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QUANTUM DIAGNOSTICS: EMERGING TECHNOLOGIES FOR NEXT-GENERATION MEDICAL DETECTION

Biomedical

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ABSTRACT

Quantum diagnostics applies principles of quantum physics to medical detection and disease monitoring. Quantum coherence, spin-based sensing, and non-classical light enable measurement sensitivities beyond classical detection limits. Over the past five years, major progress has been achieved in optically pumped magnetometer-based biomagnetic sensing, nitrogen–vacancy diamond biosensors, quantum photonic imaging, and quantum-assisted medical data analysis. This review synthesizes recent developments in quantum diagnostics and evaluates their clinical relevance in neurology, cardiology, oncology, and precision medicine. Current technological barriers and translational challenges are also discussed, together with future perspectives for clinical implementation.

KEYWORDS

Quantum diagnostics, Quantum coherence, Biomagnetic sensing

INTRODUCTION

Medical diagnostics has traditionally relied on classical measurement techniques such as electrochemical detection, optical spectroscopy, and magnetic resonance imaging. These approaches are fundamentally limited by thermal fluctuations and shot noise. Quantum diagnostics introduces a new paradigm by exploiting quantum mechanical phenomena such as superposition, entanglement, and spin coherence to achieve measurement sensitivities beyond classical limits [1]. Recent advances have enabled quantum sensors to operate under ambient conditions compatible with clinical environments, significantly accelerating translational research [2].

QUANTUM SENSING PRINCIPLES

Quantum sensing relies on quantum states whose evolution depends on environmental conditions such as magnetic fields, temperature, or electromagnetic radiation. Atomic vapor magnetometers and nitrogen–vacancy centers in diamond are currently the most mature quantum sensing platforms for biomedical applications [1].

Advantages Include:

- Ultra-high sensitivity
- Label-free detection
- Non-invasive measurements
- Room temperature operation

Neurodiagnostics Using Quantum Magnetometry

Optically pumped magnetometers (OPMs) enable magnetoencephalography (MEG) without cryogenic cooling. Clinical studies have demonstrated improved localization of epileptic activity using wearable OPM-MEG systems [3]. Wearable sensor arrays allow natural head movement and improve patient comfort compared with conventional systems [4]. Modular OPM arrays have achieved sensitivities below tens of femtotesla per √Hz, enabling accurate recording of cortical rhythms [5].

Quantum Cardiac Diagnostics

Magnetocardiography measures the magnetic fields generated by cardiac electrical activity. OPM-based magnetocardiography systems have demonstrated sensitivity comparable to superconducting sensors while operating at room temperature [6]. Clinical investigations indicate potential applications in arrhythmia detection, myocardial ischemia diagnosis, and fetal cardiac monitoring [7].

Nitrogen–Vacancy Diamond Biosensing

Nitrogen–vacancy (NV) centers in diamond are atomic-scale defects whose spin states are sensitive to magnetic fields. These centers can be optically detected at room temperature and provide nanoscale spatial resolution [8]. NV-based biosensors can detect extremely small quantities of molecules through magnetic resonance signals, including protein biomarkers and oxidative stress markers [9].

Quantum Photonic Imaging

Quantum imaging uses non-classical light such as squeezed or entangled photons to improve measurement sensitivity beyond classical optical limits. Quantum photonic techniques can achieve sub-shot-noise imaging and improved phase sensitivity [10]. Potential clinical benefits include reduced radiation exposure, lower phototoxicity, and improved contrast [11].

Quantum Machine Learning For Diagnostics

Healthcare datasets often contain high-dimensional information from genomics, imaging, and electronic health records. Quantum machine learning (QML) algorithms may improve pattern recognition in complex datasets. Early demonstrations indicate competitive performance in medical classification tasks [12]. Hybrid quantum-classical approaches represent the most realistic near-term applications [13,14].

Challenges And Limitations

- Environmental Noise: Quantum sensors are sensitive to electromagnetic noise [1].
- Manufacturing Challenges: Scalable production of high-purity diamond and integrated photonic devices remains difficult.
- Clinical Validation: Requires multi-center trials, standardized protocols, and regulatory approval [2].
- Interpretability: Outputs must be clinically interpretable to support decision-making.

Future Perspectives

Quantum diagnostics is expected to advance significantly during the next decade. Likely clinical applications include wearable brain monitoring systems, non-contact cardiac mapping, ultra-sensitive liquid biopsy tests, and quantum-assisted precision medicine. Successful clinical adoption will depend on cost reduction, regulatory approval, and demonstration of clear clinical benefits.

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