to have multidisciplinary teams that include professionals from various fields specialized in quantum technologies (e.g., physicists, mathematicians, engineers, etc.).
- **The lack of training and education for healthcare professional in the field of informatics and computation for the application of quantum, technologies in health.** Most healthcare professional do not possess basic knowledge or specific skills related to quantum technologies (such as advanced classical physics, quantum physics, programming, etc.), which would allow them to apply these technologies in clinical practice once available. While it is not necessary to provide generalized training in this field to all healthcare professional, the development of specific training and educational programs that offer essential basic notions to professionals who will be applying these technologies will ensure the effective application of quantum technologies in the future.

CONCLUSIONS Y RECOMMENDATIONS

Although still in the early stages of development, **recent advances in the field of quantum technologies position them as some of the emerging technologies with the greatest potential and impact on the future of medicine. Their application in the field of healthcare is expected to revolutionize Personalized Precision Medicine by improving the accuracy and sensitivity of diagnostics, and enabling the early detection and treatment of diseases.** Additionally, they will open **new possibilities for more precise and effective therapies, facilitate continuous and personalized health monitoring, and allow the identification of molecular targets and the development of new drugs.** They will also **optimize health data networks, improve gene therapy with more precise and safer edits, and enable personalized medical treatments at the molecular level.**

However, despite the significant advances achieved, there are still numerous challenges to implementing these technologies in the healthcare environment. Therefore, in order to advance the incorporation of these new tools in the future of medicine and their integration into the healthcare system, the following are a series of recommendations to address possible limitations and barriers in the field of quantum technologies.

RECOMMENDATIONS

- **Promote the development of comprehensive Quantum Technologies Strategy** from the Administration, establishing a common vision and short- and long-term action lines for the integration of these technologies into the healthcare system. This strategy should prioritize applications with immediate impact, as well as coordinate efforts among various stakeholders such as the government, industry, academia, and healthcare professionals, among others.
- **Analyze investment opportunities and promote funding for startups and emerging companies** working on the integration of quantum technologies in medicine, through incentives and financial support programs that foster innovation and accelerate the development of these technologies.
- **Invest in infrastructure and resources to develop and apply quantum technologies in the healthcare sector,** including advanced laboratories, improved hospital equipment, and robust data systems. These infrastructures should be designed to support the specific conditions required by quantum technologies, such as cryogenic temperatures and environments free from electromagnetic interference.

- **Promote the development of pilot projects that test scalability in controlled environments**, allowing for the identification and resolution of issues before large-scale implementation, thus ensuring the viability and efficiency of quantum solutions in the healthcare sector.
- **Promote interdisciplinarity and collaboration among professionals specialized in various fields,** such as quantum technologies, biology, medicine, and other health domains, to foster the generation of innovative ideas and the translation of results into clinical practice.
- **Develop a regulatory framework that facilitates research and the use of quantum technologies in healthcare**, ensuring safety and ethics in their application. This framework should be flexible enough to adapt to the rapid advances in the field of quantum technology and enable more efficient human clinical trials, always guaranteeing safety and efficacy.
- **Encourage the attraction and retention of specialized talent in healthcare technologies** through recruitment and collaboration models between the business sector and academia, in both public and private sector.
- **Promote the training and education of healthcare professionals in quantum technologies** through specific educational programs and continuing education courses to ensure up-to-date knowledge and proper application of technologies in clinical practice.

BIBLIOGRAPHY

1. American Physical Society. (n.d.). *The United Nations Proclaims 2025 as the International Year of Quantum Science and Technology*. Retrieved August 5, 2024, from https://www.aps.org/about/news/2024/06/united-nations-2025-iyq

2. Michael Banks. (2024, June 10). *It's official: United Nations declares 2025 the International Year of Quantum Science and Technology*. Physics World. https://physicsworld.com/a/its-official-united-nations-declares-2025-the-international-year-of-quantum-science-and-technology/

3. UNESCO. (2024). *International Year of Quantum Sciences and Technologies*. https://quantum2025.org/es/

4. Freire, N. (2024). *5 keys to understanding quantum physics*. Natural Geographic. https://www.nationalgeographic.com.es/ciencia/cinco-puntos-entender-fisica-cuantica_20763

5. Avagyan, M. (n.d.). *Quantum mechanic summary*. PCE. Retrieved June 1, 2024, from https://escuelapce.com/resumen-de-la-mecanica-cuantica/

6. Cox, B., & Forshaw, J. (2011). *The Quantum Universe: and why everything that can happen, happens. Debate*. http://www.librosmaravillosos.com/eluniversocuantico/pdf/El%20universo%20cuantico%20-%20Brian%20Cox%20y%20Jeff%20Forshaw.pdf

7. Muy Interesante. (2022). Cuantic world (Collectors' Edition, Vol. 25). Zinet. https://suscripciones.zinetmedia.es/producto/mundo-cuantico-muy-interesante-digital-ed-coleccionista-no-25/

8. Muy Interesante. (2024). Quantic physics*. How the subatomic world shapes our lives.* (Collector's Edition, Vol. 37). Zinet. https://www.amazon.es/Interesante-Coleccionista-CU%C3%81NTICA-subat%C3%B3mico-nuestra-ebook/dp/B0D14TFWBJ

9. *Quantum Physics*. (n.d.). Retrieved August 1, 2024, from https://sdsu-physics.org/physics180/physics180B/Topics/modern/phys180Bch28.html

10. Álvarez-Nodarse, R. (2019, April 12). *And waves turned into particles*. https://institucional.us.es/blogimus/2019/04/y-las-ondas-se-convirtieron-enparticu-las/

11. Sensor d*efinition*. (n.d.). Royal SPanish Academy. Retrieved June 1, 2024, from https://dle.rae.es/sensor

12. Guo, S. (2023). An Overview of NV Centers. *Journal of Applied Mathematics and Physics*, *11*(11), 3666–3675. https://doi.org/10.4236/jamp.2023.1111231

13. Fagaly, R. L. (2006). Superconducting quantum interference device instruments and applications. *Review of Scientific Instruments*, *77*(10). https://doi.org/10.1063/1.2354545

14. *What is quantum computing?* (n.d.). IBM. Retrieved June 1, 2024, from https://www.ibm.com/topics/quantum-computing

15. Swayne, M. (2024). *What Is Quantum Computing? [Everything You Need To Know]*. The Quantum Insider. https://thequantuminsider.com/2024/02/02/what-is-quantum-computing/

16. Ur Rasool, R., Ahmad, H. F., Rafique, W., Qayyum, A., Qadir, J., & Anwar, Z. (2023). Quantum Computing for Healthcare: A Review. *Future Internet*, *15*(3), 94. https://doi.org/10.3390/fi15030094

17. Nielsen, M. A., & Chuang, I. L. (2010). *Quantum Computation and Quantum Information* (10th ed.). Cambridge: Cambridge University Press. https://doi.org/https://doi.org/10.1017/CBO9780511976667

18. Cirac, J. I., & Zoller, P. (1995). Quantum Computations with Cold Trapped Ions. *Physical Review Letters*, *74*(20), 4091–4094. https://doi.org/10.1103/PhysRevLett.74.4091

19. Galindo, A., & Martín-Delgado, M. A. (2002). Information and computation: Classical and quantum aspects. *Reviews of Modern Physics*, *74*(2), 347–423. https://doi.org/10.1103/RevModPhys.74.347

20. Leibfried, D., Blatt, R., Monroe, C., & Wineland, D. (2003). Quantum dynamics of single trapped ions. *Reviews of Modern Physics*, *75*(1), 281–324. https://doi.org/10.1103/RevModPhys.75.281

21. Vlatko Vedral. (2013). *Introduction to Quantum Information Science*. Oxford Graduate Texts.

22. Devoret, M. H., & Martinis, J. M. (2004). Implementing Qubits with Superconducting Integrated Circuits. *Quantum Information Processing*, *3*(1–5), 163–203. https://doi.org/10.1007/s11128-004-3101-5

23. Clarke, J., & Wilhelm, F. K. (2008). Superconducting quantum bits. *Nature*, *453*(7198), 1031–1042. https://doi.org/10.1038/nature07128

24. Saffman, M., Walker, T. G., & Mølmer, K. (2010). Quantum information with Rydberg atoms. *Reviews of Modern Physics*, *82*(3), 2313–2363. https://doi.org/10.1103/RevModPhys.82.2313

25. Kaufman, A. M., & Ni, K.-K. (2021). Quantum science with optical tweezer arrays of ultracold atoms and molecules. *Nature Physics*, *17*(12), 1324–1333. https://doi.org/10.1038/s41567-021-01357-2

26. IBM. (n.d.). *¿What is cryptography?* Retrieved July 10, 2024, from https://www.ibm.com/es-es/topics/cryptography

27. Gisin, N., Ribordy, G., Tittel, W., & Zbinden, H. (2002). Quantum cryptography. *Reviews of Modern Physics*, *74*(1), 145–195. https://doi.org/10.1103/RevModPhys.74.145

28. Martin, V., Brito, J. P., Ortiz, L., Mendez, R. B., Buruaga, J. S., Vicente, R. J., Sebastián-Lombraña, A., Rincon, D., Perez, F., Sanchez, C., Peev, M., Brunner, H. H., Fung, F., Poppe, A., Fröwis, F., Shields, A. J., Woodward, R. I., Griesser, H., Roehrich, S., … Lopez, D. R. (2023). *MadQCI: a heterogeneous and scalable SDN QKD network deployed in production facilities*.

29. VSL. (2023, December 15). *¿What are Waveguides?* https://silexst.com/cables-guia-de-ondas-o-waveguides/#Aplicaciones_en_Comunicaciones_de_Alta_Frecuencia

30. MadQCI. (2023). *Madrid Quantum (MadQCI)*. https://madqci.es/

31. Allert, R. D., Bruckmaier, F., Neuling, N. R., Freire-Moschovitis, F. A., Liu, K. S., Schrepel, C., Schätzle, P., Knittel, P., Hermans, M., & Bucher, D. B. (2022). *Microfluidic quantum sensing platform for lab-on-a-chip applications*.

32. Luz León, E., & Torrealba Anzola, F. (2011). The Lab_on_a_chip: existing applicationsand future challenges. *Revista Digital de Investigación y Postgrado*, *1*(1), 2244–8393. https://dialnet.unirioja.es/servlet/articulo?codigo=3895312

33. Cerrillo, J., Casado, S. O., & Prior, J. (2020). *Low field nano-NMR via three-level system control*. https://doi.org/10.1103/PhysRevLett.126.220402

34. Glenn, D. R., Bucher, D. B., Lee, J., Lukin, M. D., Park, H., & Walsworth, R. L. (2018). High-resolution magnetic resonance spectroscopy using a solid-state spin sensor. *Nature*, *555*(7696), 351–354. https://doi.org/10.1038/nature25781

35. Staudenmaier, N., Vijayakumar-Sreeja, A., Genov, G., Cohen, D., Findler, C., Lang, J., Retzker, A., Jelezko, F., & Oviedo-Casado, S. (2023). *Optimal Sensing Protocol for Statistically Polarized Nano-NMR with NV Centers*. https://doi.org/10.1103/PhysRevLett.131.150801

36. Sarkar, A., Al-Ars, Z., & Bertels, K. (2021). Estimating Algorithmic Information Using Quantum Computing for Genomics Applications. *Applied Sciences*, *11*(6), 2696. https://doi.org/10.3390/app11062696

37. Flöther, F. F. (2023). *The state of quantum computing applications in health and medicine*. https://doi.org/10.1017/qut.2023.4

38. Vetter, P. J., Marshall, A., Genov, G. T., Weiss, T. F., Striegler, N., Großmann, E. F., Oviedo-Casado, S., Cerrillo, J., Prior, J., Neumann, P., & Jelezko, F. (2022). Zero- and Low-Field Sensing with Nitrogen-Vacancy Centers. *Physical Review Applied*, *17*(4), 044028. https://doi.org/10.1103/PhysRevApplied.17.044028

39. Neugart, F., Zappe, A., Jelezko, F., Tietz, C., Boudou, J. P., Krueger, A., & Wrachtrup, J. (2007). Dynamics of Diamond Nanoparticles in Solution and Cells. *Nano Letters*, *7*(12), 3588–3591. https://doi.org/10.1021/nl0716303

40. Casares, P. A. M., Campos, R., & Martin-Delgado, M. A. (2022). QFold: quantum walks and deep learning to solve protein folding. *Quantum Science and Technology*, *7*(2), 025013. https://doi.org/10.1088/2058-9565/ac4f2f

41. Cao, Y., Romero, J., & Aspuru-Guzik, A. (2018). Potential of quantum computing for drug discovery. *IBM Journal of Research and Development*, *62*(6), 6:1-6:20. https://doi.org/10.1147/JRD.2018.2888987

42. Yu, S. (2023, October 20). *Towards using quantum computing to speed up drug development*. Imperial. https://www.imperial.ac.uk/news/248638/towards-using-quantum-computing-speed-drug/

43. Chen, X., Zhang, Y. S., Zhang, X., & Liu, C. (2021). Organ-on-a-chip platforms for accelerating the evaluation of nanomedicine. *Bioactive Materials*, *6*(4), 1012–1027. https://doi.org/10.1016/j.bioactmat.2020.09.022

44. Yarnell, C. J., Granton, J. T., & Tomlinson, G. (2020). Bayesian Analysis in Critical Care Medicine. *American Journal of Respiratory and Critical Care Medicine*, *201*(4), 396–398. https://doi.org/10.1164/rccm.201910-2019ED

45. Henriquez, R. R., & Korpi-Steiner, N. (2016). Bayesian Inference Dilemma in Medical Decision-Making: A Need for User-Friendly Probabilistic Reasoning Tools. *Clinical Chemistry*, *62*(9), 1285–1286. https://doi.org/10.1373/clinchem.2016.260935

46. Campos, R., Casares, P. A. M., & Martin-Delgado, M. A. (2023). Quantum Metropolis Solver: a quantum walks approach to optimization problems. *Quantum Machine Intelligence*, *5*(2), 28. https://doi.org/10.1007/s42484-023-00119-y

47. Escrig, G., Campos, R., Casares, P. A. M., & Martin-Delgado, M. A. (2023). Parameter estimation of gravitational waves with a quantum metropolis algorithm. *Classical and Quantum Gravity*, *40*(4), 045001. https://doi.org/10.1088/1361-6382/acafcf

48. Lewis, R. J., & Wears, R. L. (1993). An introduction to the Bayesian analysis of clinical trials. *Annals of Emergency Medicine*, *22*(8), 1328–1336. https://doi.org/10.1016/S0196-0644(05)80119-2

49. Quantum diamond biomarker detection. (2022). *PhotonicsViews*, *19*(1), 48–50. https://doi.org/10.1002/phvs.202270107

50. Glenn, D. R., Lee, K., Park, H., Weissleder, R., Yacoby, A., Lukin, M. D., Lee, H., Walsworth, R. L., & Connolly, C. B. (2015). Single-cell magnetic imaging using a quantum diamond microscope. *Nature Methods*, *12*(8), 736–738. https://doi.org/10.1038/nmeth.3449

51. Arai, K., Kuwahata, A., Nishitani, D., Fujisaki, I., Matsuki, R., Nishio, Y., Xin, Z., Cao, X., Hatano, Y., Onoda, S., Shinei, C., Miyakawa, M., Taniguchi, T., Yamazaki, M., Teraji, T., Ohshima, T., Hatano, M., Sekino, M., & Iwasaki, T. (2022). Millimetre-scale magnetocardiography of living rats with thoracotomy. *Communications Physics*, *5*(1), 200. https://doi.org/10.1038/s42005-022-00978-0

52. Cohen, D. (1972). Magnetoencephalography: Detection of the Brain's Electrical Activity with a Superconducting Magnetometer. *Science*, *175*(4022), 664–666. https://doi.org/10.1126/science.175.4022.664

53. Barry, J. F., Turner, M. J., Schloss, J. M., Glenn, D. R., Song, Y., Lukin, M. D., Park, H., & Walsworth, R. L. (2016). Optical magnetic detection of single-neuron action potentials using quantum defects in diamond. *Proceedings of the National Academy of Sciences*, *113*(49), 14133–14138. https://doi.org/10.1073/pnas.1601513113

54. Larson, P. E. Z., & Gordon, J. W. (2021). Hyperpolarized Metabolic MRI—Acquisition, Reconstruction, and Analysis Methods. *Metabolites*, *11*(6), 386. https://doi.org/10.3390/metabo11060386

55. Escrig, G., Campos, R., Qi, H., & Martin-Delgado, M. A. (2024). *Quantum Bayesian Inference with Renormalization for Gravitational Waves*.

56. Instituto Nacional del Cáncer. (2019, January 8). *Radiotherapy to treat cancer*. https://www.cancer.gov/espanol/cancer/tratamiento/tipos/radioterapia#:~:text=Terapia%20de%20radiaci%C3%B3n%20(tambi%C3%A9n%20llamada,dientes%20o%20de%20huesos%20fracturados.

57. Pakela, J. M., Tseng, H.-H., Matuszak, M. M., Ten Haken, R. K., McShan, D. L., & El Naqa, I. (2020). Quantum-inspired algorithm for radiotherapy planning optimization. *Medical Physics*, *47*(1), 5–18. https://doi.org/10.1002/mp.13840

58. Niraula, D., Jamaluddin, J., Matuszak, M. M., Haken, R. K. Ten, & Naqa, I. El. (2021). Quantum deep reinforcement learning for clinical decision support in oncology: application to adaptive radiotherapy. *Scientific Reports*, *11*(1), 23545. https://doi.org/10.1038/s41598-021-02910-y

59. Chan, P., Lucio-Martinez, I., Mo, X., Simon, C., & Tittel, W. (2014). Performing private database queries in a real-world environment using a quantum protocol. *Scientific Reports*, *4*(1), 5233. https://doi.org/10.1038/srep05233

60. Anusuya Devi, V., & Kalaivani, V. (2023). Enhanced BB84 quantum cryptography protocol for secure communication in wireless body sensor networks for medical applications. *Personal and Ubiquitous Computing*, *27*(3), 875–885. https://doi.org/10.1007/s00779-021-01546-z

2018

Anticipating report
Microbiome

Anticipating report
Personalized Preventive Medicine

Anticipating report
Systems biology

2019

Anticipating report
Bioprinting

Anticipating report
Data in the era of Personalized Precision Medicine

Anticipating report
Omic sciences

2020

Anticipating report
Advanced therapies: cell therapy and gene therapy

Anticipating report
Artificial Intelligence: legal and ethical challenges

Anticipating rerpot
Exposome

2021

Anticipating report
Farmacogenomics: the path towards the personalization of treatment

Anticipating report
Nanomedicine

Anticipating report
Epigenomics

2022

Anticipating report
Nucleome 4D

Anticipating report
Radiomics

Anticipating reports
Disease risk prediction in the era of Personalized Prediction Medicine

2023

Informe Anticipando
Artificial Intelligence applications in Personalized Precision Medicine

Anticipating report
Precision vaccines

Anticipating report
Farmacological investigation en in the era of Personalized Precision Medicine

2024

Anticipating report
Deep phenotyping

Anticipating report
Quantum technologies en the medicine of the future