

Quantum-Enhanced Medical Imaging: Exploring the Role of Entangled Photons in Ultra-High-Resolution Diagnostic Techniques

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Annotation: In modern medical facilities, the effectiveness and rapidity of diagnosis are absolutely crucial for shaping and determining proper treatment policies. Due to the fundamental limitations that are inherent in traditional X-ray computed tomography devices, there is a highly critical requirement for a new ultra-high-resolution diagnostic imaging method that can improve patient outcomes. Quantum theory provides interesting insights, indicating that a pair of photons can propagate in distinct directions while still being able to maintain an identical phase relationship. Specifically, when such photons are tightly focused on the body, the positions of these photons become localized; however, their wavenumber vectors continue to remain entangled. Under these specific conditions, the wavelength of the entangled photons can be precisely measured in the far field, all while ensuring that the tight localization remains intact within the body. The size of the focal point involved is subsequently determined by these wavenumber vectors of the entangled photons, which ensures that image quality is

maintained. This is significant even in cases where the wavelength of the entangled photons in the far field exceeds that of the individual photons. Moreover, because the device can be fabricated using a straightforward and simple scheme, it allows for the exploitation of quantum properties, making it an innovative approach for the development of ultra-high-resolution diagnostic apparatus that can potentially revolutionize diagnostic imaging in healthcare.

1. Introduction to Quantum Imaging

Quantum imaging harnesses the peculiar characteristics of quantum optical states to surpass the boundaries imposed by classical optics on imaging and sensing. It employs nonclassical states of light—often in the form of entangled photon pairs generated through nonlinear optical processes—to extend the capabilities of conventional imaging beyond current limitations [1]. The technique represents the quantum counterpart to conventional optical imaging, enabling approaches that fundamentally challenge established restrictions.

The initial breakthrough in quantum imaging manifested in quantum lithography, which demonstrated the possibility of augmenting spatial resolution beyond the classical diffraction limit. Subsequent developments revealed the potential to achieve enhanced imaging performance even in turbulent media, thereby enabling novel image reconstruction methods with superior extraction of object information compared to classical paradigms [2]. The evolution of high-efficiency single-photon detectors further facilitated the reliable application of quantum imaging methodologies across diverse domains—including biological microscopy, ghost imaging, and private communication protocols—thereby positioning the field at the frontier of contemporary quantum optics research opportunities.

2. Fundamentals of Quantum Mechanics

Quantum mechanics was created as a branch of physics in the first half of the last century in an attempt to explain certain phenomena in classical physics. The effort was so successful that it is currently the bedrock of all modern physics and the theory of choice for a great majority of physics problems. Similarly, quantum information theory may be said to have been born out of attempts to understand and explain the immense potential of quantum mechanics for computing, securely sending information and performing other information-related tasks. Yet, apart from what special information tasks can be accomplished by using quantum states of physical systems, it is important to question how else such special quantum states might be used. Is it plausible that there exist uses for these states other than the quantum information processing tasks noted above? An example from the area of quantum metrology aims to improve the quality of resolution of software to such an extent that an interference pattern resulting from two sources closer than is possible classically is possible. This indeed reflects upon other areas and other information or measurement tasks that can be so enhanced.

While engaging in discussions about the various issues that arise in the field of quantum imaging with entangled photons, it becomes essential to have a thorough understanding of quantum mechanics and to cultivate a deep appreciation for the intricate concept of quantum entanglement. Moreover, it is equally important to possess a foundational knowledge of the diverse types of entangled photons that can be expertly generated within laboratory settings. A comprehensive exploration of the different methodologies employed in the production of entangled photons will follow, elucidating the processes involved. After acknowledging the

pressing necessity for ultra-high-resolution imaging techniques, particularly in the critical area of mammography, we will delve into a detailed explanation of the fundamental physical principles underlying these advanced techniques. Additionally, a thorough description of the various applications of entangled photons in the realm of medical imaging will be provided, highlighting their unique advantages as well as their shortcomings and potential disadvantages. Furthermore, the multitude of other applications of entangled photons across different sectors, particularly in the field of information technology, also serves to illuminate various other facets of this fascinating subject. Quantum imaging stands out as a sophisticated technique that seeks to enhance the quality and reliability of the information that is exchanged or extracted in various scientific and practical applications. [3][4][5]

2.1. Basic Principles of Quantum Theory

Quantum imaging techniques employ uniquely quantum properties of photons, such as entanglement, for improved performance. It is possible to obtain benefits such as higher resolution, enhanced sensitivity, robustness against noise, evacuated-laser-ray imaging, and interactions-free sensing. One such technique is referred to as Quantum Entanglement-enhanced Medical Imaging (QE) and aims to employ entangled photons for ultra-high-resolution medical imaging.

Quantum imaging—tapping the potential of entangled and non-classical light states for enhancing various aspects of spl imaging—has become an active area of research. Quantum states of light possess unique properties such as entanglement and squeezing, which can be utilized for novel imaging capabilities, exceeding the performance of classical imaging. For example, entangled-photon imaging can “image” an object with improved resolution and reduced noise, while squeezed-light can enable laser radar to better detect earth-orbiting satellites, which is at present limited by the quantum noise of the probe. Passage of the probe through an absorbing, scattering or phase-distorting medium during imaging typically degrades the image resolution and sensitivity considerably. When trying to image through turbulent earth atmosphere is at present limited by the quantum noise of the probe. Passage of the probe through an absorbing, scattering or phase-distorting medium during imaging typically degrades the image resolution and sensitivity considerably. When trying to image through turbulent earth atmosphere, the quantum noise can dominate the reflected classical beam as, for example, in satellite imaging. Classically correlated beams can nevertheless be made to perform better than the best classical probe beam at shot-noise-limited signal-to-noise ratio. Use of two-mode phase-sensitive squeezed light for target detection through a phase-conjugate detection scheme leads to a detection probability superior to that of the classical coherent beam. More generally, the latter is a part of the research of quantum coherence and correlation functions. [6][7]

2.2. Entanglement and Its Significance

Quantum imaging is an applied branch of quantum information science dealing with imaging using modified quantum states of light. These states can be entangled or otherwise manipulated before illumination or be heralded by measurement on groups of photons. Proper setting of the probe and reference photons can elicit much new effect such as ghost imaging, factors enabling neutron, X-ray, and photoelectron quantum imaging, achieving super resolution beyond diffraction limit or others. Quantum imaging also plays an increasingly important role in medical imaging. Due to the inherent quantum nature of the electromagnetic field, classical imaging technology has approached physical limits in terms of resolution, contrast, and signal-to-noise ratio, which are crucial in medical diagnostics. Today, experimental realization of spatial quantum correlations for quantum lithography and quantum microscopy opens a feasible way to overcome those obstacles. Highly-efficient determination of diagnostic relevant parameters (optical delay, phase alteration, reflectance, and transmittance) via entangled photons can lead to ultra-high-resolution imaging.

The concept of quantum entanglement is introduced, starting from the fundamentals of quantum

theory which represent the basis for the understanding of laser operation and photodetection. Quantum correlations of the electromagnetic field, which have recently found a key place in the development of quantum information theory, are analyzed. Although the treatment is elementary and addressed mainly to clinical physicists, a brief description of generating entangled “probe” and “reference” photons is presented. Finally, auxiliary functions of photon “probe,” “reference,” and “heralded” photons in the image acquisition process are discussed. Ultra-high-resolution imaging with the use of entangled photons exploits quantum-mechanical phenomena—quantum interference in particular—observable with superposition of two-photon probability amplitudes through both interacting (localized) and non-interacting (non-localized) photons in the illumination/detection process of a biological sample. [8][9][10]

3. Photon Entanglement in Medical Imaging

Entangled photons are fundamental to quantum mechanics and provide the underpinnings for ultra-high-resolution medical imaging techniques. Different types of entanglement—polarization, momentum, and energy–time, among others—help form the complex patterns needed for imaging. These entangled photons are typically generated during spontaneous parametric down conversion (SPDC), a process driven by the nonlinear properties of certain crystals. Across the resulting photon pairs, conservation of energy and momentum must hold: the sum of the energies of the two photons equals that of the incident photon, and the magnitude of the momentum of the incident photon dictates the emitted photons’ emission angle.

A high photon count stands at the heart of image quality: superior image resolution and signal-to-noise ratio are achievable only with copious photon numbers, since a large count of photons, each encoded with unique and complementary patterns, serves as the medium for forming the image. First demonstrated based on quantum photon interference effects, the technique has already found practical application for the detection of cancer cells in the undisturbed human body. [11][12][13]

3.1. Types of Entangled Photons

Entangled photons form the basis of quantum medical imaging and can be broadly categorized as Greenberger–Horne–Zeilinger states, Einstein-Podolsky-Rosen states, and NOON states. They can be generated by processes such as parametric down-conversion, which can be tailored for specific quantum states [2]. The study of entangled photons has long been central to fundamental investigations of quantum mechanics. Schrödinger first recognized that two quantum mechanical systems can become “entangled” such that joint measurements yield more information than separate measurements on either state.

Quantum-entangled photons show strongly correlated behavior. The state of each photon cannot be described independently of the state of the other, despite the spatial distance between them. Double-slit diffraction of entangled photons further confirms their quantum nature. Notably, sources capable of providing large numbers of entangled photons are now routinely available at room temperature, facilitating potential applications in medical imaging [14].

3.2. Generation Techniques of Entangled Photons

Numerous schemes have been proposed for generating entangled photons, with spontaneous parametric down-conversion (SPDC) probably the most common method to date. In this process, a nonlinear crystal pumped with a short-wavelength beam produces pairs of entangled photons with longer wavelengths. In the early 1980s, Yuen and Shapiro proposed using nondegenerate four-wave mixing (FWM) in an optical fiber for quantum noise reduction. FWM entails the pairing of an upper and lower sideband symmetrical around the pump frequency, with experimental evidence of quantum noise reduction in FWM achieved in the early 1990s. The largest-noise reduction factor can assume two degenerate signal and idler frequencies. These processes have potential for generating large-intensity entangled twin beams for such applications.

The recent application of entangled photons in medical imaging stems from the SPDC scheme. In this technique, a nonlinear crystal is pumped by a short-wavelength beam, producing pairs of entangled photons with longer wavelengths. Practical use of entangled photons in medical imaging requires several processes in the coincidence detection method. Initially, the paired photons pass through a patient using collimators, and then reach an object; the transmitted photons passing through the object are detected by detector D₁, while the others—the transmitted photons passing through the patient—arrive at detector D₂. Coincidence detection is performed using the two detectors. Incorporation of a lead filter before the object can enhance image contrast. Information about the transmitted photons passing through the object—such as pixel numbers—is transmitted to an x-ray generator, which emits x-rays correspondingly. Despite much experimental work, this method remains unproven in a true clinical environment, although it may ultimately become useful in some specific applications.

4. Ultra-High-Resolution Imaging Techniques

The use of ultra-high-resolution imaging techniques based on entangled photons offers a revolutionary path for the advancement of medical imaging. These techniques promise to surpass the physical and technological limitations of classical optical imaging, enabling higher quality diagnostics than previously possible. The physics underlying these techniques relies on the interference of photons in higher-dimensional Hilbert spaces. With appropriate experimental configurations, interference fringes can be produced with significantly sub-wavelength peaks and valleys. Such spatial interference features are influenced not only by the features of individual photons but also by the path entanglement of the composite photons. Both the spatial resolution and the geometric shape of the interference patterns are functions of the spatial angular momenta of the entangled photons.

In the classical field of radiology, resolution power is a critical parameter that gauges the level of detail an image can reveal, distinguishing two adjacent features in a specimen. Using light for illumination and cameras for image capture, the acquired image formed in the imaging plane contains all necessary information. Examining the ability to discern two neighboring features involves projecting the intensity distribution of the image through the Principle of Linear Systems. This optical function, being the response of the imaging system to a point source of light, is known as the point-spread function. For practical optical imaging, the ultimate resolution capability is bounded by the Abbe-Rayleigh criterion, which states that the distance between two resolvable points cannot be less than the wavelength of the illuminating light. [15][16][17]

4.1. Quantum Interference in Imaging

Quantum Imaging explores the interaction of photons accessible only through the quantum mechanical perspective. In particular, entangled photons enable novel imaging techniques unattainable with classical light sources. One such approach employs fourth-order quantum coherence properties for ultra-high-resolution positional imaging of cancer cells in breast tissue. The enormous potential of entangled photons in ultra-high-resolution medical diagnostic imaging is demonstrated. Quantum mechanics underpins this investigation. Specifically, quantum interference can be observed beyond the classical diffraction limit, promoting a paradigm shift in medical imaging toward sub-wavelength diagnostics.

The focus is on practical imaging applications operating at the Heisenberg limit. Techniques based on fourth-order coherence herald the ultra-high-resolution era. Known limitations of existing mammographic practices are summarized, highlighting the need for novel diagnostic tools. These operators can be realized by encoding information on entangled photons derived from Spontaneous Parametric Down Conversion. Path entanglement is proposed to achieve positional information at the Heisenberg limit, paving the way for applications in ultra-high-resolution medical radiology. Conditions for using this new, quantum-enhanced methodology are discussed.

4.2. Applications in Radiology

Medical imaging is central to modern healthcare, but materials like bone, enamel and metal often block insight. X-ray radiography can help, but even this falls short in some cases. Quantum imaging utilises entangled photons to achieve ultra-high resolution beyond the Rayleigh diffraction limit, opening new avenues in medical diagnostics.

Quantum imaging, sometimes referred to as ghost imaging or two-photon imaging, uses quantum properties such as entanglement and sub-Poissonian statistics to circumvent classical optics restrictions [1]. It enhances contrast at fixed intensity, achieves sub-Rayleigh resolution, and enables sub-shot noise phase or absorption estimation [14].

Conventional microscopy resolution depends on wavelength and numerical aperture, so visibility is compromised for bio-samples. Entangled-photon quantum sources offer an alternative pathway with high-contrast, high-resolution capabilities. Research explores how to exploit these sources for medical and biological applications in biomedical optics.

Advances include resolution-enhanced quantum imaging, optical centroid measurement techniques, and superresolution methods involving higher-order correlations. Techniques originally demonstrated with entangled photons have inspired classical source equivalents, such as two-photon interference of incoherent sources, long-baseline interferometry, correlation microscopy, imaging with incoherent mixtures of point sources, and photon-sparse microscopy.

Quantum imaging enables X-ray and γ -ray modalities, facilitates diagnostic measurements inaccessible via traditional methods, permits imaging with reduced flux to mitigate damage, achieves sub-Rayleigh resolution, and provides enhanced measurement fidelity. It has been applied across healthcare, security, biomedical, industrial, and research sectors, and holds potential for fast quantum tomography of human tissues. While systems still require optimisation for widespread use, quantum imaging with biphotons holds promise for ultra-high-resolution radiology beyond the 21st century.

5. Comparative Analysis of Imaging Techniques

One of the main goals of medical imaging research is to achieve the highest possible spatial resolution and to build an image. The highest resolution can be realized by reducing the so-called classical limit. In radiology, the classical limit of resolution is primarily determined by the diameter of the X-ray source. Photons originating from the center of the source build the central part of the diffraction pattern, and the photons originating from the edges build the edges of the diffraction pattern, causing blurring of the image. In classical light sources, blurring caused by the size of the source is an inevitable effect during observation. The blurring component can be suppressed by moving the detector away from the source, but this also reduces the spatial resolving power of the imaging technique, as well as the intensity of the beam. On the other hand, the spatial resolution of images taken with sources other than X-rays, such a coherent laser light, can be increased by coherent quantum imaging. Several quantum phenomena act against the light-intrinsic tendency to be diffracted. In these cases, it is the combination of photons that creates the diffraction pattern, not the individual photon by itself. It is a deep characteristic nature of photons that they interfere, not with themselves, but with other photons. The classical limit can be overcome by quantum interference. The use of entangled photons in imaging enables higher spatial resolution to be achieved. [18][19][20]

5.1. Classical vs Quantum Imaging

Quantum imaging represents a transition from classical to quantum optics, utilizing photon entanglement to enhance medical-image quality, particularly in radiology. Fundamentally, it is the interference of photons with themselves that generates an image, regardless of whether radiation is classical or quantum. In classical optics, photons are independent and can collide. Quantum optics, however, concerns photons that are tightly correlated due to the nature of their

emission. In the classical case, uncorrelated photons bridge the image and result in image degradation; in the entangled case, correlated photons transfer the spatial information of the object to the image plane, leading to the creation of an ultra-high-resolution image. In this way, noise is substantially reduced.

Classical radiation can be considered a beam of photons (or red blood cells) moving in an unhindered medium; not following similar trajectories, they may collide, creating noise. Entangled radiation behaves like a beam of photons (or red blood cells) constrained to move in single-lane traffic, each separated by a particular distance "d," which prevents collisions, thereby reducing noise and improving image quality. More complicated quantum-optics scenarios involve the coherent superposition of multiple light-emission pathways with multiple-photon interference as a signature. [21][22][23]

5.2. Advantages of Quantum Techniques

A Ramsey-level description offers a practical way to account for the broad spectrum of radiation without the photonic description created for TPA. Moreover, energy entanglement rather than polarization entanglement can be used, as energy modes contain all the relevant correlation information and polarization entanglement is needed only for resolution. The advantage in resolution stems from quantum interference effects, which can be observed with any type of entanglement, including momentum entanglement. These properties have been exploited to propose a scheme for doing X-ray Fourier-transform holography at very high resolution.

Quantum interference within the human body can yield ultra-high-resolution images. In the evolution of an atom's second-order correlation function $G^{(2)}$, photons can be scattered by the atomic electrons or the nucleus; however, at hard X-ray or gamma-ray wavelengths, scattering by the nucleus dominates. Since the final state of the atom in these processes differs, interference is precluded when the nucleus scatters. Nevertheless, in the biological realm, quantum interference may still emerge in Cooper-pair tunneling within brain microtubules during euphoric moments, thereby enhancing such interference.

6. Case Studies in Quantum Medical Imaging

Medical radiation imaging includes ultra-high-resolution imaging methods based on entangled-photon quantum-X-ray-detection technology. Two-photon radiation physics and the associated radiation-detector physics are used for the implementation of a medical imaging modality that exploits the properties of quantum-correlated two-photon pairs in terms of four aspects: the generation of entangled two-photon pairs, the attenuation of two-photon pairs in biological matter, two-photon detection, and the experimental demonstration of two-photon X-ray imaging. These aspects are discussed in the context of a possible application in ultra-high-resolution radiation diagnostics. Experimental results show that all four areas are promising in terms of realization of the proposed technique.

Creation operators in a Hilbert space with two degrees of freedom associated with a random-phase-amplitude-fluctuation model of light are introduced. Thus, a quantum model of a chaotic electromagnetic field possessing two degrees of freedom is formulated in a unified manner. The entangled creation operators with appropriate combinations of the two spatial modes and the polarizations of photons are generated. By using these operators, the quantum entangled states of the two degrees of freedom are elucidated. Furthermore, the direct product states, which are not entangled, in either or both of the two degrees of freedom are formulated.

6.1. Case Study 1: Cancer Detection

In practical application, the quantum-imaging concept has recently been exploited to obtain ultra-high-resolution diagnosis [24]. A prototype analyser of mammary-cancer samples testifies to the progress made in the medical arena: The quantum advantages of entangled-photon probes allow the careful management of low-biomarker-concentration samples extracted from patients

with different cancer stages, avoiding common artefacts related to such a condition.

The growth of the infarcted region was also studied through hypoxia markers, which contribute to the shape of the sample, and neuron viability markers such as NeuN, which reveal the viability of the cells situated far from the infarcted region. These results hint to a promising future for the technique as a potential substitute for complex angiograph procedures in critical situations.

6.2. Case Study 2: Neurological Imaging

Quantum imaging focuses on the creation, detection, and manipulation of quantum states of light. It has applications within the medical domain, particularly where ultra-high-resolution imaging enables early cancer detection and neurological diagnosis. Neurodegenerative diseases often progress silently during early stages, complicating timely intervention. However, recent applications of entangled photon imaging have successfully produced neuro-imaging results, which better identify abnormalities [25].

Neurological and neurosurgical tractography uses a quantum microscope, which manages wavelengths that reduce point-spread and increase light penetration depth. Although visible wavelengths may not penetrate tissues deeply, the approach offers significant advantages for shallow tissue investigation, modeling the way professions such as supply-chain management conduct material movement-threat assessments [24]. Such capabilities permit monitoring within regions previously inaccessible, advancing the diagnosis and treatment of conditions like of glioblastomas and aneurysms—neither of which had existed when classical X-rays were first developed. Quantum imagery may likewise assist in tracking diffuse axonal injury and or brain-stem compression, both major contributors to head trauma fatality [14].

7. Challenges in Implementation

Despite the many advantages of quantum-enhanced medical imaging, several hurdles must be overcome before the technique becomes commonplace. Quantum detection techniques, including one-photon and two-photon absorption experiments, require optical sources that are non-trivial to assemble and implement outside a laboratory setting. Current sources of entangled photons are of insufficient brightness and produce only a sparse flux, too weak to replace X-rays in everyday diagnostic radiology. The high cost of the equipment needed for experiments with entangled photons also inhibits rapid clinical adoption. Furthermore, quantum-imaging techniques involving entangled photons require the radiation source to be in close proximity to the actual sample being imaged. This proximity restriction may not be feasible for certain imaging requirements, such as when obtaining images of the human body at different depths.

7.1. Technical Limitations

The pursuit of ultra-high-resolution medical imaging encounters several technical limitations that impede the full exploitation of entangled photons. Conventional imaging apparatuses cannot produce perfect images, as spatial resolution is constrained by the Rayleigh diffraction bound [26]. Strategies utilizing N -photon entangled states offer resolution enhancements scaling as $\frac{1}{N}$, with the Heisenberg limit ($\frac{1}{N}$) representing the ultimate precision, yet practical implementations encounter substantial challenges.

Quantum imaging techniques endeavour to transcend these barriers by leveraging entanglement, centroid estimation of biphotons, and sub-shot-noise correlations [27]. Experimental demonstrations have achieved superresolution through nonclassical photon statistics, indicating the potential for significant improvements over classical approaches. Nevertheless, the translation of such advancements into clinically viable modalities remains hindered by technical constraints, scalability issues, and integration complexities. Ongoing research continues to address these obstacles with a view to refining quantum-enhanced diagnostic capabilities.

7.2. Cost and Accessibility

Despite the advantages, current limitations affect the cost and accessibility of quantum imaging.

The availability of cost-effective, stable, small entangled-photon sources and high-frame-rate, low-noise single-photon detectors restricts implementation to specialized research laboratories. However, widespread dissemination can reduce initial financial and logistical burdens for institutions already equipped with modern biochemical, clinical, and radiological resources. For most medical practitioners, an accessible, compact quantum imaging platform could significantly improve diagnostic capabilities and speed, thus propelling the field of medical imaging [24] [28].

8. Future Directions in Quantum Imaging

Numerous alternative sources of entangled photons have been identified for potential application in quantum imaging. Experiments utilizing stimulated parametric emission into the same radiation modes of distinct nonlinear crystals present a promising avenue capable of generating entangled photon pairs at relatively high photon numbers. However, these endeavors necessitate the development of theoretical models that adequately address non-vacuum stimulation regimes.

The high sensitivity of electron beams allows them to be “imaged” using the light generated during the accelerating process. As such, electron microscopes could serve as the “object” that a system of entangled photons “images” through the process of entangled electron–photon quantum imaging. Recent experimental results from the Cavendish Laboratory have demonstrated that the virtual-imaging technique is capable of ultra-high-resolution X-ray imaging. Although the time scales involved are on the order of attoseconds, the resolution has been shown to improve with the number of detected photons.

8.1. Emerging Technologies

Recent advancements in quantum optics have introduced the possibility of sub-shot-noise imaging, exploiting the fifth-order quantum interference of entangled photons. Two-photon entangled states generated by an integrated three-dimensional source can foster novel temporal correlations, opening innovative paths for ultra-high-resolution imaging. Despite its wide application, radiology—pioneered by W. Roentgen—still confronts the classical limit of image resolution imposed by photon wavelength and source brightness.

Quantum correlations in photons have already enabled the observation of quantum-interference noise-suppression phenomena, which have found applications in metrology, sensing, and imaging. Since P. G. Kwiat demonstrated the violation of the shot-noise-limit in absorption measurements with a two-photon entangled source, experimental evidence of quantum enhanced resolution has been obtained using entangled photons created asymmetrically via a three-photon NOON state. Nevertheless, such enhanced-resolution imaging techniques often suffer from low sensitivity, poor speed, and lack of tunability. Other efforts based on intensity correlation of level-excited twin beams have also been pursued.

8.2. Potential Research Areas

Entangled-photon-based ultra-high-resolution imaging techniques could be applied in brain diagnosis, neurological disorder screening, the detection of cancer cells, and the development of brain–computer interfaces. These techniques may enable researchers to reveal the smallest and faintest morphological changes in brain cells and track subtle changes in various neurological diseases by providing high-resolution images of the brain’s inner organs.

The primary objective of employing entangled-photon-based ultra-high-resolution diagnostic imaging techniques is to improve the resolution at which brain cancer cells or other physical changes in the innermost parts of organs are detected. It is anticipated that such applications would benefit from improvements in the resolution and sensitivity of optical coherence tomography, especially in diagnoses that involve the brain, nerves, and other cells. Incorporating ultra-high-resolution entangled-photon-based diagnostic imaging technologies into brain–computer interfaces is expected to provide more precise and detailed data on brain function, thereby enhancing the overall effectiveness of these technologies.

9. Ethical Considerations

As the evolution of quantum-enhanced medical imaging gains speed, so does the importance of handling the ethical aspects of applying technologies that allow ultra-precise measurements on material systems. Patients' privacy and potential abuse therefore have to be addressed; discussed here are patient data protection, careful consideration of the ethical challenges around such sensitive information, and critical evaluation of current digital technologies.

Quantum imaging permits a correlation unlike any other. While quantum entanglement is a crucial resource in ultra-high-resolution diagnostic techniques, as demonstrated for the first time in radiology, it is equally beneficial for ensuring secure communication between scanners and data storage facilities. The high resolution itself opens new possibilities for the diagnosis and detection of countless diseases, ultimately leading to healthier patients and increased longevity. Balancing the technological benefits against potential privacy concerns is essential for the responsible advancement of quantum imaging in healthcare.

9.1. Patient Privacy and Data Security

Ensuring patient data remains confidential after image acquisition is critical, especially with public communication channels involved. The adoption of quantum imaging requires rigorous scrutiny of patient privacy and data security, including considerations about input data access. Secure storage and transmission of patient data must account for only authorized entities having access to protected health information stored in these images. Privacy regulations for remote medicine can vary and require appropriate attention depending on local laws [29]. Healthcare administrators and policymakers must address concerns around data disclosure and secondary usage of confidential information. Even if sensitive medical data is handled with optimal security and robustness, privacy regulations pertaining to disclosure of confidential expressions cannot be overlooked. Regions differ widely; psychiatrists may need extra precaution with identifying expressions of patients' facial features linked to histrionic disorders. Web-based applications and cloud computing are widely used for data across different jurisdictions. Protocols for sharing and analyzing images must consider heterogeneity of stored patient data to prevent misidentification and ensure secure compensation for costly cloud storage for collaboration among healthcare specialists. Efficient extraction of holistic patient metadata enables predictive approaches for disease identification from novel cloud-based substrates.

9.2. Regulatory Challenges

In the regime of quantum medical imaging, where entangled photon pairs illuminate the entire body, photon energy corresponds directly to tissue penetration capability, allowing control over imaging depth. This control is crucial for achieving ultra-high-resolution images of specific tissues. Entangled photons not only serve as illumination sources with unique transparency properties; they also enable differentiation between tissues in healthy or ill states [25]. By collecting light scattered by tissues, the characteristics of the scattered photons provide powerful discrimination tools, accounting for the diffuse nature of scattering occurring within the first microns in tissue. Consequently, quantum medical imaging devices play pivotal roles in public health, capable of detecting tumors, guiding surgery, and examining cardiovascular structures.

Despite these advantages, some forms of quantum medical imaging remain experimental. On the regulatory front, the FDA has advanced guidelines pertaining to clinical research in quantum technology; however, no comprehensive standards have been issued to regulate quantum technology-based medical devices systematically. Consequently, the 510(k) premarket notification process allows these devices to access the market via predicate rule, as regulatory interpretation of quantum techniques is still considered preliminary. Meanwhile, other jurisdictions, such as the European Union, Japan, and China, require conformity assessments before market access, reflecting regional differences in regulatory approaches to quantum-enhanced medical imaging.

10. Interdisciplinary Collaboration

As with the development of any technology that is not readily understood by everyone that benefits from its implementation, a clear, concise, and coherent effort must be taken to ensure that all parties are able to actively cooperate and understand the conception of the technology. Quantum imaging approaches require an understanding of the nature of reality and, in particular, quantum theory. In addition to a precise understanding of the pathways for implementing such systems, sources and sources of error in these complex modern machines need to be methodically analysed in an effort to maximise the quality of the image produced. Due to these intricate factors, it is crucial that physicists, who have devoted their careers to the understanding of the fundamental nature of reality, work closely with medical practitioners who know optimal practices in applying diagnoses.

The sophisticated nature of quantum imaging systems requires joint efforts from the deepest fundamental theoreticians to address and explain the underpinning concepts, leading experimental groups to demonstrate pivotal proofs-of-concept, and engineers to simplify and miniaturise. Involving the medical community on this journey is necessary to enable the technology to fully benefit mankind. Active collaboration between the physics, medical, and technology sectors will reduce confusion and misunderstanding whilst encouraging dialogue for the advancement of the technology. Quantum-enhanced medical imaging techniques will lead to faster medical decisions with higher confidence and precision, allowing the earlier identification of medical conditions associated with a better prognosis.

10.1. Role of Physicists and Clinicians

The clinical application of new methods and technologies demands significant effort not only from clinical professionals but also from experts in the relevant natural or technical sciences, such as physicists. Healthcare providers looking for novel techniques to improve diagnostic and therapeutic reliability heavily depend on collaboration with companies capable of producing technically reliable tools. Industrial partners often lack clinical experience, which can be acquired only through interdisciplinary cooperation.

Special emphasis must therefore be placed on providing support and establishing suitable conditions for collaborative projects involving clinicians, physicists, and companies. The implementation of quantum-enhanced medical imaging serves as a recent example of such interdisciplinary cooperation.

10.2. Partnerships with Technology Firms

Small and large technology companies are extensively collaborating with academic and industrial research centres to advance quantum technologies. These partnerships are recognised as a positive strategy for leveraging complementary expertise and fast-tracking the development of quantum-based products and solutions [25]. Major information technology firms are well positioned to bridge the gap from laboratory to market and to develop use cases in fields such as metrology, sensing or advanced imaging, and even quantum key distribution.

11. Conclusion

The exploration of quantum imaging with entangled photons demonstrates that even on a classical-physics level, the use of these quantum entities yields benefits for medical imaging. There is no astonishing violation of the diffraction limit or an unexpectedly good temporal resolution of examinations. The resolution advantage of quantum imaging, however, results from the complete representation and recognition of the complex spatial autocorrelation of entangled photons, which appear either at one inside or two distinct locations in the SPDC crystals employed as radiation source, depending on the method of image acquisition. Monitoring the full spatial autocorrelation of such different photon patterns offers the possibility of obtaining subsampling or step-scan in-plane, slice or volumetric images with higher resolution and thus

shorter acquisition time. Such higher-resolution images permit an earlier recognition of pathological changes in patients and more precise classification of cancerous tissue during operations. However, the clinical application of quantum-imaging methods still demands substantial progress in related technologies."

Ultimately, the full utilization of quantum optics in medical imaging is crucially dependent not only on ongoing research in quantum imaging, but also on innovations in ultra-bright, ultrastable quantum-light sources, ultra-sensitive detector arrays with low noise and ultra-fast postprocessing software, an area where the medical clinic and science community must join forces with the system-development industry.

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