"Exploring Quantum Technologies in Healthcare: A Systematic Review"

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***Abstract*—*Quantum technologies are rapidly transforming healthcare by offering capabilities beyond classical systems across sensing, materials, and communication. Traditional quantum sensors like SQUIDs provide high sensitivity but require cryogenic cooling and fixed infrastructure, while newer platforms such as optically pumped magnetometers, NV-diamond sensors, and ultra-low-field MRI deliver portable, cryogen-free, high-resolution solutions suitable for point-of-care use. In quantum materials, toxicity concerns with cadmium-based quantum dots have accelerated the development of safer, biocompatible alternatives including carbon quantum dots, indium nanocrystals, and doped semiconductor materials, which retain strong optical performance for in vivo imaging.nwhile, the rise of quantum computing challenges classical healthcare cybersecurity, making quantum key distribution and post-quantum cryptography essential for securing medical networks and IoMT devices. For all hurdles such as hardware immaturity and regulatory gaps, emerging quantum technologies offer clear benefits in precision, scalability, safety, and data security, positioning them as fundamental elements of future healthcare systems.*

Keywords: quantum sensing, quantum materials, quantum dots, quantum communication

I INTRODUCTION

Quantum technology is a modern field of science and engineering that uses the principles of quantum mechanics they are superposition, entanglement, tunneling, and discrete energy levels to build advanced devices and systems. There are many branches in the quantum technologies they are Quantum Computing, Quantum Communication, Quantum Sensing/Metrology, Quantum Materials, Quantum Imaging. The quantum technologies have rapidly emerged as enabling tools with the modern medicine. Modern healthcare needs high-precision diagnostics, ultra-secure data communication, and biocompatible materials areas in which quantum technologies have distinct advantages. This review we are going to discuss about quantum technology such as quantum sensing, quantum material and quantum communication. Being able to control and study quantum matter to all sorts exciting things.

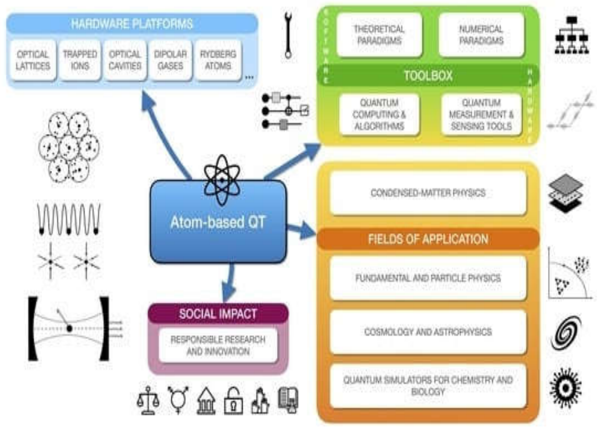


Fig 1.1 Applications of quantum

At first, people-built quantum simulators mainly to explore tricky problems in condensed matter physics stuff that was almost impossible to study directly.

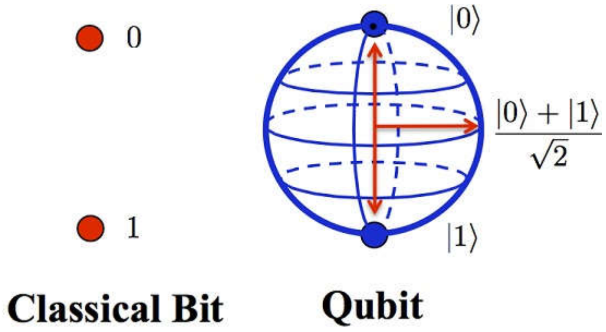


FIG 1.2 Qubit representation

But things have moved way past that. Now, these tools are turning up everywhere. And helping scientists dig into questions about the universe and fundamental physics, pushing the limits of precision in quantum sensing and communication, and driving the quest for better qubits in quantum computing.

II. LITERATURE REVIEW

Recent advances in quantum science have significantly influenced the evolution of next-generation healthcare technologies, particularly in the areas of sensing, secure communication, and nanomaterial-enabled diagnostics. Quantum sensing has emerged as a breakthrough approach for detecting extremely weak biological signals by utilizing quantum coherence, spin dynamics, and phase sensitivity, allowing measurements beyond classical limits [11]. These capabilities are especially relevant in medical diagnostics, where physiological signals such as neural magnetic fields and cardiac bioelectrical activity are inherently faint and require ultra-sensitive detection systems. Developments in atomic and optical quantum platforms have further enhanced the feasibility of applying quantum sensors in biomedical environments by enabling room-temperature operation and improved stability. Such progress supports the development of wearable and non-invasive diagnostic tools capable of high-resolution physiological monitoring [12]. In particular, solid-state quantum sensors based on nitrogen–vacancy centers in diamond have demonstrated the ability to detect magnetic signals from neurons and cellular structures, opening new possibilities for nanoscale neuroimaging and early-stage disease diagnostics [14]. These advances collectively indicate that quantum sensing could transform clinical diagnostics by enabling earlier detection and more precise monitoring of neurological and cardiovascular disorders [18].

similar to sensing technologies, quantum communication is gaining attention in healthcare due to its potential to ensure fundamentally secure data transmission. Quantum key distribution provides encryption security based on the principles of quantum mechanics, where any eavesdropping attempt disturbs the quantum state and can be detected, offering an unprecedented level of cybersecurity for sensitive medical data [20]. Practical implementations of quantum communication protocols have demonstrated progress in overcoming real-world challenges such as transmission losses and noise, bringing quantum-secured healthcare networks closer to reality [6]. These developments indicate that quantum communication may play a vital role in protecting patient privacy and ensuring data integrity in future smart healthcare systems [4].

In this the sensing and communication, quantum materials are driving innovation in biomedical imaging, biosensing, and therapy. Materials whose properties arise from quantum confinement and nanoscale electronic effects offer tunable optical and electrical characteristics that are highly beneficial for medical applications [17]. Quantum dots, in particular, have attracted widespread interest because of their size-dependent fluorescence, high brightness, and superior photostability compared to conventional dyes, making them powerful tools for bioimaging and molecular diagnostics [2]. Carbon-based quantum dots, including graphene quantum dots, have further advanced the field by offering improved biocompatibility and reduced toxicity, expanding their suitability for in vivo imaging and therapeutic applications [7]. Graphene-derived quantum materials have also shown exceptional performance in biosensors due to their high surface area and enhanced electronic properties, enabling ultra-sensitive detection of biomolecules for early disease diagnosis [24]. Furthermore, quantum dots are increasingly being explored for theranostic applications, where imaging and drug delivery functions are combined in a single nanoscale platform to improve treatment precision and reduce side effects [23].

And the literature demonstrates that quantum sensing enhances diagnostic precision, quantum communication strengthens medical data security, and quantum materials enable advanced imaging and therapeutic strategies. Together, these quantum technologies are shaping the future of healthcare by enabling non-invasive diagnostics, secure digital health systems, and highly targeted treatments.

1.QUANTUM SENSING IN HEALTHCARE

Quantum sensing takes advantage of how sensitive quantum states are things like spin, phase, and coherence time to pick up on tiny changes in the world around us. Compared to old-school sensing methods, quantum sensors tap into wild effects like coherence and superposition, which means they can measure really faint magnetic, electric, or thermal fields with incredible accuracy. That's a big deal in healthcare, where so many important signals inside the body are weak and tough to spot with standard tools.

In medicine, these quantum sensors can pick up faint biomagnetic and bioelectric signals think of the activity in your brain, your heartbeat, or even what's going on inside your cells. Their sensitivity opens the door to catching diseases sooner, getting sharper images, and monitoring your body's signals without having to do anything invasive. It usually find three main types of quantum sensing platforms in healthcare. First up: superconducting circuits, like SQUIDs (superconducting quantum interference devices). These are some of the most sensitive magnetometers out there, and doctors use them to detect the tiny magnetic fields from your brain and heart. Next are atomic ensemble sensors, which most often show up as optically pumped magnetometers (OPMs). These use lasers and atomic vapors to measure magnetic fields, and they work at or near room temperature, so they're smaller and can even be worn.

Last, it got solid-state spin systems, especially nitrogen–vacancy centers in diamond. These weird little defects in the crystal make excellent quantum sensors, reacting to magnetic and electric fields, even temperature, and they work at microscopic sometimes even nanoscale levels. All together, these quantum sensing tools are changing the game in medical diagnostics and research. They let us measure things that used to be totally out of reach ultra-sensitive, non-invasive, and way beyond what classical sensors could do.

HTS SQUIDs don't match LTS SQUIDs when it comes to sensitivity, but they win in other ways. They're easier to use and a lot cheaper to run, so they fit the bill for many real-world uses.

1.3 Emerging Quantum Sensing Technologies

1.3.1 Optically Pumped Magnetometers (OPMs)

Right now, OPMs lead the pack as the most clinically developed quantum sensors. Several companies are racing to build commercial versions for magnetoencephalography and magnetocardiography. Unlike superconducting quantum interference devices which need cryogenic cooling OPMs work at room temperature.

Coolant	**Operating Temperature**	**Cost**	**Availability**	**Vaporization Rate**
Liquid Helium	~4.2 K	Very expensive	Limited to labs/industrial	Vaporizes quickly
Liquid Nitrogen	~77 K	Very cheap including	Widely available, remote areas	Vaporizes slowly

T**able 1.1** Comparison of coolants

They use alkali vapor cells, usually rubidium or cesium, and tap into the spin dynamics of those atoms to measure magnetic fields no cooling required. They're small, portable, and you can put them right on the scalp, which means they deliver sharper MEG images than SQUIDs ever could. The Circa Magnetics OPM-MEG system, for example, is getting close to regulatory approval and looks set to shake up the world of accessible neuro diagnostics.

1.3.2 NV-Center Diamond Sensors

Nitrogen-vacancy centers in diamond offer a whole new way to sense tiny electromagnetic changes. These sensors are stable, biocompatible, and can see down to the nanoscale, making them a great pick for wide-field cellular imaging and neuromorphic biosensing. NV centers basically atomic-scale quantum sensors inside diamond crystals pick up on magnetic, electric, and temperature shifts at room temperature, all with nanometer precision. Lately, researchers have managed to boost their sensitivity and unlock widefield imaging.

A 2024 study pushed things even further by pairing widefield diamond quantum sensing with neuromorphic vision sensors. The result? Imaging with both high spatial and temporal resolution, letting scientists track live cellular magnetic fields in real time. This breakthrough is opening up new ways to study neural activity, watch cancer cell metabolism, and even catch early-stage protein clumping in neurodegenerative diseases. Quantum Diamonds GmbH brought out the world's first commercial quantum device for checking semiconductors in 2024, showing it's possible to build these tools at an industrial scale. The company started with semiconductor inspection, but the technology easily crosses over into biology—for example, hunting down magnetic nanoparticles used in targeted cancer therapy or mapping magnetic fields inside cells.

1.*3.3 Ultra-Low-Field (ULF) MRI and Enhanced Imaging*

Low-field MRI is getting a facelift by combining low-Tc SQUID volume gradiometers with AI-powered noise cancellation. The result? Cheaper, smaller machines that still deliver solid diagnostic images. These new systems are already being tested for portable and pediatric imaging.

2. QUANTUM MATERIALS (QUANTUM DOTS) IN HEALTHCARE

2.1 Introduction to Quantum Materials and Quantum Dots

Quantum materials are honestly in a league of their own. Thanks to quantum mechanics and the way electrons interact inside them, they show off some pretty wild electronic, optical, and magnetic properties that just don’t show up in regular, classical materials. These materials behave collectively charge, spin, orbital, and even their lattice structure all play together, leading to things like strong quantum coherence and strange ways electricity moves around. Quantum dots, or QDs, are a standout example. They’re tiny, nanoscale semiconductors where quantum confinement makes their optical and electronic properties depend on size. You can tune their fluorescence, they’re tough under light, and scientists can tweak their surfaces, making them perfect for biomedical imaging, biosensing, and new quantum tech. People are especially excited about how QDs are already changing cancer diagnostics and therapy.

2.2 Graphene Quantum Dots (GQDs)

Graphene quantum dots, or GQDs, take things up a notch. They’re tiny carbon-based dots that come from slicing up graphene sheets. Thanks to their size and the way their edges are set up, they show unique optical and electronic tricks. Since GQDs first turned up, researchers have flocked to them—they’re stable, glow brightly, and get along well with biological systems. In medicine, GQDs have helped push theranostics forward, combining diagnosis and therapy in one shot. They excel at fluorescence imaging, biosensing, and even delivering drugs right where they’re needed.

2.3 Carbon Quantum Dots (CQDs)

Carbon quantum dots, or CQDs, are another big player. Unlike older quantum dots made with heavy metals, CQDs are biocompatible and much less toxic. Scientists have figured out new ways to make and modify them, so now they’re used in imaging, biosensing, and drug delivery. Their light emission is strong and tunable, they dissolve in water, and they’re chemically stable—ideal traits for diagnosing and treating disease, especially where low toxicity matters most.

2.4 Applications of Quantum Materials in Healthcare.

2.4.1 Diagnostic Imaging and Biosensing

Quantum dots and other 2D quantum materials make incredibly efficient fluorescent probes. They light up cells and tissues with high resolution and let researchers detect several biomarkers at once, which helps catch diseases early and track treatments in real time.

2.4.2 Drug Delivery and Theranostics

Surface-tuned quantum materials also work as smart nanocarriers. They can deliver drugs right where they're needed, responding to triggers like pH changes, enzymes, or even light. Because their surfaces can do more than one job, these nanocarriers handle both imaging and therapy, aiming to hit the disease without harming healthy tissue.

2.4. 3 Photothermal and Photodynamic Therapy

strong absorption and ability to turn light into energy, quantum materials are perfect for light-based therapies. Doctors can use them to heat up and destroy cancer cells, leaving nearby healthy tissue mostly untouched. It's a less invasive way to fight cancer and has a lot of promise.

3.4.4 Quantum-Enhanced Biosensors

The scientists add quantum materials to biosensors, these devices get way better more sensitive, more selective, and able to detect tiny amounts of biological molecules. This boost comes from the quantum effects and the huge surface area of these materials, letting doctors spot problems earlier and more accurately than ever before.

Quantum materials bring some real advantages to healthcare that you just don't get with regular biomaterials. Thanks to their unique structure and the way you can tweak their surfaces, they pick up on things with incredible sensitivity even down to single molecules or those hard-to-find disease markers that show up early. That's huge for early diagnosis. And if you design them right and treat their surfaces properly, most of these materials are safe for the body and work well inside living systems. So, they're actually a solid fit for realworld medical use. Even with all the excitement around quantum materials, a few big hurdles keep them from hitting mainstream clinical use. Manufacturing is a headache. You need super-precise methods and tight quality control just to make sure everything works the same way each time—and that gets even tougher when you scale up. Then there's the whole regulatory mess. Nobody's nailed down standard ways to test these materials, and we still don't have good long-term toxicity data. That means approvals crawl along at a snail's pace. Price is another problem. especially for personalized and precision medicine.

Property	**Traditional Materials**	**Quantum Materials**
Fluorescence Stability	Minutes-hours (organic dyes)	Days-months (quantum dots)
Detection Sensitivity	Nanomolar-picomolar	Femtomolar-attomolar
Toxicity	Variable (cadmium high)	Low (GQDs, CQDs)
Multifunctionality	Single mode	Theranostic (imaging+therapy)
Drug Loading Capacity	10-50% by weight	100-200% by weight
Cost per Gram	\$10-\$100 (fluorophores)	\$100-\$1,000 (GQDs, 2024)

Table 1.2 comparison of materials

Modern healthcare systems increasingly rely on digital infrastructures such as telemedicine platforms, electronic health records, and interconnected wearable medical devices, all of which require the secure exchange of highly sensitive patient data.

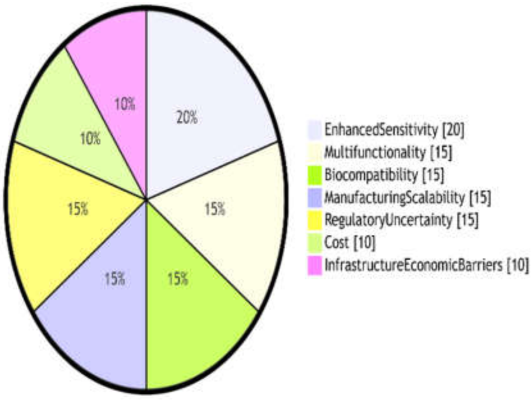


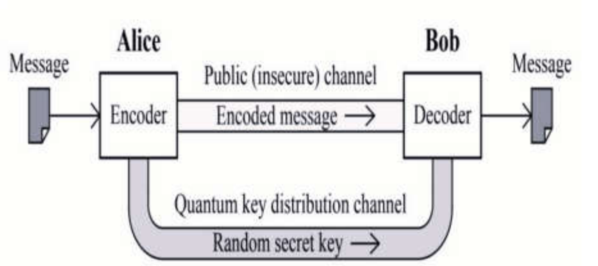
FIG 1.3 Pie chart for the comparison

Conventional cryptographic methods, including RSA and elliptic curve cryptography (ECC), are vulnerable to future quantum computers, particularly due to quantum algorithms capable of efficiently solving problems that underpin their security Bennett & Brassard [20]. The potential impact of quantum computing on data security has therefore accelerated the need for quantum-resistant and quantum-secure communication protocols in healthcare environments. Preparing for these emerging threats involves transitioning toward hybrid cryptographic frameworks that combine classical security with quantum-safe technologies to ensure long-term data protection.

3.*2 Quantum Key Distribution (QKD)*

Quantum Key Distribution (QKD) is a secure communication method that uses quantum states of light to establish encryption keys between two parties, typically referred to as Alice and Bob. The security of QKD is based on the fundamental principles of quantum mechanics: any attempt by an eavesdropper to intercept the key disturbs the quantum states and can be detected immediately. This feature enables provably secure key exchange, independent of computational assumptions. In healthcare, QKD could be used to secure hospital-to-hospital communication links, protect the transfer of medical imaging and patient records, and safeguard control signals in Internet of Medical Things (IoMT) systems.

Despite its strong theoretical security, practical implementation of QKD faces challenges related to transmission distance, infrastructure costs, and network integration. Nevertheless, several experimental and pilot QKD networks have demonstrated the feasibility of secure quantum communication in real-world settings Pirandola et al. [19]. Advances in continuous-variable QKD protocols have also contributed to making QKD more compatible with existing optical communication technologies Laudenbach et al. [6].



3.2.1 QKD with Qubit Pairs and Auxiliary Keys

Extensions of traditional QKD protocols, such as schemes using qubit pairs and auxiliary keys, introduce additional layers of security beyond standard implementations like BB84. In such approaches, the sender transmits pairs of entangled or correlated qubits rather than single qubits. The receiver then randomly assigns one qubit from each pair to generate the primary secure key while using the other to establish an auxiliary key for verification or error checking. This dual-key strategy enhances resilience against certain eavesdropping strategies and improves overall protocol robustness Bennett & Brassard [2

Fig 1.4. QKD Communication

The diagram illustrates the basic principle of Quantum Key Distribution (QKD)–based secure communication between two parties, commonly referred to as Alice and Bob. While the encrypted message is transmitted over a classical public channel, the secret cryptographic key used for encryption and decryption is generated and shared through a quantum channel. Any attempt to intercept the quantum key disturbs its quantum states, allowing the communicating parties to detect eavesdropping and ensure secure key

Feature	**Traditional Cryptography**	**Quantum Cryptography**
Key Distribution	Classical key exchange, vulnerable to future quantum attacks	Quantum Key Distribution (QKD), guaranteed eavesdropping detection
Vulnerability	Susceptible to brute-force and quantum attacks	Theoretically unbreakable, detects eavesdropping in real-time
Key Management	Complex, with risk if key is compromised	Simplified through QKD, secure key generation & distribution
Tamper Detection	Limited to algorithmic and software controls	Physical disruption of quantum states reveals tampering
Future-proofing	Vulnerable as quantum computing evolves	Resistant to quantum computing advances
Implementation Complexity	Well-established, mature technology	Emerging technology, high setup and maintenance cost
Use Cases in Healthcare	Securing medical records, telemedicine, EHRs	Secure communication, telemedicine, real-time patient data security, drug discovery
Regulatory and Ethical	Established compliance frameworks	Developing standards and ethics around quantum tech

Table 1.4 Comparison of cryptography

exchange, thereby providing a high level of security for sensitive data transmission Bennett & Brassard [20].

3.3 Post-Quantum Cryptography (PQC)

Quantum cryptography takes the weird rules of quantum physics stuff like superposition, entanglement, and the fact that you can’t copy a quantum state and uses them to keep your data safe from prying eyes. Instead of relying on hard math problems, like classical cryptography does, this approach leans on the laws of physics themselves. That means even if someone builds a super-powerful quantum computer one day, your secrets stay locked down. At the heart of it all is Quantum Key Distribution, or QKD. It’s how two people can create a secret key together, without anyone else listening in. PQC consists of classical algorithms designed to resist quantum attacks without requiring new physical infrastructure. PQC is more immediately deployable across existing healthcare IT systems and is a strong near-term mitigation strategy while QKD scales.

Hybrid models combining PQC for broad compatibility and QKD for highest-value links are recommended. (Marengo & Santamato, 2025).

4.4 Quantum Internet and Interoperability

The vision of a quantum internet an interconnected network of quantum processors and quantum communication links extends the promise of secure communication to advanced digital infrastructures. In healthcare, such a network could enable secure multi-party computation, allowing hospitals and research institutions to collaboratively analyze sensitive datasets, such as genomic records and epidemiological statistics, without exposing raw patient data. This would preserve privacy while fostering large-scale medical research and innovation.

A quantum internet could also support advanced authentication and access control through quantum-based identity verification schemes. These methods would provide strong guarantees of authenticity for users and connected medical devices, thereby enhancing the security of electronic health records (EHRs) and Internet of Medical Things (IoMT) systems. Furthermore, the integration of hybrid quantum–classical networks would allow quantum communication technologies to be gradually introduced alongside existing healthcare IT infrastructure, ensuring interoperability and minimizing operational disruption.

4.5 Applications in Healthcare

4.5.1 Secure Transmission of Electronic Health Records (EHRs)

Healthcare institutions routinely exchange large volumes of sensitive data, including electronic health records, diagnostic imaging, prescriptions, and laboratory reports. Conventional encryption techniques such as RSA and elliptic curve cryptography are expected to become vulnerable in the era of quantum computing. Quantum communication technologies, particularly those based on Quantum Key Distribution (QKD), provide a solution by enabling end-to-end encrypted communication secured by the laws of quantum physics.

In QKD-secured systems, any attempt at eavesdropping introduces detectable disturbances in the transmitted quantum states, allowing immediate identification of security breaches. This ensures tamper-proof transmission of patient data and supports compliance with strict privacy regulations such as HIPAA and GDPR. As healthcare systems become increasingly digitized and interconnected, quantum-secure communication will play a vital role in safeguarding patient confidentiality and maintaining trust in digital health services.

III. DISCUSSION

Quantum technologies are rapidly reshaping healthcare by improving diagnostic precision, treatment strategies, and data security. Quantum sensing enables detection of extremely weak physiological signals, offering new possibilities for early diagnosis of neurological and cardiovascular disorders where conventional tools often lack sufficient sensitivity **[11]**. Advances in portable and room-temperature quantum sensors further support their future integration into clinical and wearable monitoring systems **[12]**.

Quantum materials, particularly quantum dots, contribute significantly to biomedical imaging and biosensing due to their tunable fluorescence and surface functionalization capabilities, which allow accurate detection of biological targets **[2]**. Carbon-based quantum dots, including graphene quantum dots, enhance clinical potential because of their improved biocompatibility and reduced toxicity, making them suitable for in vivo applications **[7]**. Their incorporation into biosensor platforms also enables highly sensitive detection of low-concentration biomarkers **[24]**. In parallel, quantum communication addresses the growing need for secure medical data exchange. Quantum key distribution provides fundamentally secure encryption by allowing detection of any interception attempts, making it highly relevant for protecting electronic health records and telemedicine systems **[20]**. As practical implementations improve, quantum-secured networks may become an essential component of future healthcare infrastructure **[19]**.Despite these advances, challenges such as high cost, technical complexity, and the need for regulatory and clinical validation remain barriers to implementation. Overcoming these issues will require interdisciplinary collaboration to translate quantum innovations into safe, scalable, and clinically reliable healthcare technologies **[18]**.

IV CONCLUSION

Quantum technologies are shaking up healthcare in a big way. They're making it easier to spot diseases early, treat them more precisely, and keep patient data safe. Quantum sensors can pick up on tiny changes in our bodies, which means doctors can catch tricky conditions sooner, and they don't always have to use invasive tests. Then you've got quantum materials like quantum dots—they're tiny, but they pack a punch. They make medical imaging sharper, help with targeted therapies, and can even sense what's happening inside your body at the cellular level. On top of that, quantum communication is changing the game for healthcare data security. It lets hospitals and clinics share information in ways that are basically hack-proof, even against the super-powerful computers coming down the line. Put it all together, and it's clear: quantum sensing, materials, and communication are set to make healthcare more accurate, more personal, and a whole lot safer.

VI FUTURE DIRECTION

Future research in quantum technologies for healthcare will focus on translating laboratory advances into scalable, clinically viable solutions that integrate seamlessly with existing medical infrastructure. In quantum sensing, efforts will center on miniaturized, low-power devices such as NV-diamond and optically pumped magnetometer sensors, combined with AI-driven signal analysis for real-time, high-precision diagnostics. Developments in quantum materials will prioritize the creation of highly biocompatible, stable, and functionalized quantum dots and nanostructures for targeted imaging, biosensing, and therapy, supported by comprehensive long-term safety evaluations. Meanwhile, progress in quantum communication will aim at deploying compact and cost-effective quantum key distribution systems and incorporating post-quantum cryptographic protocols into healthcare data networks to ensure long-term cybersecurity. These advancements are expected to enable more precise diagnostics, personalized treatments, and robust protection of sensitive medical data, ultimately shaping a secure and technologically advanced healthcare ecosystem.

VII REFERENCE

[1] Y. Wang, T. Li, Y. Li, R. Yang, G. Zhang, 2D-materials-based wearable biosensor systems, Biosensors, 12(11), 936, 2022. DOI: 10.3390/bios12110936.

[2] N. Le, K. Kim, Current advances in the biomedical applications of quantum dots: Promises and challenges, International Journal of Molecular Sciences, 24(16), 12682, 2023. DOI: 10.3390/ijms241612682.

[3] H. Dutta, A.K. Bhuyan, Quantum communication: From fundamentals to recent trends, challenges and open problems, IEEE, 2023.

[4] S.R. Hasan, M.Z. Chowdhury, M. Saiam, Y.M. Jang, Quantum communication systems: Vision, protocols, applications, and challenges, 2023.

[5] S.-K. Liao et al., Satellite-to-ground quantum key distribution, Nature, 549, 43–47, 2017. DOI: 10.1038/nature23655.

[6] F. Laudenbach et al., Continuous-variable QKD with Gaussian modulation – Theory of practical implementations, arXiv preprint, arXiv:1703.09278, 2018.

[7] S. Chung, R.A. Revia, M. Zhang, Graphene quantum dots and their applications in bioimaging, biosensing, and therapy, Advanced Materials, 33(22), 1904362, 2021. DOI: 10.1002/adma.201904362.

[8] P.A. Rasheed, M. Ankitha, V.K. Pillai, S. Alwarappan, Graphene quantum dots for biosensing and bioimaging, RSC Advances, 14, 16001–16023, 2024.

[9] K.S. Novoselov et al., Room-temperature electric field effect and carrier-type inversion in graphene films, Nature, 438, 197–200, 2005.

[10] A.K. Geim, K.S. Novoselov, The rise of graphene, Nature Materials, 6(3), 183–191, 2007. DOI: 10.1038/nmat1849.

[11] C.L. Degen, F. Reinhard, P. Cappellaro, Quantum sensing, Reviews of Modern Physics, 89(3), 035002, 2017. DOI: 10.1103/RevModPhys.89.035002.

[12] J. Ye, P. Zoller, Quantum sensing with atomic, molecular, and optical platforms for fundamental physics, Physical Review Letters, 132, 190001, 2024. DOI: 10.1103/PhysRevLett.132.190001.

[13] J.M. Ni et al., Absence of magnetic thermal conductivity in the quantum spin liquid candidate $EtMe_3Sb[Pd(dmit)_2]_2$ – revisited, arXiv preprint, arXiv:1904.10395, 2019.

[14] J.F. Barry et al., Optical magnetic detection of single-neuron action potentials using quantum defects in diamond, Proceedings of the National Academy of Sciences (PNAS), 113(49), 14133–14138, 2020.

[15] L. Rondin et al., Magnetometry with nitrogen-vacancy defects in diamond, Reports on Progress in Physics, 77(5), 056503, 2014. DOI: 10.1088/0034-4885/77/5/056503.

[16] H.M. Wiseman, G.J. Milburn, Quantum Measurement and Control, Cambridge University Press, 2009.

[17] V. Giovannetti, S. Lloyd, L. Maccone, Advances in quantum metrology, Nature Photonics, 5, 222–237, 2011.

[18] B. Schrinski et al., Quantum sensing in healthcare: Emerging clinical opportunities, Nature Reviews Physics, 2023.

[19] S. Pirandola et al., Advances in quantum cryptography, Advances in Optics and Photonics, 12(4), 1012–1236, 2020.

[20] C.H. Bennett, G. Brassard, Quantum cryptography: Public key distribution and coin tossing, in: Proceedings of the IEEE International Conference on Computers, Systems and Signal Processing, 1984.

[21] S. Jiang et al., Quantum materials for biosensing applications, Chemical Reviews, 121, 123–189, 2021.

[22] G.C. Schatz, M.A. Ratner, Quantum Mechanics in Chemistry, Prentice Hall, 2013.

[23] G. Chen et al., Quantum dots for cancer diagnostics and therapy, Chemical Society Reviews, 48, 550–569, 2019.

[24] A. Esfandiar et al., Graphene-based sensors for biomedical applications, Nature Communications, 12, 1–14, 2021.

[25] J.Y. Malo, L. Lepori, L. Gentini, M.L. Chiofalo, Atomic quantum technologies for quantum matter and fundamental physics applications.