

Supplementary Information

Quantum Oncology

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Table S1: Quantum Technologies in bioelectrical modalities

Technique	Quantum Technologies	Advantages/Benefits	Impact on detection of cancer-related activity
EEG	Quantum transfer learning & QSVMs. ¹⁻⁴ Quantum-enhanced analysis of cognitive decline (e.g. QEEGNet). ^{5,6}	-Early detection of cancer-related cognitive decline -More accurate brain activity detection (65.6% for valence and 75.0% for arousal dimensions)	Potential for earlier brain disease prediction; Faster treatment modifications and improved outcomes for brain-related changes
ECG	Quantum-inspired AI & machine learning. ⁷	-Handling high-dimensional data and non-linear relationships more effectively -Improved correlations with sonomicrometry for longitudinal and circumferential strain components -Quantum approaches predicted 50.03% of positive samples as positive and 44.65% of negative samples as negative, compared to traditional methods which predicted 49.78% of positive samples as positive and 44.31% of negative samples as negative -Quantum methods consumed an average of 670 μ s for training, whereas traditional methods took 862.5 μ s, indicating a significant reduction in training time	Enhance the accuracy and speed of 3D echo and strain analysis, leading to better detection of subtle cardiac dysfunction. Improve the identification and management of cardiotoxicity caused by treatments like chemotherapy.
EMG	Quantum ML algorithms. ^{7,8}	- Improve the signal-to-noise ratio (SNR) by up to 30 dB, allowing for better detection of subtle changes in muscle activity. ⁹ - Achieve higher classification accuracy, with a 5-10% improvement over traditional ML algorithms when handling high-dimensional EMG data ¹⁰ . - Faster training times, reducing the average training time from 862.5 μ s to 670 μ s, translating to quicker analysis and real-time monitoring capabilities. ¹¹	Cancer-related neurotoxicity; Detection of muscle weakness caused by cancer treatments ¹² , such as chemotherapy-induced peripheral neuropathy; Tailored rehabilitation plans based on individual muscle function

Table S2: Quantum Technologies for tissue biopsy techniques

Technique	Potential Quantum Uses	Key Improvements	Impact on Cancer Extraction / Detection/ Biopsy
Fine Needle Aspiration (FNA); Core Needle Biopsy (CNB)	(Quantum-assisted surgical robots); Quantum Sensors (e.g. NV centers in diamonds); Quantum Machine Learning; Quantum Imaging; Quantum Communication.	Improved precision of the intelligent injector (i2T2): Quantum sensors could provide highly sensitive detection of tissue resistance changes, ensuring the injector stops at the exact tissue layer required.	<i>Earlier detection of cancer with lower sample volumes; Improved diagnostic accuracy; Reduced need for invasive tissue biopsies.</i>
		Real-time data analysis and optimization: QML and quantum imaging could analyze data from the injector in real-time, optimizing the injection process and adapting to different tissue types and conditions. Enhanced biomarker detection: Quantum sensors could potentially improve the detection of biomarkers (e.g., microRNAs) in aspirated cells. Secure and fast data transmission: Quantum communication can ensure the secure and efficient transfer of data between the injector and monitoring systems	
Image-guided biopsies	Quantum machine learning (QML) (e.g. hybrid quantum-classical convolutional neural networks (HQCNN)). ^{8,13–16}	Enhanced Accuracy: Improved performance in classifying medical images. Faster Processing: More efficient handling of large and high-dimensional datasets. Improved Precision: Better handling of intricate data relationships and increased resistance to noise.	Improved Identification: Better differentiation between benign and malignant tumors. Targeted Biopsies: More precise biopsies and potentially personalized treatment plans.
Surgical biopsy	Quantum-assisted surgical robots. Robots equipped with quantum sensors (e.g., quantum magnetometers)	Minimally invasive and highly precise procedures: Quantum-assisted robots could enable more precise and less invasive surgical procedures, reducing damage to surrounding tissues. Reduced surgical trauma and faster recovery times: Minimally invasive procedures often lead to less pain, shorter hospital stays, and faster recovery times.	<i>Less patient discomfort and potentially improved surgical outcomes</i>
Endoscopy ; Colonoscopy or Bronchoscopy	Integrated quantum microscopy ¹⁴ or quantum sensors, (e.g. optical detection or mapping of magnetic resonance with NV centers). Quantum-guided scopes (e.g., using quantum gyroscopes) Quantum simulations for modeling or automated diagnosis and classification	Miniaturized sensors: Quantum sensors can be integrated into scopic devices without increasing their size or weight. -Real-time imaging: Quantum-enhanced scopy offers real-time imaging, allowing for immediate assessment of tissue conditions. -High-resolution, high-sensitivity imaging: The technology provides detailed, accurate images of the gastrointestinal tract and respiratory system, revealing subtle abnormalities. -Enhanced diagnostic capabilities: Quantum-enhanced procedures can detect subtle abnormalities, measure cellular-level temperature changes, and potentially enable earlier diagnosis of diseases such as colorectal cancer and lung cancer. -Improved navigation: Quantum-guided scopes can navigate complex anatomical structures more accurately, improving access to hard-to-reach lesions (e.g. lungs) - Personalized risk assessment: Quantum simulations can identify individual patients at higher risk for cancer, enabling targeted screening and early intervention.	Enhanced visualization leading to early detection of abnormalities, potentially preventing upper gastrointestinal cancers. More targeted and minimally invasive procedures, reducing the need for extensive surgery. Improved navigation and biopsy Identify individual patients at higher risk for colorectal cancer, enabling targeted

Cystoscopy	Quantum sensors for early detection of bladder cancer in urine samples (e.g., detecting specific protein markers) [17]	Non-invasive screening for bladder cancer	screening and early intervention.
	Quantum-powered imaging for improved visualization of uterine abnormalities during hysteroscopy (e.g., using magnetoencephalography) [16]		Early intervention and less aggressive treatment
Hysteroscopy		Enhanced detection of endometrial cancer and other uterine pathologies	Early diagnosis and potentially better treatment outcomes

Table S3: Quantum Technologies in liquid samples

Technique	Potential Quantum Uses	Key Improvements	Impact on Cancer Extraction/ Detection/ Biopsy
Bone Marrow Aspiration	(Quantum-assisted surgical robots); Quantum Sensors (e.g. NV centers in diamonds); Quantum imaging techniques (e.g. quantum ghost imaging or quantum phase estimation); Quantum computing with QML. ^{17–20}	Faster, more accurate diagnosis, reduced patient discomfort, non-invasive techniques, early detection of disease progression. Precise needle placement; real-time tissue resistance monitoring; reduced risk of complications.	Leukemia, lymphoma, multiple myeloma, myelodysplastic syndromes.
Blood Draw	Quantum sensors, like nitrogen-vacancy (NV) centers in diamond ^{21,22} or quantum dot-based sensors ^{23–26} ; Quantum computing	Improved sensitivity and specificity in detecting biomarkers, faster and more accurate results, early detection of disease recurrence.	Various cancers, including breast, lung, prostate, and colorectal cancer.
CTC Enrichment Filtration; Centrifugation; Immunomagnetic separation	Quantum dot-based immunomagnetic separation, quantum entanglement, quantum computing	Higher capture efficiency and viability of CTCs, improved detection of rare cancer cells, earlier detection of metastasis. Quantum entanglement could be used to enhance the capture efficiency of CTCs by creating entangled pairs of particles, one of which is bound to a CTC and the other to a detector. This could improve the sensitivity of CTC detection.	Various cancers, including breast, lung, prostate, and colorectal cancer.
cfDNA Isolation	Quantum computing, quantum entanglement.	Higher yield and purity of cfDNA, more accurate detection of genetic mutations, earlier detection of disease recurrence. Quantum entanglement could be used to improve the accuracy of cfDNA sequencing by reducing errors and increasing the signal-to-noise ratio.	Various cancers, including breast, lung, prostate, and colorectal cancer.
Cell Separation (Flow cytometry; density gradient centrifugation; acoustic sorters)	Quantum acoustic manipulation (coherence; superposition); quantum-enhanced acoustic force fields ; Quantum magnetic fields or quantum materials (metamaterials; quantum nanostructures); Quantum magnetic fields or quantum materials (metamaterials; quantum nanostructures). Quantum computing;	Enhanced precision and efficiency in cell sorting, reduced sample loss, improved purity, earlier detection of disease recurrence.	Various cancers, including leukemia, lymphoma, and solid cancers.

Table S4: Quantum Chemotherapy and Hormone therapy

Feature	Description	Quantum Mechanics Principles	Benefits (Targeted for all drug classes)
Drug Design and Simulation	Simulates molecular interactions at the atomic level, focusing on electron-rich interactions and quantum effects for drug activation, optimizing drug design.	- Density Functional Theory (DFT)^{27–35}, HF, QMC, Molecular dynamics, Chemical reaction modeling. - Fragment Molecular Orbitals (FMO), QM/MM methods³⁶, Quantum Machine Learning (QML). - Quantum surface chemistry (e.g., tunneling effects). - Schrödinger equation for energy states & wavefunctions.^{37,38} - Variational Quantum Eigensolvers (VQEs).³⁹ - Sensor agent design & electronic structure theory (wavefunctions & energy levels).^{37,38,40} - Modeling dynamic cancer cell behavior & resistance prediction.	- Precise drug design with improved binding affinity to target proteins or receptors.. - Optimized stability, solubility, and bioavailability for small molecules and hormone analogs. - Faster, cost-effective drug discovery processes, reducing time-to-market for new therapies. - Reduced off-target effects and improved efficacy through better understanding of steric and electrostatic effects
Quantum Control in Synthesis and Delivery	Quantum control enhances drug synthesis	- Quantum energy beams for spin state control. - Quantum tunneling and coherence to optimize synthesis. - Tailored molecular geometry and electron density distribution. - Quantum-engineered nanoparticles for controlled release.	- Increased drug purity, improving clinical outcomes. - Enhanced stability and shelf life for chemotherapeutics and hormone analogs. - Optimized drug-receptor interactions. - Improved drug delivery through controlled nanoparticle release.
Passive Activation Mechanisms	Drugs/nanoparticles activated by internal stimuli (tumor microenvironment or receptor interactions).	Quantum-designed agents improve pH-sensitive, temperature-sensitive, and enzyme-responsive drug systems.	- Selective activation in tumor environments to minimize systemic toxicity. - Localized action in hormone therapies (e.g., estrogen, androgen receptor targeting). - Reduced systemic side effects (e.g., nephrotoxicity) via environment-sensitive activation.
Active Delivery	External stimuli (e.g., light, ultrasound, magnetic fields) trigger precise control over targeting and drug release	- Quantum agents integrated with NV diamond nanoparticles, quantum dots for unique optical (e.g., fluorescence), magnetic, and spin properties. - Mechanisms include (quantum resonance effects and magnetoelastic effects); ultrasound-induced acoustic cavitation.	-Precise spatial and temporal release of chemotherapeutic agents. - Enhanced hormone therapy targeting with externally guided nanoparticles. - Minimized systemic exposure, improving patient safety and therapeutic efficacy. - Effective deep-tissue activation of targeted drug release.

Table S5: Quantum Computing for Oncology Research

<i>Category</i>	<i>Term</i>	<i>Description</i>	<i>Current benefits</i>
Algorithms & Machine Learning	Variational Quantum Eigensolver (VQE)	Simulates protein-drug interactions. ⁴¹	Accelerates drug discovery by 10-100x compared to classical methods. ^{42,43}
	Quantum Annealing	Finds the lowest energy state of a system. ⁴⁴	Optimizes treatment schedules and hospital resource allocation (a speedup of up to (10^8) times over classical systems for certain optimization problems or speed up genetic analysis). ^{45,46}
Quantum Machine Learning (QML)	Quantum Neural Networks (QNNs)	Leverage superposition and entanglement for superior performance. ⁴⁷	Sharper MRI scans, real-time surgery analysis, enhanced CT scan reconstruction (accuracy rates up to 94.8%, sensitivity of 95.2%, and specificity of 92.4% in brain tumor detection). ^{48,49}
	Quantum Support Vector Machines (QSVMs)	Quantum-enhanced versions of classical Support Vector Machine SVMs. ^{50,51}	Improved accuracy in classification tasks (a 7.14% increase in sensitivity and a high F1-Score of 93.33% in prostate cancer detection) ⁵¹
	Quantum Bayesian Networks	Probabilistic graphical models leveraging quantum parallelism. ⁴⁶	Efficient inference in causal reasoning and decision-making (a square-root speedup in inference tasks compared to classical methods) ⁵²
Architectures	Gate-Based Quantum Computers	Use quantum gates to manipulate qubits. ^{53,54}	Handle complex molecular problems more efficiently than classical computers. Versatile for various applications, including drug discovery and biological simulations. ^{41,55}
	Topological Quantum Computers	Employ topological qubits for increased error resistance ⁵⁶	Lower error rates (1000x), suitable for complex simulations ⁵⁶
	Photonic Quantum Computers	Utilize photons as qubits. ^{57,58}	Scalability, fault tolerance, high-speed processing. ^{57,58}
Error Correction	Quantum Error Correction (QEC)	Techniques to identify and correct errors (e.g. surface or topological codes). ⁵⁹	Increased reliability, accuracy with reduced logical error rates to (10^{-6}) compared to (10^{-9}) for classical error correction. ^{60,61}
Quantum Cloud Platforms	IBM Quantum Experience; Microsoft Azure Quantum; Amazon Bracket; Google Quantum AI; Rigetti Quantum Cloud Services; D-Wave Leap or Alibaba Cloud Quantum Computing	Offer access to a variety of quantum hardware and software solutions, including quantum computers from clouds, as well as quantum simulators and programming frameworks such as Qiskit, Q#, and Cirq. ^{62,63}	Offer a range of features, including high-performance quantum processors, hybrid computing capabilities, diverse hardware support, optimization tools, error correction techniques, real-time capabilities, and specialized applications for various tasks. ⁶⁴⁻⁶⁷

Table S6: Quantum Clouding for Oncology Research

Cloud Platforms	What do they do...	Benefits	Applications
IBM Quantum Experience	Access to quantum hardware and simulators via Qiskit or a graphical interface. ^{63,68–78}	Coherence times up to 100 microseconds. Quantum Volume of 128.	Improving molecular modeling and drug discovery.
Microsoft Azure Quantum	Diverse quantum hardware and software solutions supporting Q#, Qiskit, and Cirq. ^{79–87}	Combines classical and quantum computing. Resource estimation tools for optimizing performance and costs.	Enhancing genomic analysis and medical imaging.
Amazon Bracket	Access to quantum computers from D-Wave, IonQ, and Rigetti. ^{84,88–91}	Supports superconducting qubits, trapped ions, and quantum annealers. Optimizes runtime with parametric compilation and active qubit reset.	Optimizing treatment plans and improving diagnostic accuracy.
Google Quantum AI	Quantum computing services via the Sycamore processor. ^{92–99}	Performs computations faster than classical supercomputers. Focuses on error correction techniques.	Accelerating the analysis of complex biological data.
Rigetti Quantum Cloud Services	Cloud-based quantum computing services with access to quantum processors. ^{84,89,92–94}	Low latency for real-time hybrid algorithms. Active qubit reset for efficient computations.	Optimizing treatment plans and improving diagnostic accuracy.
D-Wave Leap	Access to quantum annealing processors for optimization problems ^{95–102}	Quantum annealing for optimizing radiation therapy schedules and drug delivery. Handles larger problem sizes.	Optimizing radiation therapy schedules and drug delivery systems.
Alibaba Cloud Quantum Computing	Quantum computing services with scalable solutions integrating quantum and classical infrastructure. ^{84,96,111–115}	Enhances performance for large-scale data analysis. Provides optimized quantum algorithms for molecular modeling and genomic analysis.	Enhancing performance for large-scale data analysis. Improving molecular modeling and genomic analysis.

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