Original Research Paper

Volume - 16 | Issue - 08 | August - 2026 | PRINT ISSN No. 2249 - 555X | DOI : 10.36106/ijar

Oncology

QUANTUM BIOLOGY INTEGRATED WITH CANCER CARE: MECHANISMS, EMERGING TECHNOLOGIES, AND THERAPEUTIC HORIZONS

Daniel Finney Sankuru	Senior Resident, Department of Community Medicine, Government Medical College & Hospital, Eluru, Andhra Pradesh, India
Deena Sunayani Peters	Duty Medical Officer, Department of General Medicine, Ramdevrao Hospital, Hyderabad, Telangana, India
Chinnababu Sunkavalli	Senior Consultant Surgical & Robotic Oncologist, Clinical Director – Surgical Oncology, Yashoda Hospital, Hitech City, Hyderabad, Telangana, India
G Ganga Bhavani	Professor & HOD, Department of Community Medicine, Government Medical College & Hospital, Eluru, Andhra Pradesh, India
Raghavendrarao MV	Professor, Microbiology, World Academy of Medical Sciences, Netherlands

ABSTRACT Quantum biology examines the functional roles of quantum mechanical phenomena—electron and proton tunnelling, coherence, superposition, and spin-dependent processes—in living systems. Although long considered negligible in physiological environments, experimental evidence now indicates that these effects contribute to enzymatic catalysis, mitochondrial electron transport, DNA mutagenesis, and redox signalling. In oncology, these mechanisms intersect with carcinogenesis, tumour metabolism, and therapy resistance. Concurrently, quantum technologies (sensing, imaging, control, and computing) are being applied to cancer detection and treatment. This review critically synthesises the current evidence. We examine quantum contributions to the origin and progression of cancer, with emphasis on quantum metabolism and adaptive mutation models. We evaluate quantum-dot probes and solid-state sensors for high-sensitivity imaging. We analyse the strongest experimental advance to date—wireless bio-nanoantennae that exploit quantum biological electron tunnelling (QBET) to induce selective apoptosis in patient-derived glioblastoma cells. We assess quantum control strategies for radiotherapy and drug delivery, and the emerging role of quantum computing in molecular modelling and multi-omics analysis. Throughout, we distinguish robust experimental findings from theoretical proposals and highlight remaining challenges of decoherence, delivery, reproducibility, and regulatory translation. Quantum biology is progressing from speculative concept toward an experimentally grounded discipline with potential to complement existing paradigms in precision oncology.

KEYWORDS : quantum biology; quantum oncology; electron tunnelling; quantum dots; bio-nanoantennae; quantum control; quantum computing; mitochondrial redox; precision oncology

INTRODUCTION

Cancer remains one of the principal causes of morbidity and mortality worldwide. Despite major advances in genomic characterisation, immunotherapy, targeted agents, and multi-omics approaches, inter- and intra-tumour heterogeneity, adaptive resistance, late detection, and treatment-related toxicity continue to limit clinical success. Classical models of carcinogenesis—centred on sequential accumulation of genetic and epigenetic alterations, Darwinian selection of fitter clones, and metabolic reprogramming—have yielded substantial benefits, yet they do not fully account for the complexity of cellular decision-making under therapeutic or microenvironmental stress.

Quantum biology offers a complementary conceptual and experimental framework. It asks whether non-trivial quantum effects remain functionally relevant in the warm, wet, and noisy cellular milieu. Processes such as electron and proton tunnelling, long-lived coherence in photosynthetic and enzymatic systems, radical-pair spin chemistry, and quantum contributions to energy transduction have moved from theoretical speculation to experimental investigation (1). These same processes intersect directly with DNA fidelity, mitochondrial bioenergetics, redox homeostasis, and cellular stress responses—all of which are dysregulated in cancer (1,2).

In parallel, quantum technologies—quantum sensing, quantum imaging, quantum control, and quantum computing—are maturing rapidly. Their application to oncology, sometimes termed "quantum oncology," promises enhanced sensitivity in early detection, atomic-scale modelling of biomolecular interactions, and novel modalities for precise intervention (3–5). The convergence of natural quantum biological mechanisms with engineered quantum systems defines a new interdisciplinary frontier.

This review provides a critical synthesis of the field. We first outline core principles of quantum biology, then examine evidence for quantum contributions to carcinogenesis and tumour biology. Subsequent sections evaluate quantum probes and sensors, the most advanced experimental therapeutic platform (bio-nanoantennae mediating quantum biological electron tunnelling), quantum control strategies, and quantum computing applications. We conclude with a realistic appraisal of challenges and a roadmap for clinical translation, maintaining a clear distinction between experimentally supported findings and theoretical proposals.

Fundamentals of Quantum Biology Relevant to Oncology

Principal Quantum Phenomena

The central phenomena under investigation are:

- **Quantum tunnelling:** Electrons and protons traverse energy barriers classically forbidden. Electron tunnelling underpins sequential transfer in respiratory-chain complexes and photosynthetic reaction centres. Proton tunnelling contributes to enzyme catalysis and may influence DNA base tautomerization (1).
- **Quantum coherence and superposition:** Phase relationships among quantum states persist for biologically relevant timescales, observed most robustly in light-harvesting complexes and certain enzymatic active sites (1).
- **Spin-dependent chemistry and radical pairs:** Singlet–triplet interconversion of radical pairs is sensitive to weak magnetic fields and participates in certain mitochondrial redox reactions (1).
- **Entanglement:** While theoretically intriguing, robust experimental evidence for functionally relevant entanglement in macroscopic biological systems under physiological conditions remains limited (1).

Intersection with Cancer-Relevant Physiology

Mitochondrial electron-transport chains rely on sequential electron tunnelling whose rates and fidelity influence reactive oxygen species (ROS) generation (Figure 1). Dysregulated ROS contributes to genomic instability, signalling rewiring, and metabolic plasticity—hallmarks of cancer (1,2). Differences in coherence lifetimes and electron-transfer parameters (reorganisation energy,

electronic coupling) between healthy and cancerous mitochondria are beginning to be mapped by ultrafast spectroscopy and quantum sensing, and may ultimately serve as diagnostic or therapeutic biomarkers (1). Proton tunnelling in DNA has been linked to spontaneous mutagenesis, providing a possible quantum contribution to the stochastic component of carcinogenesis (2).

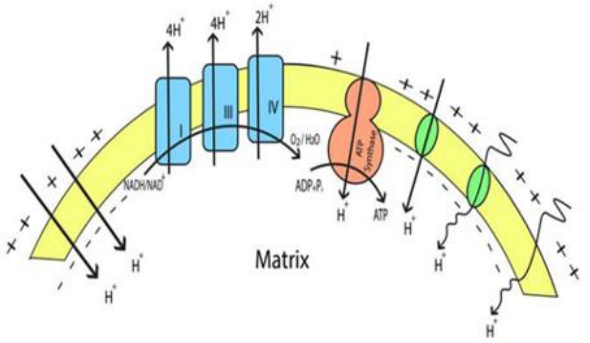

Figure 1: Schematic representation of the mitochondrial electron transport chain (Complexes I–IV and ATP synthase). Electron transfer between redox centres occurs primarily by quantum tunnelling. Disruptions in these processes contribute to elevated ROS and metabolic reprogramming in cancer cells.

Quantum Mechanisms in Carcinogenesis and Tumour Biology

Quantum Metabolism

Davies, Demetrius and Tuszynski advanced a quantum-metabolism framework inspired by the quantum theory of solids (6). They proposed that differences in metabolic rate between oxidative phosphorylation (predominant in normal cells) and aerobic glycolysis (the Warburg phenotype of many cancer cells) can be understood through quantum statistical mechanics of energy transduction. Combined with principles of natural selection, this framework supplies an ontogenic and evolutionary rationale for the origin and proliferation of sporadic cancer as an age-related metabolic disease driven by mitochondrial DNA abnormalities and compensatory glycolytic upregulation (6,7). While the model is conceptually coherent and generates testable predictions, direct experimental validation of the quantum-statistical assumptions under physiological conditions remains incomplete.

Adaptive Mutation and Directed Evolution

Theoretical models of "quantum cancer" invoke basis-dependent quantum selection as a possible mechanism of directed adaptive mutation under selective pressure (2). In this view, quantum principles may contribute to the generation of mutations preferentially in genes that enhance survival under therapeutic stress, thereby accelerating resistance evolution. These models remain largely theoretical; rigorous experimental tests of their predictions concerning mutation spectra are still required (2).

Redox Signalling and Mitochondrial Quantum Dynamics

Recent reviews emphasise that disruptions in quantum electron-transfer parameters within mitochondria may constitute early indicators of bioenergetic dysfunction and therapeutic vulnerability (1). Targeting these nodes via spin modulation, tunnelling-aware drug design, or external electromagnetic control is an emerging conceptual strategy, but clinical translation has not yet been demonstrated.

Quantum Probes and Sensing for Cancer Detection

Quantum dots (QDs) and related nanoscale quantum sensors offer size-tunable emission, high quantum yield, resistance to photobleaching, and facile surface functionalisation (3,8). Iron selenide QDs conjugated with anti-HER2 antibodies have shown superior performance relative to conventional organic fluorophores for specific imaging of HER2-overexpressing breast-cancer cells both in vitro and in xenograft models, with multiphoton excitation enabling deeper tissue penetration (3). Broader reviews of QDs in oncology document applications in biosensing, multimodal imaging, drug delivery, and photodynamic therapy (8). Solid-state quantum sensors, including nitrogen-vacancy centres in diamond, are being explored for nanoscale magnetometry and thermometry within the tumour microenvironment. Quantum control techniques can substantially improve signal-to-noise ratios in imaging modalities, although most clinical-trial activity remains in early phases (4).

Quantum-Enabled Therapeutic Strategies

Bio-Nanoantennae and Quantum Biological Electron Tunnelling (QBET)

The most advanced experimental demonstration to date is the 2024 study by Jain et al. published in Nature Nanotechnology (9). Gold bipolar nanoelectrodes (approximately 100 nm) were functionalised with reduced cytochrome c and zinc porphyrin, creating "bio-nanoantennae." Patient-derived glioblastoma cells that had internalised these particles were exposed to a remote alternating-current electric field (3 MHz, 0.65 V cm^{-1}). The field polarised the nanoelectrodes, enabling wireless electrochemistry that switched the redox state of cytochrome c via quantum biological electron tunnelling (Figure 2). This triggered caspase-3/7-mediated apoptosis, producing an approximately 50 % reduction in metabolic activity in glioblastoma cells while effects on normal astrocytes were significantly milder (9). Transcriptomic analyses revealed selective regulation of apoptosis, proliferation and tumour-suppressor pathways without substantial ROS elevation or temperature change. Subsequent commentary has framed the work as a prototype of "quantum functional medicine" (10). The platform remains preclinical (in vitro and patient-derived cell models only); in-vivo efficacy, long-term toxicity, and scalability have not yet been established. Nevertheless, it constitutes the first clear experimental control of a quantum tunnelling event for selective cancer-cell death (9–11).

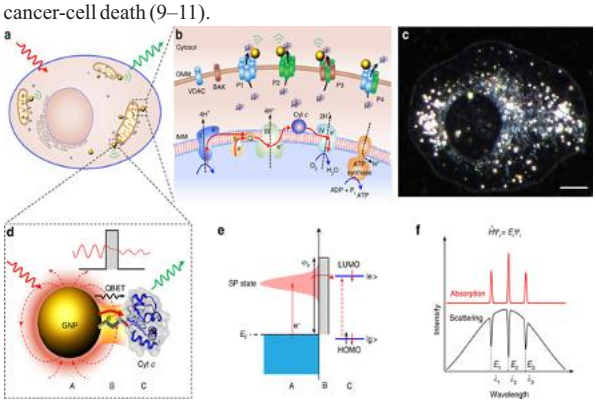

Figure 2. Schematic illustration of quantum biological electron tunnelling (QBET). A gold nanoparticle (GNP) functionalised with cytochrome c enables remote electric-field-controlled electron transfer, switching the redox state of Cyt c and triggering apoptosis in cancer cells. Panel (d) highlights the QBET process at the nanoparticle–protein interface.

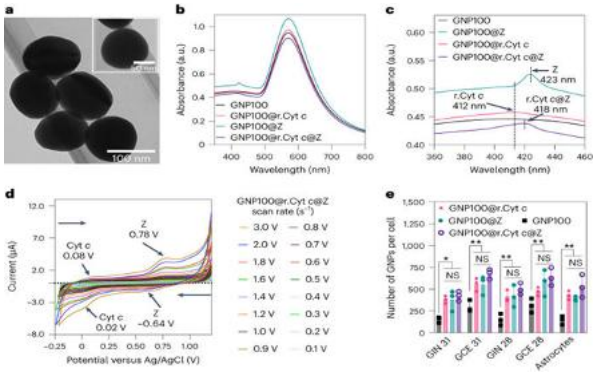

Figure 3. Physico-chemical characterisation of bio-nanoantennae (GNP100@r.Cyt c@Z). (a) Transmission electron microscopy image; (b,c) UV–visible absorbance spectra confirming surface functionalisation; (d) Cyclic voltammetry demonstrating redox activity of cytochrome c and zinc porphyrin; (e) Quantification of nanoparticle association with patient-derived glioblastoma cells versus astrocytes. Adapted from Jain et al. (9).

Quantum Control in Radiotherapy, Drug Delivery and Surgery

Perspective articles argue that quantum control can optimise energy deposition in radiotherapy (more precise Bragg-peak placement), enable real-time tracking during surgery, and permit stimulus-responsive release of chemotherapeutic or immunotherapeutic agents from nanoparticle carriers (4). Modelling studies suggest potential reductions in normal-tissue toxicity on the order of 30 %. These projections await rigorous experimental and clinical validation (4).

Photodynamic and Photoelectric Approaches

Iodine-carrying nanoparticles that exploit the photoelectric effect have been shown to enhance radiation-induced DNA double-strand breaks and rapid tumour-cell death in spheroid models. Quantum dots themselves can function as photosensitisers or energy donors in photodynamic regimens (8). These approaches rest on well-established quantum phenomena but require further optimisation of targeting and light-delivery strategies.

Quantum Computing and Machine Learning in Oncology

Quantum computing offers potential advantages for molecular simulation (protein folding, ligand–target binding, reaction pathways), combinatorial optimisation (treatment scheduling), and machine learning on high-dimensional multi-omics datasets (5). Hybrid quantum–classical algorithms such as the variational quantum eigensolver are already being applied to model electron-transfer parameters in redox-active proteins. Early quantum machine-learning models have shown promise in predicting immunotherapy response in selected cohorts (5). Current noisy intermediate-scale quantum hardware restricts problem size; meaningful clinical impact will depend on continued hardware progress and error mitigation.

Challenges and Critical Appraisal

- **Decoherence under physiological conditions:** Demonstrating that quantum effects persist with sufficient amplitude and duration to influence macroscopic cellular outcomes remains the central experimental challenge (1).
- **Delivery and selectivity of nanoparticle platforms:** Bio-nanoantennae and quantum dots must achieve efficient tumour targeting, endosomal escape and clearance while minimising off-target toxicity and immune recognition (8,9).
- **Reproducibility and accessibility:** Many quantum-biology experiments require specialised ultrafast spectroscopy or precisely controlled electromagnetic environments that are not widely available.
- **Regulatory pathways:** Novel physical modalities and quantum devices lack established regulatory frameworks comparable to those for conventional drugs and biologics (4).
- **Risk of over-interpretation:** Highly abstract or speculative models must be clearly distinguished from experimentally grounded findings to preserve scientific credibility (2,6).

Outlook and Roadmap

Near-term priorities include: rigorous replication and expansion of QBET-based apoptosis studies to additional cancer types and in-vivo models (9,10); development of quantum sensors capable of real-time mapping of mitochondrial redox and ROS dynamics in living tumours (1); integration of quantum-computed molecular parameters into conventional drug-discovery pipelines (5); incorporation of quantum-enhanced imaging endpoints into early-phase clinical trials (4); and establishment of multidisciplinary consortia spanning physics, chemistry, biology, engineering and clinical oncology. A closed-loop pipeline linking first-principles quantum simulation, experimental validation, multi-omics readout and adaptive clinical decision-making offers a coherent translational architecture (1).

CONCLUSIONS

Quantum biology is evolving from a largely theoretical domain into an experimentally accessible field with direct implications for cancer research. Evidence for quantum contributions to mitochondrial function, mutagenesis and redox signalling is strengthening. Engineered quantum systems—probes, sensors, bio-nanoantennae and computing platforms—are beginning to demonstrate tangible advantages in detection sensitivity, mechanistic insight and therapeutic selectivity. The bio-nanoantennae platform represents the clearest experimental proof-of-principle that quantum tunnelling events can be externally controlled to achieve selective cancer-cell death. Substantial scientific, technological and regulatory hurdles remain. Continued rigorous, interdisciplinary research will determine whether quantum approaches become integral components of next-generation cancer care.

REFERENCES

1. Sung JY, et al. Quantum biology: from mechanisms to medicine. Clin Transl Med. 2026;16(5):e70694. doi: 10.1002/ctm2.70694
2. Bordonaro M. Quantum biology and human carcinogenesis. Biosystems. 2019;178:16-24. doi: 10.1016/j.biosystems.2019.01.010
3. Abbas M, Kurian P. Quantum probes in cancer research. *Nat Rev Cancer*. 2022;22(6):311-312. doi:10.1038/s41568-022-00465-2
4. Matarèse BFE, Purushotham A. Unlocking clinical quantum oncology through quantum control. Eur J Cancer. 2025;226:115632.
5. Ramesh S, Tomesh T, Riesenfeld SJ, et al. Quantum computing for oncology. Nat Cancer. 2024;5:811-6. doi: 10.1038/s43018-024-00770-9
6. Davies P, Demetrius LA, Tuszynski JA. Implications of quantum metabolism and natural selection for the origin of cancer cells and tumor progression. AIP Adv. 2012;2(1):011101. doi: 10.1063/1.3697850
7. Demetrius LA, et al. Cancer proliferation and therapy: the Warburg effect and quantum metabolism. Theor Biol Med Model. 2010;7:2. doi: 10.1186/1742-4682-7-2
8. Mohammadi J, et al. A comprehensive review of lessons learned from quantum dots in cancer therapy. Biomed Mater. 2024;19(5):052004. doi: 10.1088/1748-605X/ad68af
9. Jain A, Gosling J, Liu S, Wang H, Stone EM, Chakraborty S, et al. Wireless electrical–molecular quantum signalling for cancer cell apoptosis. Nat Nanotechnol. 2024;19(1):106-14. doi: 10.1038/s41565-023-01496-y
10. Rawson FJ. Towards a quantum therapy in cancer. Clin Transl Med. 2025;15(7):e70411. doi: 10.1002/ctm2.70411
11. Zamberlan F. Quantum leap against cancer. Nat Chem Biol. 2023;19:1290. doi: 10.1038/s41589-023-01467-3