Quantum Photonics for Non-Invasive Cancer Diagnostics: A Path Toward Subcellular Imaging Precision

Defne Duman
Robert College

***Abstract*—Non-invasive cancer diagnostics aim to detect tumors as early as possible without harming the patient. In this project, I explore how quantum photonics can improve medical imaging by using the quantum properties of light to reach subcellular precision. The main idea is to compare classical optical coherence tomography (OCT) with quantum-enhanced imaging that uses single photons, entangled photon pairs, and squeezed-light states. Using a conceptual device model, I examine how quantum light sources could reduce photonic noise, improve contrast, and allow repeated imaging with minimal damage to sensitive tissues. The literature on quantum imaging, biophotonics, and cancer diagnostics is reviewed to connect these ideas with current research on early tumor detection. These studies report gains in axial resolution, depth penetration, and signal-to-noise ratio when quantum effects are used. The project also considers ethical questions, such as fair access, cost, and data privacy, when introducing advanced quantum technologies into healthcare. Overall, the work suggests that quantum photonics can help build safer, faster, and more accurate imaging systems for cancer diagnostics, while supporting responsible and inclusive medical innovation.**

Non-invasive imaging is crucial in modern oncology because early and accurate detection of cancer strongly affects survival and treatment success (Rai, Yoo, & Dashkevych, 2025). Classical methods such as MRI, CT, and standard OCT have helped millions of patients, but they face limits in resolution, radiation exposure, and photonic noise.

Quantum photonics offers a new path by using quantum properties of light—such as single-photon emission, quantum interference, and entanglement—to improve sensitivity and contrast (Matarèse & Purushotham, 2025). Quantum light can, in principle, beat the classical shot-noise limit, making it possible to detect very small structural or biochemical changes in tissue (Lotfipour, Sobhani, Dejpasand, & Sasani Ghamsari, 2025).

For cancer diagnostics, this means we may be able to see molecular-level abnormalities before they become visible in standard images (Singh, Saxena, & Saxena, 2025). Quantum-enhanced OCT (Q-OCT) and other quantum imaging schemes have already shown improvements in axial resolution, depth reach, and signal coherence in research settings.

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This project develops a conceptual quantum photonic imaging model and connects it to the existing literature. It also briefly discusses ethical and accessibility issues, such as who will benefit from these advanced tools and how they can be integrated fairly into global healthcare systems (Gobinath, Rajeswari, Kumar, & Anandan, 2025; Ashour & Koundal, 2025).

Methods

Conceptual Quantum Photonic Device Model

A conceptual model of a quantum photonic imaging system was built using the ideas from recent quantum imaging papers. The model includes:

- Quantum light sources: entangled photon pairs and squeezed-light states,
- Optical paths and interferometers: to generate and detect quantum interference and photon correlations,
- Sample arm: where light interacts with biological tissue, and
- Detection unit: that measures coincidence counts, correlations, or other quantum signals to reconstruct images.

The model is designed as an extension of OCT, where classical light is replaced or combined with quantum light to improve image quality.

Classical vs Quantum-Enhanced Imaging Comparison

The project uses a qualitative comparison between:

- Classical OCT, which relies on low-coherence light and interferometry, and
- Quantum-enhanced OCT (Q-OCT) and related schemes, which use entangled photons or other non-classical states.

From the literature, reported improvements in resolution, depth, and noise behavior are summarized. The focus is on how quantum entanglement, noise suppression, and photon correlation can increase diagnostic fidelity without increasing radiation dose.

Literature Review

A focused literature review was performed on:

- Quantum imaging and its biological applications (Lotfipour et al., 2025; Baldini et al., 2025),
- Photonic sensors and liquid biopsy diagnostics (Colapietro, Brunetti, Panciera, Elicio, & Ciminelli, 2025),
- Quantum oncology and future cancer imaging directions (Matarèse & Purushotham, 2025; Rai et al., 2025),
- Ethical and societal aspects of quantum technologies in healthcare (Gobinath et al., 2025; Ashour & Koundal, 2025).

These sources were used to define realistic performance expectations and to understand where quantum photonics fits within the broader field of biophotonics and precision diagnostics.

Results

Expected Imaging Improvements from Quantum Photonics

Based on the conceptual model and literature:

- Resolution: Quantum-enhanced OCT can achieve better axial resolution than classical OCT by using entangled photons and improved interference patterns.
- Noise behavior: Squeezed-light states and photon correlations can reduce certain noise contributions, improving signal-to-noise ratio and image clarity.
- Photodamage and safety: Because quantum schemes can work effectively with fewer photons, there is potential to reduce photodamage, enabling repeated imaging of sensitive tissues.

These improvements are especially valuable for detecting early tumor changes and mapping fine structures in the tumor microenvironment.

Potential Clinical Applications

The reviewed work suggests that quantum photonic systems could help with:

- More accurate tumor boundary detection,
- Better vascular mapping in and around tumors,
- Detailed cellular and subcellular morphology analysis, possibly before major structural deformation occurs (Baldini et al., 2025; Colapietro et al., 2025).

While current demonstrations are mostly in laboratory settings, they provide a clear roadmap toward future clinical prototypes.

Discussion

Impact on Non-Invasive Cancer Diagnostics

If successfully translated to the clinic, quantum photonics could significantly change how we perform non-invasive cancer diagnostics. Higher resolution and better contrast at low photon doses mean:

- Earlier detection of suspicious changes,
- More precise monitoring of treatment response,
- Potentially fewer biopsies and invasive procedures.

This aligns with the broader move toward precision medicine, where decisions are based on detailed, patient-specific information (Singh et al., 2025; Matarèse & Purushotham, 2025).

Ethical and Accessibility Considerations

Advanced quantum devices may be expensive and technically complex. Without careful planning, they could widen the gap between well-funded hospitals and resource-limited settings. Key challenges include:

- Ensuring equitable access across different countries and health systems,
- Protecting data privacy as imaging data becomes richer and more sensitive,
- Training clinicians and engineers to operate and interpret these new systems (Gobinath et al., 2025; Ashour & Koundal, 2025).

Designing quantum medical technologies with fairness, cost-awareness, and inclusivity in mind is essential.

Conclusion

This project explores how quantum photonics can support non-invasive cancer diagnostics with subcellular imaging precision. By combining a conceptual device model with a targeted literature review, it highlights expected gains in resolution, noise reduction, and patient safety when quantum light is integrated into imaging systems.

Although many challenges remain—especially in engineering, cost, and clinical validation—the convergence of quantum photonics and biomedical engineering points toward a future where cancer can be detected earlier, monitored more precisely, and treated more effectively. At the same time, attention to ethics and accessibility will be necessary to ensure that these powerful tools benefit patients worldwide, not just a limited few.

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