Quantum Decoherence Tomography with Entangled 511 keV Photon Pairs for Image-Guided Radiotherapy

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Abstract

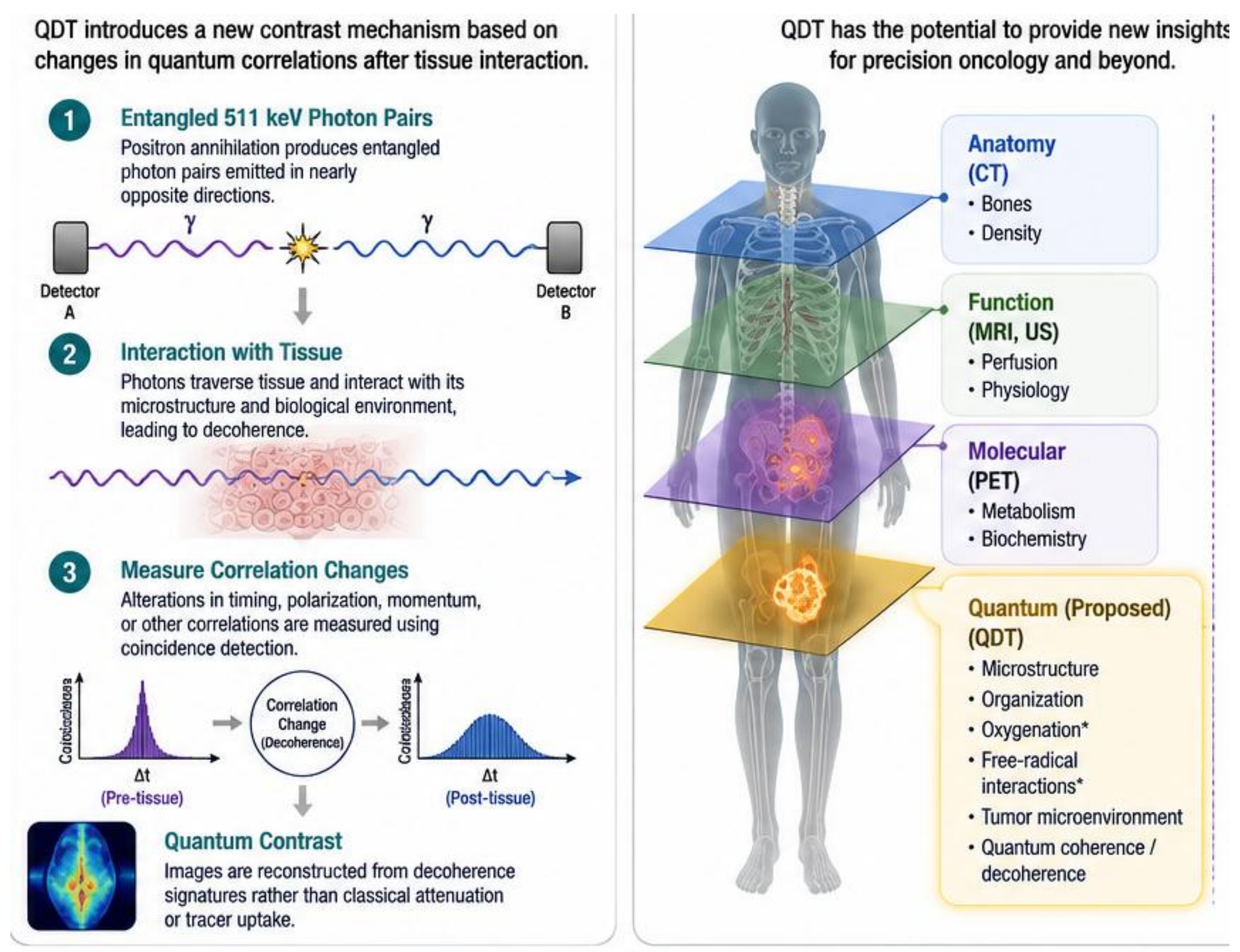
- Recent experimental studies have demonstrated that 511 keV photon pairs produced during positron annihilation are quantum entangled.
- Here, we propose Quantum Decoherence Tomography (QDT), a novel imaging paradigm that exploits changes in entanglement coherence as a contrast mechanism to probe tissue structure and dynamics during radiotherapy.
- QDT seeks to quantify decoherence signatures, including changes in coincidence timing, correlation visibility, and polarization or momentum correlations, to probe tissue microstructure and dynamic biological processes beyond the capabilities of conventional attenuation- or emission-based imaging.
- The approach provides a fundamentally new imaging contrast

Introduction

- Medical imaging has traditionally relied on anatomical, functional, and molecular contrast mechanisms.
- Recent experimental studies demonstrating quantum entanglement of 511 keV photon pairs produced during positron annihilation suggest the possibility of exploiting quantum correlations as a fundamentally new source of imaging contrast.
- Quantum Decoherence Tomography (QDT) is a proposed imaging paradigm that measures changes in the correlation properties of entangled photon pairs after their interaction with tissue, using quantum coherence loss (decoherence).
- Unlike conventional imaging, which is primarily sensitive to attenuation, emission, or relaxation properties, QDT seeks to probe tissue microstructure, organization, and dynamic biological processes that influence quantum correlations.
- As an initial application, QDT is being investigated for real-time image-guided radiotherapy and tumor microenvironment monitoring, with the broader vision of establishing quantumical contrast as a new imaging dimension alongside anatomical, functional, and molecular imaging.

Methods and Materials

- QDT leverages coincidence detection of entangled 511 keV photon pairs generated via positron annihilation processes occurring in radiotherapy-relevant environments, including external positron sources and linear accelerator–induced pair production pathways.
- Angularly resolved coincidence timing measurements are used to quantify decoherence metrics such as entanglement visibility, timing jitter, and polarization or momentum correlation degradation.
- These metrics are mapped tomographically to infer sub-voxel tissue heterogeneity and microenvironmental changes. The approach builds on recent experimental demonstrations of entangled annihilation photons and extends them to high-flux, clinically relevant geometries using detector arrays with ≤75 ps coincidence timing resolution and enhanced Compton background rejection



Results

- Monte Carlo and phantom-based simulations indicate that QDT can provide micron-scale localization sensitivity and detect subtle microstructural changes beyond conventional PET or CT.
- Decoherence signatures are predicted to correlate with tissue density gradients, anisotropy, hypoxia-linked microstructural heterogeneity, and dynamic tumor response during irradiation, supporting potential real-time adaptive radiotherapy guidance.
- Detector simulations confirm high Compton background rejection (>90%) and robust angularly resolved entanglement measurements under clinically relevant photon fluxes

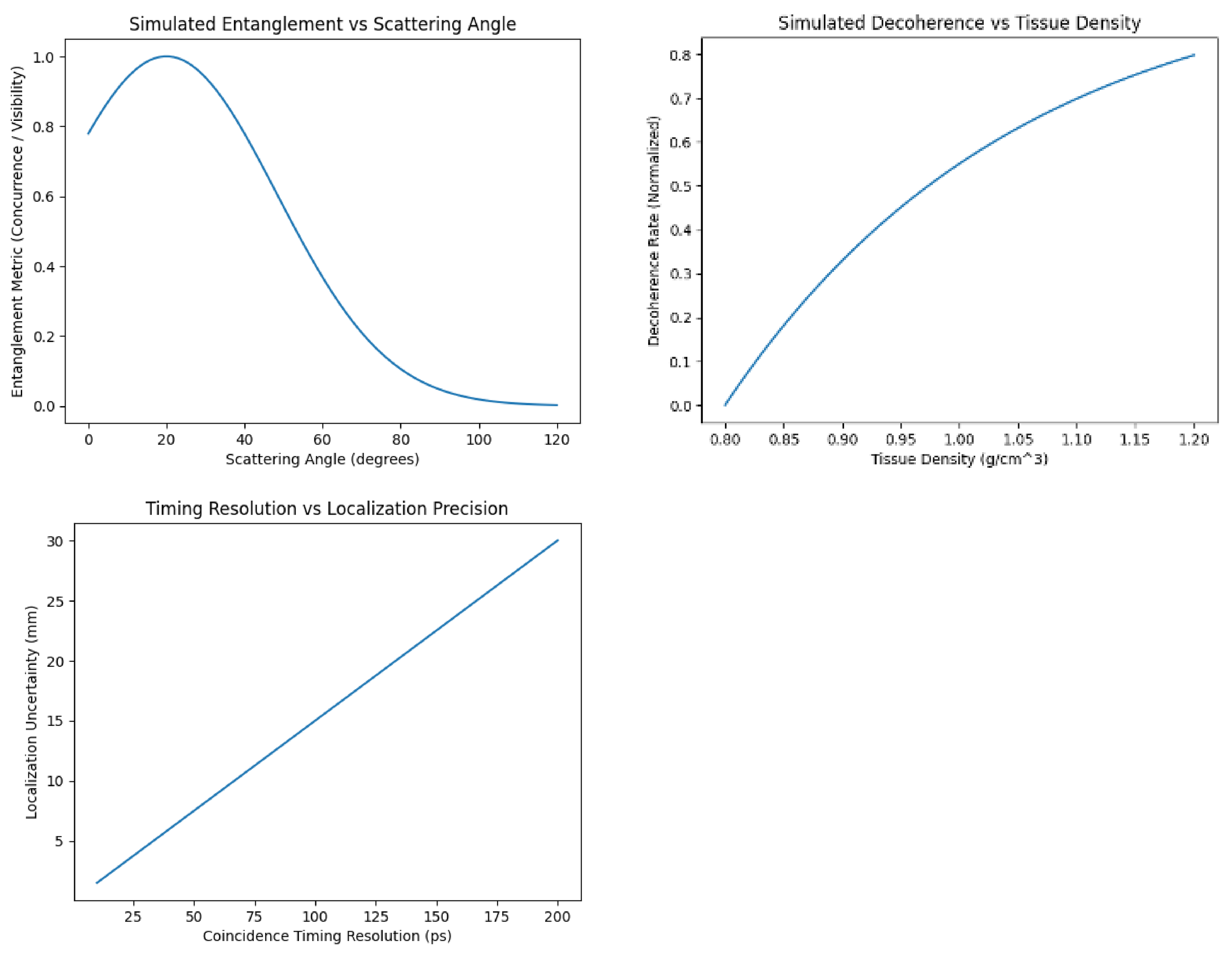


Figure 2. (Top left) Angular dependence of entanglement visibility for 511 keV annihilation photon pairs. High entanglement is preserved at small scattering angles and progressively decoheres at large angles due to environmental interactions and measurement back-action. (Top right) Decoherence rate as a function of tissue density, illustrating sensitivity of quantum coherence loss to microstructural heterogeneity and scattering properties. (Bottom) Relationship between coincidence timing resolution and spatial localization uncertainty derived from time-of-flight (TOF) constraints. Sub-100 ps timing enables centimeter-scale TOF localization.

Discussion

- **Significance:** Real-time monitoring of tumor anatomy and microenvironment during radiotherapy remains limited by classical imaging contrast and temporal latency.
- **Quantum Decoherence Tomography (QDT)** introduces a fundamentally new contrast mechanism based on **loss of quantum coherence in entangled 511 keV photon pairs**, enabling sensitivity to microstructural and compositional tissue changes beyond attenuation-based imaging.
- QDT has the potential to support **intra-fraction adaptive radiotherapy (ART)**, early treatment-response assessment, and longitudinal tumor microenvironment (TME) characterization.
- **Innovation:** QDT is the first proposed imaging paradigm to exploit **entanglement decoherence as a tomographic signal** in a clinical radiotherapy context.
- Key innovations include: (1) angularly resolved entangled-photon coincidence detection integrated with radiotherapy geometries; (2) dual-regime imaging combining ghost imaging (anatomical) and decoherence tomography (functional/molecular); (3) physics-informed AI inversion using open-quantum-system models; and (4) high-flux, clinically relevant detector architectures with sub-100 ps timing.
- This framework transforms quantum noise into a **quantitative biological contrast channel**.

Conclusions

- Quantum Decoherence Tomography introduces a fundamentally new contrast mechanism for radiotherapy imaging based on quantum coherence loss rather than classical attenuation or scattering.
- If experimentally validated, QDT could enable real-time tumor microenvironment monitoring and adaptive radiotherapy with unprecedented spatial and temporal resolution, with broader applications in biomedical imaging and quantum-enabled sensing.
- Just like CT, MRI, and PET Imaging, QDT provides a new imaging contrast mechanism that could transform imaging revealing a new layer of biology in medical imaging.

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References

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