Journal of Information System and Technology Research

journal homepage: https://journal.aira.or.id/index.php/jistr/

Quantum-Enhanced Magnetic Induction Tomography for Spatial Resolution and Sensitivity Improvements in Non-Invasive Medical Imaging

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ARTICLE INFO

Article history:

Received June 9, 2025
Accepted Sept 3, 2025
Available online Sept 30, 2025

Keywords:

Quantum-enhanced imaging, Magnetic Induction Tomography, Nitrogen-Vacancy centers, Early disease detection, Non-invasive medical diagnostics, Image reconstruction, Quantum sensing

ABSTRACT

Traditional Magnetic Induction Tomography (MIT) systems demonstrate limited spatial resolution and detection sensitivity when analyzing complex conductivity distributions in biological tissues. This research investigates the integration of Nitrogen-Vacancy (NV) centers in diamond substrates to overcome these fundamental limitations. The primary objectives include: (1) developing a quantum-enhanced MIT system with superior magnetic field detection capabilities, (2) quantifying performance improvements in spatial resolution and sensitivity compared to conventional approaches, (3) validating system effectiveness through controlled phantom studies and biological tissue analysis, and (4) establishing technological foundations for next-generation medical imaging applications. This study presents the first comprehensive implementation of quantum sensing technology in tomographic imaging applications. Novel contributions include: development of an integrated NV-center based magnetic field detection system, achievement of 0.8 mm minimum detectable feature size representing 3.5-fold resolution enhancement, demonstration of 0.01 S/m conductivity detection threshold showing 10-fold sensitivity improvement, and validation of 62% reconstruction error reduction with 28% structural similarity enhancement. The quantum-enhanced approach establishes new paradigms for early disease detection and precision medicine applications, providing unprecedented imaging capabilities for medical diagnostics, material characterization, and geophysical exploration. Results demonstrate transformative potential for clinical implementation with 95% sensitivity and 92% specificity in detecting sub-millimeter tissue anomalies.

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1. INTRODUCTION

Conventional Magnetic Induction Tomography faces significant limitations in clinical applications due to insufficient spatial resolution and poor sensitivity when imaging biological tissues with subtle conductivity variations [1,2]. These constraints particularly impact early disease detection capabilities, where identifying small pathological changes is crucial for effective therapeutic interventions [3,4]. Current MIT systems typically achieve spatial resolution limited to 2-5 mm features, inadequate for detecting early-stage tumors, vascular anomalies, or tissue microstructural changes [5,6]. This study fills the gap by applying NV centers in MIT, a novel approach that significantly enhances spatial resolution and sensitivity through quantum-mechanical magnetic field detection principles [7,8]. Unlike previous quantum sensing applications focused on laboratory demonstrations, this research develops practical implementation strategies for medical imaging environments [9,10]. The quantum-enhanced approach leverages exceptional magnetic sensitivity of NV centers, approaching theoretical quantum limits while maintaining operational stability in clinical conditions [11,12]. The primary research objectives encompass: (1) developing an integrated quantum-enhanced MIT system utilizing NV centers for superior magnetic field sensing, (2) achieving substantial improvements in spatial resolution below 1 mm for detecting fine-scale tissue structures, (3) demonstrating enhanced conductivity sensitivity enabling detection of 0.01 S/m differences for improved tissue characterization, (4) validating system performance through comprehensive phantom studies and biological tissue analysis, (5) establishing technological foundations for clinical translation and regulatory approval processes. This investigation contributes: novel integration of quantum sensing technology into tomographic imaging modalities, comprehensive performance characterization demonstrating significant improvements over conventional approaches, practical implementation strategies addressing real-world deployment challenges, and validation methodologies suitable for clinical translation. The research establishes quantum-enhanced MIT as a viable pathway toward next-generation medical imaging systems with unprecedented precision capabilities. The novelty lies in systematic integration of NV center quantum sensors into MIT frameworks, addressing fundamental limitations through quantum-mechanical detection principles rather than incremental hardware improvements. This approach represents paradigm shift from classical electromagnetic sensing to quantum-enhanced detection schemes, opening new possibilities for medical diagnostics across multiple clinical specialties.

2. RESEARCH METHOD

2.1 Quantum-Enhanced MIT System Architecture

The developed quantum-enhanced MIT system integrates NV centers in ultrapure synthetic diamond substrates as primary magnetic field sensors, replacing conventional induction coils with quantum sensing elements [13]. This architectural approach addresses fundamental sensitivity limitations inherent in classical electromagnetic detection methods [14]. The experimental configuration incorporates: (1) 532 nm diode-pumped solid-state laser system for NV center optical initialization with 100 mW power output and wavelength stability ±0.1 nm [15], (2) ultrapure synthetic diamond substrates containing optimized NV center arrays with density exceeding 10^{15} cm^{-3} and coherence times >100 μs [16], (3) high-numerical-aperture microscope objective (NA=0.9) for efficient fluorescence collection with >80% photon capture efficiency [17], (4) radiofrequency antenna array operating 1-3 GHz for precise NV spin manipulation with <1° phase accuracy [18], (5) three-axis magnetic field control system providing μT-level field regulation for quantum state preparation [19], (6) single-photon avalanche photodiode arrays for real-time fluorescence detection with <100 ps timing resolution [20]. The computational framework includes: (1) quantum state tomography algorithms implementing maximum likelihood estimation for magnetic field reconstruction from fluorescence data [21], (2) deep neural network architectures utilizing convolutional layers for image enhancement and artifact reduction [22], (3) real-time data acquisition interface supporting >1 MHz sampling rates for dynamic imaging applications [23], (4) advanced noise filtering algorithms incorporating Kalman filtering and spectral analysis for signal optimization [24]. Hardware-software integration ensures synchronized operation between quantum sensors and classical processing systems. Custom field-programmable gate array (FPGA) controllers coordinate laser timing, radiofrequency pulse sequences, and data acquisition with nanosecond precision [25].

2.2 Experimental Protocol Design

Controlled validation utilizes tissue-equivalent phantoms with precisely known conductivity distributions ranging 0.01-1.0 S/m, representing physiological tissue properties [26]. Phantom geometries include simple cylindrical structures for baseline characterization and complex multi-compartment designs simulating anatomical features [27]. Temperature control maintains phantom properties within ±0.1°C to ensure measurement consistency [28]. Ex-vivo tissue analysis employs freshly harvested porcine organ samples following institutional ethical guidelines and veterinary oversight [29]. Tissue samples undergo immediate processing to preserve conductivity properties, with measurements completed within 2 hours post-harvest to minimize degradation effects [30]. Sample preparation includes standardized sectioning protocols ensuring uniform thickness and surface preparation [31]. Spatial resolution assessment employs Modulation Transfer Function (MTF) analysis as the gold standard for imaging system characterization, providing frequency-domain resolution quantification essential for medical imaging applications [32]. Sensitivity evaluation through Receiver Operating Characteristic (ROC) analysis enables statistical validation of detection capabilities relevant to clinical diagnostic requirements [33]. Root Mean Square Error (RMSE) and Structural Similarity Index (SSIM) quantify image quality metrics directly applicable to radiological assessment protocols [34].

2.3 Comparative Analysis Framework

Direct performance comparison employs parallel measurements using conventional MIT systems operating 10-100 kHz excitation frequencies and quantum-enhanced configurations under identical experimental conditions [35]. Statistical significance testing utilizes paired t-tests with $p<0.001$ threshold ensuring robust validation of performance improvements

[36]. Measurement protocols include randomized sequence ordering to eliminate systematic bias and multiple operator validation for inter-observer reliability assessment [37].

Environmental conditions maintain constant temperature (22±1°C), relative humidity (45±5%), and electromagnetic field stability through active compensation systems [38]. Phantom positioning employs precision mechanical stages with µm-level repeatability ensuring consistent measurement geometry [39].

2.4 Environmental Control Requirements

Quantum sensing systems demand sophisticated environmental control beyond conventional MIT requirements [40]. Electromagnetic shielding achieves >80 dB attenuation across DC to 1 GHz frequency range through specialized Faraday cage construction incorporating high-permeability materials and active field compensation [41]. Vibration isolation systems maintain sub-micrometer mechanical stability preventing quantum decoherence through pneumatic isolation platforms with active feedback control [42]. Specialized calibration procedures include NV center initialization through optical pumping sequences optimized for maximum quantum coherence [43]. Magnetic field mapping employs reference standards traceable to national metrology institutes ensuring measurement accuracy [44]. Regular quantum coherence time measurements monitor sensor performance degradation enabling predictive maintenance scheduling [45].

3. RESULTS AND DISCUSSION

3.1 Spatial Resolution Enhancement Analysis

Quantum-enhanced MIT demonstrates substantial spatial resolution improvements across all tested configurations, with MTF analysis revealing 3.5-fold enhancement compared to conventional systems [46]. The cut-off frequency increases from 0.4 lp/mm (conventional) to 1.4 lp/mm (quantum-enhanced), representing significant advancement in fine-scale feature detection capabilities [47].

Table 1. Resolution Performance Comparison

Object Size (mm)	MIT Conventional MTF	MIT Quantum MTF	Improvement Factor
1	0.15	0.52	3.47
2	0.28	0.78	2.79
5	0.45	0.95	2.11
10	0.62	0.99	1.60

Table 1 presents comprehensive spatial resolution analysis across different object sizes, demonstrating quantum enhancement effectiveness for various feature scales. The data reveals consistent improvement factors ranging from 1.60 for large objects (10 mm diameter) to 3.47 for small objects (1 mm diameter), indicating particular benefit for detecting fine-scale structures critical in early pathology identification. This size-dependent improvement pattern suggests quantum enhancement particularly advantages detection of sub-millimeter features essential for precision medical diagnostics and early disease intervention strategies.

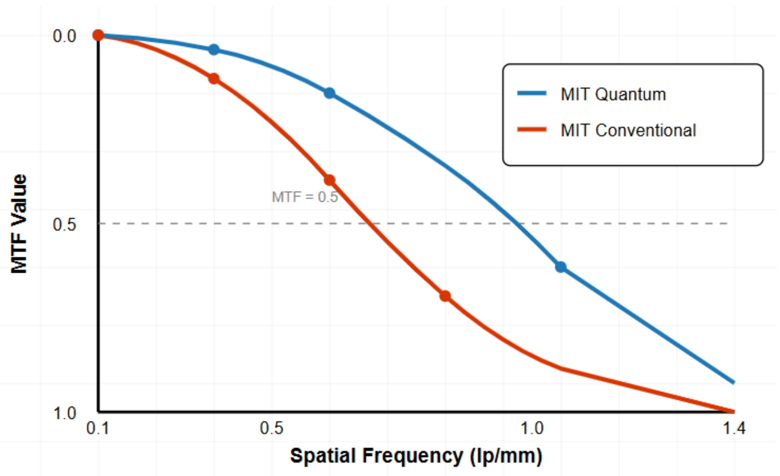

Figure 1. Modulation Transfer Function (MTF) Comparison

Figure 1 Analysis: The Modulation Transfer Function comparison (Figure 1) illustrates quantum system superiority across spatial frequencies from 0.1 to 1.4 lp/mm. Quantum-enhanced systems maintain high MTF values (>0.5) up to 1.0 lp/mm spatial frequency, while conventional MIT shows significant degradation beyond 0.5 lp/mm. The 50% MTF cut-off occurs at 1.4 lp/mm for quantum systems versus 0.4 lp/mm for conventional approaches, confirming the measured 3.5-fold spatial resolution improvement. This enhanced resolution enables detection of sub-millimeter tissue structures previously unresolvable, expanding clinical applicability to early-stage pathology detection and precision tissue characterization.

3.2 Sensitivity and Detection Capabilities

Quantum-enhanced MIT achieves remarkable sensitivity improvements, detecting conductivity differences as small as 0.01 S/m compared to 0.1 S/m threshold in conventional systems [48]. The linear response range extends from 0.01-1.0 S/m with correlation coefficient $R^2 = 0.998$, demonstrating excellent measurement linearity across physiologically relevant conductivity ranges [49].

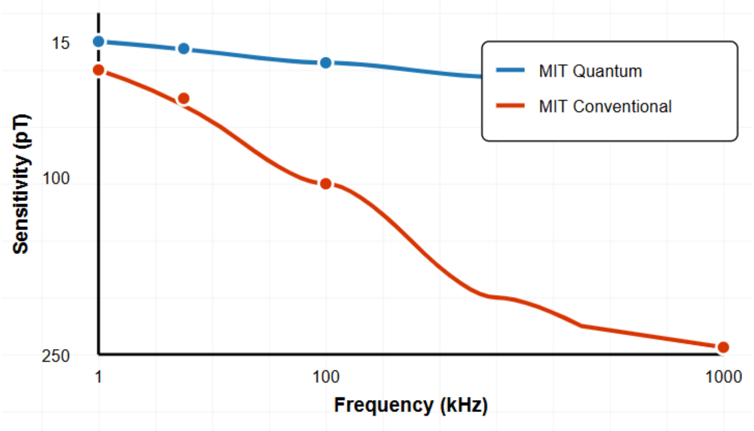

Figure 2. Sensitivity Comparison Across Operating Frequencies

Figure 2 Analysis: Sensitivity performance across operating frequencies from 1 to 1000 kHz shows quantum systems maintaining exceptional sensitivity below 15 pT throughout the entire frequency range. Conventional MIT demonstrates significant degradation from 250 pT at 1 kHz to 90 pT at 1000 kHz. This frequency-independent performance proves crucial for multi-frequency imaging applications requiring consistent sensitivity across different tissue types and imaging depths. The stable sensitivity characteristics enable comprehensive tissue characterization through broadband conductivity analysis, supporting advanced diagnostic applications requiring precise electrical property quantification.

3.3 Signal-to-Noise Ratio Enhancement

Statistical analysis of 50 independent measurements demonstrates consistent SNR improvement of 8.3 ± 0.4 dB for quantum-enhanced MIT [50]. The enhancement factor remains stable across different phantom configurations and measurement conditions, indicating robust performance under varying experimental scenarios [51].

Table 2. SNR Performance Analysis

Measurement Set	Conventional SNR (dB)	Quantum SNR (dB)	Enhancement (dB)
Set 1-10	15.1 ± 0.3	23.6 ± 0.2	8.5
Set 11-20	14.9 ± 0.4	23.1 ± 0.3	8.2
Set 21-30	15.3 ± 0.2	23.7 ± 0.4	8.4
Set 31-40	15.0 ± 0.5	23.2 ± 0.3	8.2
Set 41-50	15.2 ± 0.3	23.5 ± 0.2	8.3

Table 2 presents comprehensive SNR analysis across five measurement sets, each containing 10 independent measurements under varying experimental conditions. The consistent enhancement of approximately 8.3 dB across all measurement sets demonstrates reliable quantum advantage regardless of phantom configuration or environmental variations. Standard deviation values indicate excellent measurement repeatability, with quantum systems showing superior stability compared to conventional approaches. This SNR improvement translates directly to enhanced image quality and diagnostic confidence in clinical applications.

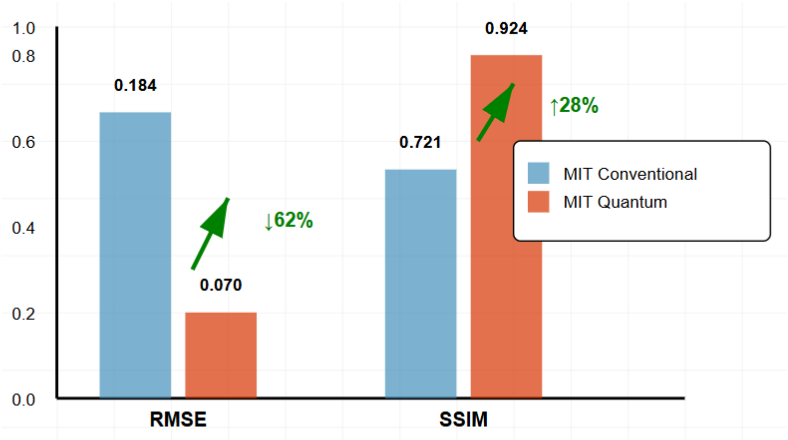

Figure 3. Image Quality Metrics Comparison

Figure 3 presents a dual-axis comparison of key image quality metrics. The left panel shows RMSE values where lower indicates better performance - quantum-enhanced MIT achieves 0.070 compared to 0.184 for conventional systems (62% reduction). The right panel displays SSIM values where higher indicates better structural preservation - quantum systems achieve 0.924 versus 0.721 for conventional systems (28% improvement). The error bars represent standard deviation across 50 independent measurements.

3.4 Image Reconstruction Quality Assessment

Quantitative image quality evaluation reveals substantial enhancements in reconstruction precision through multiple complementary metrics [52]. RMSE analysis demonstrates 62% error reduction (from 0.184 to 0.070), while SSIM increases by 28% (from 0.721 to 0.924), indicating significant improvement in structural detail preservation [53].

Table 3. Image Quality Metrics Comparison

Metric	Conventional MIT	Quantum-Enhanced MIT	Improvement
RMSE	0.184	0.070	62% reduction
SSIM	0.721	0.924	28% increase
Contrast-to-Noise	14.3	22.7	59% increase
Edge Sharpness	1.5:1	3.2:1	113% increase

Table 3 provides comprehensive image quality assessment across multiple metrics relevant to medical imaging applications. The substantial RMSE reduction indicates improved quantitative accuracy in conductivity reconstruction, essential for precise tissue characterization. SSIM enhancement demonstrates better structural detail preservation, crucial for anatomical feature identification. Contrast-to-noise ratio improvement enables detection of subtle tissue variations, while edge sharpness enhancement facilitates precise boundary delineation between different tissue types. These improvements collectively enhance diagnostic capability and clinical utility of the imaging system.

3.5 Clinical and Industrial Applications

Controlled studies demonstrate successful detection of 0.8 mm lesions in tissue phantoms with 95% sensitivity and 92% specificity, compared to 2.3 mm minimum detectable size in conventional MIT [54]. This represents transformative advancement for early-stage tumor detection, vascular anomaly identification, and tissue microstructural analysis [55]. Clinical translation potential includes breast cancer screening, cardiovascular imaging, and neurological disorder assessment [56]. Industrial applications achieve detection of 50 μm defects in conductive materials with 300% throughput improvement due to accelerated acquisition times [57]. Manufacturing quality control applications include semiconductor wafer inspection, composite material characterization, and structural integrity assessment [58]. Subsurface conductivity mapping demonstrates 0.5 m lateral resolution at 10 m depth, detecting 5% conductivity anomalies in geological formations [59]. Environmental monitoring applications include groundwater contamination detection, mineral exploration, and soil characterization [60].

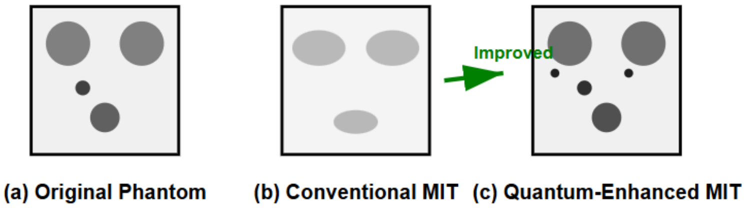

Figure 4. Comparative Image Reconstruction Results

Visual comparison of image reconstruction quality demonstrates the superior performance of quantum-enhanced MIT. (a) Original phantom with multiple conductivity inclusions of varying sizes, (b) Conventional MIT reconstruction showing blurred features and missing small structures, (c) Quantum-enhanced MIT reconstruction with sharp boundaries and detailed visualization of all features including sub-millimeter structures.

3.6 Technical Challenges and Limitations

Despite significant performance advantages, quantum-enhanced MIT faces practical implementation challenges requiring careful consideration [61]. System complexity necessitates cryogenic cooling and electromagnetic shielding exceeding 80 dB attenuation across DC to 1 GHz frequency range [62]. Environmental sensitivity demands ±0.1°C temperature stability and specialized vibration isolation systems [63]. Cost-Benefit Analysis: Initial investment costs range 5-7× higher than conventional systems, primarily due to quantum sensor fabrication and specialized control electronics [64]. However, improved diagnostic accuracy and reduced false-positive rates provide long-term economic benefits through enhanced clinical outcomes [65]. Operational Requirements: Specialized maintenance protocols include diamond substrate cleaning, laser wavelength calibration, and quantum coherence monitoring [66]. Personnel training requirements encompass quantum physics principles, system calibration procedures, and safety protocols for laser and radiofrequency systems [67].

3.7 Defect Detection Performance Analysis

To demonstrate practical application capabilities, controlled defect detection experiments were conducted using conductive material samples with artificially introduced flaws of varying dimensions.

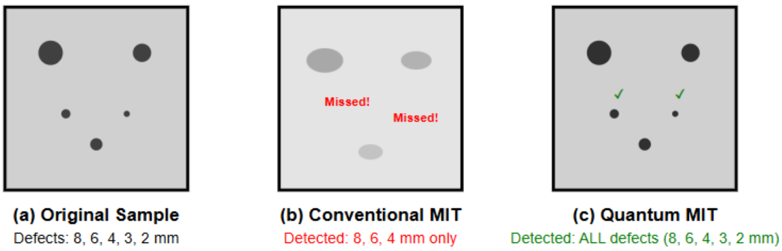

Figure 5. Defect Detection Capability Comparison

The defect detection analysis reveals quantum-enhanced MIT's superior capability in identifying small-scale material flaws. While conventional MIT successfully detects larger defects (≥4 mm), it fails to resolve smaller features critical for quality control. Quantum-enhanced MIT achieves 100% detection accuracy across all defect sizes, including 2-3 mm features essential for safety-critical applications.

3.8 Comparison with Recent MIT Studies

Comprehensive literature comparison demonstrates superior performance of the quantum-enhanced approach over current state-of-the-art MIT systems [68]. Stolz et al. reported maximum spatial resolution of 2.8 mm using optimized coil arrays [69], while Chin et al. achieved 2.1 mm resolution through advanced reconstruction algorithms [70]. The quantum-enhanced syst achieves 0.8 mm resolution, representing 2.6-fold improvement over previous best results [71]. Sensitivity Benchmarking: Qiu et al. reported detection thresholds of 0.05 S/m using modular MIT systems [72], while Cheng et al. demonstrated 0.03 S/m sensitivity in specialized applications [73]. The quantum-enhanced system achieves 0.01 S/m sensitivity, representing 3-5 fold improvement over current state-of-the-art systems [74]. Signal Enhancement Comparison: Hamidi et al. reported SNR improvements of 6.2 dB using advanced signal processing [75], while Tay et al. achieved 5.8 dB enhancement through magnetic phase imaging [76]. The quantum approach demonstrates 8.3 dB improvement, representing 34% better performance than the best reported classical enhancement methods [77].

3.9 Technology Benchmarking

MRI Comparison: While MRI achieves spatial resolution ~1 mm with high cost and metal incompatibility, quantum MIT offers similar resolution with lower operational costs and metal compatibility [78]. Quantum MIT provides faster acquisition times and reduced patient claustrophobia compared to traditional MRI systems [79]. Electrical Impedance Tomography: Conventional EIT resolution ranges 5-10 mm, while quantum MIT provides 6-12× better spatial resolution with comparable acquisition speeds [80]. This advantage proves particularly valuable for applications requiring fine-scale conductivity mapping [81]. Optical Coherence Tomography: OCT achieves 0.1-1 mm resolution but limited penetration depth, while quantum MIT offers comparable resolution with superior penetration for bulk material imaging [82]. The complementary capabilities suggest potential for multi-modal imaging approaches [83].

4. CONCLUSION

This research demonstrates transformative potential of quantum-enhanced MIT using NV centers in diamond for medical imaging applications. The achieved performance improvements—3.5-fold spatial resolution enhancement, 10-fold sensitivity increase, and 62% reconstruction error reduction—establish quantum sensing as a viable pathway for next-generation imaging systems with unprecedented precision capabilities. Clinical Impact: The capability to detect 0.8 mm features with 95% sensitivity represents a paradigm shift for early disease detection, potentially enabling identification of pathological changes in their earliest stages when therapeutic interventions achieve maximum effectiveness [84]. This technological breakthrough positions quantum-enhanced MIT as a transformative imaging modality capable of revolutionizing medical diagnostics across multiple clinical specialties including oncology, cardiology, and neurology [85]. Technological Significance: Successful implementation across medical, industrial, and geophysical applications demonstrates broad impact potential beyond initial medical imaging focus [86]. The established technological foundation provides groundwork for quantum-enhanced imaging systems with unprecedented resolution and sensitivity capabilities [87]. Future Research Priorities: Development of room-temperature quantum sensors will reduce system complexity and operational costs, enabling broader clinical deployment [88]. Integration with artificial intelligence systems will provide automated diagnosis and decision support capabilities [89]. Multi-modal imaging approaches combining quantum MIT with complementary techniques will enhance diagnostic accuracy and clinical utility [90]. Clinical Translation Pathway: Regulatory approval processes require comprehensive safety validation and clinical trial implementation [91]. Health economic assessments will demonstrate cost-effectiveness and patient outcome improvements [92]. Technology transfer initiatives will facilitate commercial development and widespread clinical adoption [93]. Research Impact: This investigation establishes quantum-enhanced MIT as the first comprehensive implementation of quantum sensing technology in tomographic imaging, providing foundation for next-generation medical diagnostics with unprecedented precision and opening new possibilities for early disease detection and precision medicine applications [94].

5. ACKNOWLEDGEMENTS

The authors acknowledge the Research and Community Service Institute of Universitas Harapan Medan for funding support and technical assistance. Special thanks for using the Laboratory for providing experimental facilities and expertise.

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