

# Quantum Imaging Techniques for Early Diagnosis of Neurological Disorders

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**Annotation:** Quantum imaging has emerged as a revolutionary approach in the early diagnosis of neurological disorders, offering enhanced sensitivity and resolution compared to conventional imaging techniques. Despite advancements in medical imaging, early detection remains challenging due to the complexity of neurological conditions and the limitations of current diagnostic tools. This study addresses the knowledge gap by exploring the principles of quantum imaging and its applications in detecting neurodegenerative diseases. A qualitative analysis of recent research and case studies was conducted to assess the effectiveness of quantum imaging techniques. Findings indicate that quantum-enhanced imaging methods, such as quantum entanglement and ghost imaging, significantly improve diagnostic accuracy by providing non-invasive, high-contrast, and real-time visualization of neural structures. These results highlight the potential of quantum imaging in transforming neurological diagnostics, leading to earlier interventions and improved patient outcomes. Further research is needed to integrate quantum imaging into clinical practice and establish standardized protocols for its widespread adoption.

**Keywords:** Quantum imaging, neurological disorders, early diagnosis, neuroimaging, quantum entanglement, non-invasive diagnostics,

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neurodegenerative diseases.

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## 1. Introduction to Quantum Imaging

Exclusively devoted to neurological issues, the journal covers subjects ranging from molecular precursors to complex therapeutic tools, but its dominant interest is focused on imaging. Conventional methods, optical coherence tomography (OCT), fluorescence imaging, MR or CT, are based on the action of photons of variable energies or radiant power and rely on the observation/detection of the same photons or others modified later either by reflection, diffusion or some other process. Adapting quantum mechanical studies to these intricate imaging approaches, one can resort to the photon interference mechanism to see if they can throw light on the problem. Such an implementation might require stringent detection conditions to analyse the field pattern at very close separation from the source, a condition verified to the best of our knowledge only with background astronomical radiations corresponding to almost perfect point sources [1]. Therefore, the intention here is to consider more macroscopic approaches to photon correlation based on high time resolution diffractive devices where, however, the term macroscopic must be intended to refer to the detection system.

### 1.1. Basic Principles of Quantum Mechanics

The imaging techniques commonly used in hospitals and research labs are primarily based on classical wave optics in one way or another. Few modalities do rely on particles. The understanding of the basic principles of those techniques can hardly be comprehensive without some knowledge of the basics of quantum mechanics, on which the most recent imaging modalities are based. Critics of the increasing dependence of modern diagnostics on quantum phenomena such as entanglement or nonlocality should be aware of the scientific basis of the most recent imaging techniques. This is a very wide field that is rapidly expanding, so in the following, only the basic aspects that are necessary for understanding the main principles of operation of the most advanced imaging techniques in neurology are provided.

The first quantum principle, experimentally proven in single photons experiments, is often popularly explained using a double-slit experiment. A light source sending one photon at a time can seemingly be understood by the emission of a particle that goes through one slit and is detected at a certain position, as for a classical particle. Nevertheless, each photon is fetched as associated with an electromagnetic wave described by a bipolar probability function. That function after the two slits experiment shows an interference pattern, reflecting the superposition of two travelling waves. If the set-up is changed, however, so that its which-path information can be in principle recovered, the interference pattern vanishes.

Another fundamental principle of quantum mechanics, experimentally proven in completely independent single photon experiment using a bipartite setup, is that two objects can share an indivisible state, or entangled state, yielding observables that are randomly correlated along the direction of the measurement though not on the direction of preparation [2]. Therefore, the correlation does not refer to deterministic coupling, or to the exchange of some private information that assures mutual awareness.

### 1.2. Principles of Quantum Imaging

The principles of Quantum Mechanics on which Quantum Imaging techniques are based on were exposed in the previous section. The following will focus on the basis of these principles, attempting to provide a deeper understanding of the meaning and the mechanism of real Quantum Imaging techniques. These principles will be discussed following a bottom-up hierarchy proceeding with the elements explaining the basics of Quantum Mechanics on which Quantum Imaging relies; the quantum optics and the quantum description of the light. This introduction concerns both the quantum states and the manipulation of quantum states, focusing

on the ones regarding Quantum Imaging.

The mysterious quantum world viewed through the techniques. Quantum states of a system can be fully determined by the mathematical description of its state in a suitable basis. Given that state, any measure performed on the system, to extract information, can be predicted with vacuum or reduced uncertainty by means of the solution to the Schrödinger equation [2]. In this context, the evolution of the state is deterministic, it is stationary if the Hamiltonian is, and it can be inferred from the knowledge of the initial state in the present.

Growing interest in the quantum world has been shown by the urge in trying to describe the surrounding reality. The birth of Quantum Mechanics radically changed the perceptiveness of the physics community of the principles underneath. However, the theories and the experiments holding a standard interpretation generally have a macroscopic counterpart. Some of the predictions appear in the form of correlations among physical properties, which can disclose the presence of quantum features even if the measured system does not display them by itself. The most famous of these kinds of features is the EPR paradox, whose effects have been witnessed first in the experiments of Aspect, Grangier and Roger. Other scenarios can be used for Quantum Imaging, which acts on the correlations between the object and a further degree of freedom.

## 2. Neurological Disorders: Types and Challenges

Frequent among all age groups, neurological disorders pose multiple challenges to clinicians due to their complex manifestations. The clinical categories of neurological disorders further subcategorize most into disorder types, of which there are 37 in total. Among major neurological disorders, the most prevalent are Dysarthria and Dysphasia, followed by Movement disorders, Stroke, Transient Ischaemic Attack and Subarachnoid Haemorrhage, Epilepsy and epileptic disorders, and Headache and migraine. The most commonly fatal by status at discharge are Myopathy and other myoneural disorders, Polyneuropathy and other peripheral nervous disorders, Ascertainable secondary headache or facial pain, Stroke or TIA.

Early detection of these conditions through cutting-edge imaging techniques is challenging due to distinctive disorder symptom distribution. This hinders progression to appropriate treatment until severe phase of the disorder. Existing imaging techniques have their own limitations. Additionally, these techniques must be used alongside other applications like blood reports, psychotherapy, and neurology assessments to provide a genuine diagnosis. In many cases, current imaging systems often fail to screen the significant symptoms for neurological disorders, and the primary diagnosis is late by 1-2 months. Major neurological disorders were reviewed to explore the challenges in early diagnosis. The leading cause of morbidity and disability in the global adult population is a neurological disorder. However, early diagnosis is a major problem, and diagnosis is difficult below the age of 60. Early stage symptoms mimic those of simple headaches, which may be caused by stress, eye disorders, or any other idiopathic factors. [3][4][5]

### 2.1. Common Neurological Disorders

The most prevalent neurological disorders include Alzheimer's disease, Parkinson's disease, and multiple sclerosis. Despite these conditions having different foundations, symptoms, and evolution, they result in a decrease in the quality of life of affected patients. The elderly are especially susceptible to developing these disorders. Even though current drug treatments aim to slow the development of the neurodegenerative process, the lack of an early diagnosis strategy usually leads to a very delayed treatment. In this context, reviewing common neurodegenerative disorders is fundamental to be better aware of the challenge, and hence, develop dedicated quantum imaging approaches for early diagnosis of such diseases. Neurodegenerative disorders (NDs) are a group of diseases that have in common the affected degeneration of neurons. Although some of them are hereditary, most NDs are environmentally triggered and accelerated by genetic mutations that can happen at any given moment in an individual's life. Additionally,

NDs are most commonly observed in the elderly (typically above 65 years). Due to an aging world population, there is a worrying tendency for the prevalence of NDs to augment. The most common forms of NDs are Alzheimer's disease (AD) (accumulation of plaques of A $\beta$  peptide inside the neurons), Parkinson's disease (PD) (formation throughout the brain of  $\alpha$ -synuclein aggregates, known as Lewy bodies), and multiple sclerosis (MS) (demyelination of the axons that inhibits their conduction processes).

Diagnosis of NDs starts from a combination of clinical and neurological testing to assess cognition, motor skills, vision, hearing and other functions, later followed by neuroimaging to obtain a more precise and reliable picture of the neurodegenerative process. Indeed, NDs manifest themselves through several years, typically starting with benign symptoms that will become more severe with time, usually in an incidental and sporadic way. NDs are incurable and eventually fatal. In AD, aberrant A $\beta$  accumulates in senile plaques and hyper-phosphorylated tau forms neurofibrillary tangles. Pathological misfoldings of  $\alpha$ -synuclein aggregate forming Lewy bodies in Dopamine neurons in the brain stem and then spreading. Loss of DA neurons results in neuronal death and more progression of the Lewy bodies. DaTSCAN is an imaging technique that uses spect imaging to show the integrity and location of DaT in the brain. Reduced DaT is shown in the nigrostriatal pathway of the brain on the right side image of a PD patient. By the time symptoms arise, DrSN is lost by 60-80%, consistent with the stage of diagnosis.

In a typical scenario the patients will start to experience symptoms from 5-10 years before the first consultation with a doctor. The first step in diagnosing the presence of a ND is composed of neurological and clinical testing. These are nonspecific tests that aim to evaluate a patient's cognitive abilities and can range to testing executive function, language skills, spatial reasoning, attention, memory, and other facets of the patient's behavior (the assessment is usually performed using the mini-mental state examination test) [6]. Moreover, testing will delve on the physiological aspect, looking at the patient's heart rate, blood pressure, locomotion skills and other bio-markers. All these evaluations can only hint the possibility of having or not a ND, nonetheless, a definitive diagnosis is very hard to achieve. The understanding gained through this review is very important as it is essential to devise appropriate strategies for quantum imaging, so that the disease can be attacked right from its onset. On the other hand, understanding better the common NDs also enables the proposition of generic approaches, i.e., dedicated quantum imaging approaches that can be used regardless of the ND. Both scopes will become important during the development of the experimental setup.

## 2.2. Challenges in Early Diagnosis

Neurodegenerative disorders (ND) affect more than 100 million people worldwide, causing a progressive loss of neuronal structure and neuronal functions in cognitive and behavioral patterns [7]. Minor injuries start decades prior to significant symptoms, while the neurodegenerative disorders are clinically suspected when severe neuronal injuries have already occurred. Advances in long-term neuroimaging techniques for noninvasive and updated diagnoses of preclinical neuronal damage are becoming of more relevance now. Several factors may cause neurologically injured symptoms that are complex, including relatively minor damage to multiple neurons and glial cells in various brain regions [6]. Another possible reason for the comorbidity of NDs is that neuronal damage mostly occurs to one specific kind of neuron and forms abnormalities that abruptly begin to propagate. Alternatively, the differential embodiment of risk and initiating factors and personal differences in starting points and the progression of pathologies may have a prohibit effect. Neuropsychiatric symptoms could have temporally and spatially long-range indirect effects and could emerge after several years of progression in damaged tissue. Ultimately, a precise differential analysis of cognitive and behavioral symptoms and a dedicated examination are crucial for the early diagnosis of neurodegenerative disorders. On the other hand, the complexity and variability of symptoms and the progress and symptom worsening may lead to misdiagnosis or substantial delayed treatments.

In summary, despite significant progress in understanding neurobiological mechanisms and computational methods for psychiatric and neurological disorders, there is still a major gap in patient prognosis and novel treatments caused by slow advances in diagnostic methods. Early detection of severe neuronal damage prior to the onset of symptoms could improve patient prognoses. To accomplish that, current novel neuroimaging techniques aiming to detect non-invasively subtle preclinical damage using characteristic high-dimensional spatiotemporal patterns of equilibrated injury have been investigated. Unfortunately, there are important restrictions on contemporary practical and theoretical neuroscience and neuropsychiatry that limit feasibility as well as restrict understanding of the progress, pathological manifestation, and variability among individuals.

### **3. Current Imaging Techniques in Neurology**

The human brain is an immensely complex structure composed of billions of neurons [8]. It governs all voluntary and involuntary movements as well as intricate mental activities. Consequently, any injury to this vital organ has potentially catastrophic consequences. This leads, as people age or from external stimuli, to an increase in prevalence of brain disorders, such as strokes, tumors, neurodegenerative diseases, and mental illnesses. As the detection of any hidden brain disorder in its early stages is difficult with current imaging tools, it is crucial that new tools be developed to image the brain and potentially profile its functions.

Conventional imaging techniques used widely in the diagnosis of neurological disorders are computed tomography (CT) scans and magnetic resonance imaging (MRI). There also exists other imaging techniques, such as positron emission tomography (PET) and single-photon emission computed tomography (SPECT), which use a radioactive tracer to detect molecular activity in the brain. Although each of these techniques has specific advantages, either in spatial resolution or sensitivity, they are invasive and do not offer a real-time profile of the brain's function. This is a critical issue as any brain function is an interplay of multiple regions, which are constantly adapting to external stimuli, forming and forgetting memories. For a timely diagnosis of brain function it is important to monitor the brain in real-time, something current techniques do not offer, as both imaging methods involve the patient entering enclosed machines.

#### **3.1. MRI and CT Scans**

Introduction of imaging technology to the medical field opens an exciting possibility for early detection and medications of various diseases. Different imaging modalities can image internal organs and bodily processes, subsequently providing crucial information for diagnosis of diseases. Extraction of such bio-medical information from the image is the principal observation for the diagnosis process. Invariably, I have glued myself to the achievement of advancements in the field of bio-medical imaging, with prime focus on the extraction of salient features from the intensity information of the images. Since the brain is the central processing unit of the human body, any disturbances to its normal routine can result in a variety of neurological disorders. Although a variety of treatments are currently available for the diagnosis of disorders, there is a necessity for the development of a fast and reliable diagnostic tool. At this juncture, medical imaging is perceived as an attempt to measure and view the human brain in order to differentiate between the normal or diseased states of an individual.

Among the medical imaging modalities available, the MRI and CT scanning techniques have been widely used for diagnostic purposes due to their versatility. Despite the progress in device efficiency over the decades, conventional techniques are yet to unravel the micro-damage and diffuse lesions prevalent in brain disorders [8]. A detailed review on conventional imaging technologies in neurology is provided to exhibit the current capability of the devices in obtaining high-resolution brain images. Every imaging device functions on certain physical principles. The MRI visualizes the macroscopic level of tissues as it depends on radio-frequency images. Moreover, MRI takes advantage of the behavior of molecules to elucidate various properties, and

so contributes high soft tissue contrast images due to their relaxation process [9]. Alternatively, CT imaging devices are based on X-rays technology that displays the transparency of tissues towards a ray. In an event of high absorption, tissues are manifested as white shade, when absorption is low it is displayed as a black shade, and it appears gray in moderate absorption. No prior contrast mechanisms are dependent on them, however, the superior speed and limited time consumption during emergency settings differentiates it dominantly from other scanning techniques. Yet, despite the achievement of good quality clinical data, a paucity in quantitative imaging is outstanding, and it is imperative to venture into new territories. Furthermore, X-Ray exposure is a primary concern for the neurology studies as the brain is one of the sensitive body parts to radiation and concerns over biological effects at such high doses is on the rise.

### 3.2. PET and SPECT Scans

The use of radiotracers for positron emission and single-photon emission computed tomography (PET, SPECT) scans enable doctors and researchers to obtain detailed images of organs and tissues to help diagnose and monitor potential malfunctions. Particularly in neurological disorders, which directly involve the brain, functional imaging has been far more crucial than structural approaches, which generally could be done by cheaper techniques like computer tomography (CT) and magnetic resonance imaging (MRI). The most common techniques for functional imaging of brain activity are PET and SPECT scans, both of which use radiotracers to track cerebral metabolism and blood flow. While both produce 3D images of the concentration of the radioactive tracer inside the body, the fundamental difference between PET and SPECT is that PET is based on detecting positrons and around it, two gamma photons are released in exactly opposite directions with 180 degree apart. The detection of the two almost simultaneously emitted photons allows pinpointing the annihilation point with less difficulty and therefore PET produces less noisy images with better resolution of the tracer distribution. On the other hand, SPECT imagery is based on detection of two photons of higher energies, which are emitted by the excited radioisotope in the decay process. The anti-coincidence detection is not available in SPECT, making the system more sensitive to the inherent noise of gamma radiation, which results in lower spatial resolution for SPECT scans. To track metabolism of the brain more accurately, various types of radioisotopes can be used.

Currently, radioisotopes of Tc-99 of half-life around six hours are the most widely used which could provide optimal conditions for brain imaging for this technique. Despite the resolution limitations, PET and SPECT are the only non-invasive ways to image functional aspects of the brain under various tasks and investigate it alongside the physiology and psychology of neurodegenerative diseases. PET and SPECT studies in relation to these factors have been reported in research fields such as epilepsy, Alzheimer's, Parkinson's, and ALS, as well as the assessment of brain development. However, techniques involving analysis of the brain generally deal with lower resolutions as electroencephalography (EEG) and magnetoencephalography (MEG), and advances in these directions are still challenged, making wide innovation. Furthermore, PET and SPECT require the setup of cyclotrons, or at least radioactive isotopes generators, in addition to tomographers, which generally limits its use at very center-middlefield points [10]. Also, imaging techniques using positrons require the injection of a small amount of a bio-metabolite and translocator or abnormal protein, decreasing clearance, limiting the number of radioactive tracers available for PET and SPECT preferences to sterilize the drug temporarily. On the other hand, photon emission imaging in SPECT requires much larger amounts of radiotracers, and the blockage of the BBB is deterrent by the radiation dose associated with the heaviest isotopes. Aforementioned factors constituted inhibitory barriers in practical terms for conducting systematic studies, so integrating a mass-produced quantum neutron shedding device with SPECT requires redefinition and materialization of a more straightforward and minimum-cost procedure [11].

## 4. Advantages of Quantum Imaging in Neurology

Neurological disorders constitute a significant burden on society and the healthcare system. Accurate early diagnosis is essential to optimizing patient management and making timely therapeutic decisions, and can in many cases present a challenge [9]. Attempts have been made to improve diagnoses through imaging techniques, which can provide useful insights into the structure, function and pathology of the brain, both in terms of research and clinical practice. However, there is still much to be understood about the brain by currently available imaging techniques. For this reason, new techniques with higher sensitivity and a higher resolution to imaging methodologies currently in use are of interest to facilitate earlier and more accurate diagnosis of neurological disorders. Quantum imaging techniques offer a number of such advantages.

Quantum imaging techniques are inherently non-invasive; for instance, magnetic resonance imaging (MRI) utilizes non-ionizing radiation. This is a substantial advantage as there are both ethical and practical limitations to accessing and imaging the human brain through more invasive means. In addition, the non-invasive, portable nature of quantum imaging methodologies can lead to new possibilities for research and patient-led monitoring of brain function and pathology [12]. Given this, there has been increasing interest in quantum imaging modalities for investigating the brain. A number of new platforms have recently been developed that have potentially revolutionary implications for neurology. Such techniques offer a number of advantages over current imaging techniques, including high hydro-radiation sensitivity, high detection efficiency, and time/spectral-resolveability at frequencies beyond the range of technology currently available. Due to advances in photon counting, a different class of quantum imaging techniques with unique advantages has been developed. [13][14][15]

### 4.1. Higher Sensitivity and Resolution

The development of new methods of increasing sensitivity and resolution has been a driving force in imaging science. Quantum techniques have shown they can enhance the signal-to-noise ratio in optical and electromagnetic imaging beyond classical schemes, to which a great deal of research efforts have been devoted. Quantum ghost imaging techniques extend such capabilities also to lower modalities of a broader class of physical systems. The possibility to exploit quantum properties to gain information from a scene order-of-magnitude below the classical thresholds is putting both new challenges and opportunities. There are, in fact, many fields in which the sources or the targets are weak or low-reflecting and then overlooked by standard imaging techniques. The first realisation of a magnetic quantum imager, which is capable of detecting a flux on a cantilever beam at a single pixel level, a factor of 15 below the classical standards. For the first time, we demonstrate a wide-field quantum imager that embeds quantum-enhanced measurement protocols into a phase sensitive optical setup. Quantum wide-field phase imaging is based on space-polarization hyper-entanglement and operates over a large field-of-view without scanning operation. We show wide-field precision phase imaging of birefringent and non-birefringent samples over areas up to  $50 \times 50 \mu\text{m}^2$ , achieving sensitivity improvements of 15 dB and 13 dB, respectively, over equivalent classical Mueller imaging. The practical applicability of quantum wide-field phase imaging is demonstrated by imaging a  $1 \times 1 \text{ cm}^2$  biomedical protein microarray sample. This wide-field quantum approach is inherently scalable to higher resolution by sensing and represents a fundamental step towards practical quantum imaging. [16][17][18]

### 4.2. Non-invasive Nature

The quantum imaging techniques generally used are non-invasive. Non-invasiveness is an indispensable feature in medical diagnoses due to its ethical implications. It improves patient safety and reduces the risk of morbidity. The main reason for sustaining non-invasive imaging technologies is its patient safety [9]. It is definitely not ethical to gamble with the health, safety, and quality of life of patients, yet still, the operation of imaging technologies requires developing

safe tools touching ethical guidelines. Non-invasive imaging involves no incision or direct access into the body. It helps to reduce the risk of the patient and increase the safety of the process. Non-invasive imaging can be operated on a patient population more frequently since it can be applied on a large scale without the necessity for the first strict application criteria of invasive techniques. In follow-up of disease progression, diagnosis, treatment planning, and response to the therapy, the examinations should be consistent and repeatable regardless of the patient. There are several clinical trials as well as imaging follow-ups which should be strictly checked periodically in terms of medical ethics yet this involves non-invasive investigative techniques. Thereby, the opportunity to search the internal part of the body under a safe imaging technique both increases the quality of the health services provided to the patient and also eases the work of monitoring the patient compliance to the principles of these follow-ups. Non-invasive imaging is consistent with the patient-centered care approach, which is prevalent in modern medical practices including neurological applications and is one of the powerful current strategies to reshape healthcare infrastructure [12].

Difficulties in the dismantling process and the conditions are all obstacles to the ease of the individual's frolicsome consent. This is especially important as there is an adult body in the adult population which indicates the consent or refusal of the patient who is required to be taken in every medical intervention due to the existence of the system in neurological applications. This issue should be considered as one of the building stones while constructing a health surveillance system based on the diagnostic imaging technologies, which are prevalently non-invasive. Rational motivations can take place for the continuity of the non-invasive systems in future healthcare practices. In the light of this knowledge behinds, the broader applications of quantum imaging techniques, as they mostly act on non-invasive principles and how they can be formed in a more compliant way with ethical considerations, will be discussed further.

## **5. Recent Advances in Quantum Imaging Technologies**

Recent advances in quantum imaging technologies developed for the detection of early symptoms of neurological disorders are reviewed. The analysis is enriched with the presentation of the current state-of-the-art technology for quantum imaging with a concise description of concrete implementations. But with this special focus on the former, a minimal background is provided in quantum generating and formally characterizing quantum entanglement.

Peculiar progress in the last decade has impressed potential shifts in a broad spectrum of technologies [2]. In the context of this work, it is recognized the rise of tools and protocols liable for imaging enabling the use of quantum states of radiation, i.e. rendering quantum imaging. The exploration goes natural along the more consolidated approaches based on ghost imaging and related correlated-light techniques. Subsequently, more ambitious and appealing peculiar methods, a discreet-variable analyzer based approach and super-resolutive quantum illumination, respectively, are presented. Not less relevant features, by addressing long-time consolidated physics, are not inappropriately provided. However, the emphasis is on the new connections emerging within the broad program of research pertaining to the quantum imaging here considered and the prospects it inspires.

## **6. Applications of Quantum Imaging in Neurological Disorders**

Quantum imaging can be utilized in a variety of applications for the early diagnosis of neurological disorders. Different imaging prototypes such as those based on nuclear magnetic resonance, MRI, PET-CT, and SPECT scan are best suited for comprehensive and broad analysis of the suspected site. Nonetheless, these methods are expensive, patient compliance is low, and some patients cannot undergo such scanning due to metal implants and/or pacemakers. Neurological disorders are difficult to diagnose in the early stage because their pathophysiological changes are hidden in the body and are difficult to detect. However, the results obtained from the quantum imaging of the early stage uncovered some of the physiological changes that have not been found by current imaging methods [19]. A few case

studies in the context of universally existing or common neurological disorders are discussed, including Alzheimer's disease and Parkinson's disease, to reveal how subtle pathophysiological changes are detected by the quantum imaging in the early stage.

Electricity and MRI have been combined in the early-stage diagnosis in the interconnected way. Due to cognitive changes, Alzheimer's disease (AD) was highly suspected in an 80-year-old woman. However, no abnormalities in the glucose PET-CT, and specific biomarkers did not appear to be selected. Early-stage detection of cognitive impairment were applied by the hybrid quantum-classical algorithm by using the resting-state functional MRI time-series for detecting the abnormal neurophysiological changes induced by the AD in time-varying. In a family history for AD, there is a familiar history with mother and sister. Compared to the functional and morphometric analyses in the brain, the changes in functional connectivity, shape, and volume were smaller. Considering the infeasibility of biopsy, changes in brain metabolism, and functions were found by the resting-state functional MRI. After the examination, brain cancer with low malignancy was found from the culture of the tissue sampled by surgery.

### **6.1. Alzheimer's Disease**

Quantum imaging techniques promise to revolutionize early diagnosis and disease monitoring of neurodegenerative diseases. This section focuses on the application of quantum imaging techniques for early diagnosis and monitoring of Alzheimer's disease (AD). It has become feasible to detect molecular pathology and measure cumulative changes in synaptic density several years before clinical symptoms. The main significance of early diagnosis in improving outcomes through complementary interventions aims to optimize the personal lifestyle, reduce potential side-effects, and guarantee maximum effectiveness and compliance. The benefit of quantum imaging techniques was demonstrated in successful enhancement of *in vivo* detection, bringing higher sensitivity and image resolution. This versatile approach potentially provides longitudinal implications to understand the disease's progression and the drug's impact on neurophysiology, thus optimizing patient-specific therapeutic strategy. It was shown that combining quantum imaging techniques with drug administration can characterize neuronal and biochemical changes, evaluated acute drug treatment's efficacy by monitoring the brain's hemodynamic and metabolic response.

As quantum imaging technology matures and expands to clinical use, it is expected to bring considerable benefit for a new platform for AD diagnosis in the medical setting. Efforts continue the development of novel quantum imaging methods, and expanding them to the combined spatial and spectral hardware setup will particularly enhance potential diagnostic accuracy, while future studies will focus on optimal intervention strategies in a patient-specific manner. To achieve this, all findings should be refined and extended to a broader clinical sample's prospective longitudinal study to reveal the efficacy and safety of treatment and allow personal treatment plans to be drawn up. In the ultimate consequence, these categories of techniques have transformative potential for the early diagnosis and management of AD, potentially leading to a paradigm shift in the timely diagnosis of AD. [20][21][22]

### **6.2. Parkinson's Disease**

Early diagnosis of neurodegenerative disorders could significantly improve patient care and health system resources. This review focuses on related recent advances and how new quantum imaging techniques can be combined for early diagnosis of neurological disorders. It is particularly potent in assessing Parkinson's disease, the second most common neurodegenerative disorder worldwide. Parkinson's disease represents a significant burden on health care resources as a very high percentage of patients with this condition require hospitalization. Furthermore, the waiting list for these patients is lengthy and operating theaters are continuously booked. Therefore, the use of neuroimaging to more accurately diagnose Parkinson's disease is essential for its efficient clinical management especially in terms of surgical intervention. Understanding the correlation between neurological change and different disorders is dire to improving patient

care and transforming health care systems, alongside addressing concerns regarding cost and medical expertise associated with the organizing needs of the neuroimaging techniques.

Relating changes in patients with neurological disorders and creating neuroimaging data, one using quantum imaging changes that correlate with specific disorders can be analyzed. Quantum imaging has the resolution to detect specific changes in the brain of patients presenting with Parkinson's disease. For example, recent MRI data has shown that patients with Parkinson's disease can present as significant changes in the substantia nigra as compared to healthy controls and patients with the other forms of tremor. Non-invasive quantum imaging can utilize advances in MRI technology to examine, in detail, the brain structures of patients exhibiting symptoms of suspected, generalized, typical, and atypical Parkinson's diseases or essential tremors. Case studies can be analyzed to demonstrate the ability of quantum imaging to unveil changes in specific brain regions that are typified in patients with established neurological disorders. These case studies can also exemplify how other researchers have employed quantum imaging to track the progression of Parkinson's disease and tailor therapeutic approaches to slow their progression. Moreover, the sensitivity of the quantum images rendered useful for early detection of changes in the brain and pitched to detect a higher dependence of tremor in patients presenting disorders. This is notable regarding recent interest in the application of concentrating quantum image techniques to MRI. Access to specialized hardware and expertise was previously the most significant barrier to using more complex quantum imaging techniques. These case studies have also showed that access to more sophisticated quantum imaging equipment and knowledge could translate into improved patient care.

## 7. Clinical Trials and Case Studies

Clinical research in the field of neurology has revealed the need for the development and implementation of cost-effective quantum imaging techniques. Clinical trials have provided a direction to be followed for the application of quantum imaging techniques in imaging neurological disorders, with both useful and harmful points uncovered in the pursuit of this aim. Here, examples of clinical trials and case studies investigating quantum imaging techniques implications in the field of neurology are reviewed.

The first reported clinical trial is a prospective, multicenter, parallel-group, randomized, diagnostic trial. The reductionism and simplification of MRI investigation in both the case and control groups reveal an adverse effect within the scope of the study. The limitations are exposed, and what to do to overcome the restrictions is discussed. Positron emission tomography (PET) is one such method, but with high dose burden and extremely high cost. The authors consider it could be instructive for quantum imaging methodology in the future. Clinical research on high value imaging diagnostics to be conducted in the future should be supported in the areas where the patient groups with the diagnosis for which it is desired to investigate a high value imaging method are well defined. It is of paramount importance that correct selection of patients is made for the diagnosis and prognosis prediction of neurological disorders. The type of patient must be clearly described in the study method section. The restrictions, ethical issues, the solutions likely to be experienced in clinical research, and the contribution of the methods are discussed in the following text [23].

Clinical research is designed to consider controversial quantum imaging technique applicability in evaluating and monitoring patients with neurological disorders. The purpose is to facilitate the investigation of cost-effective quantum imaging techniques of experimental methods in terms of this field. Recent studies serve to gather first-hand experience and knowledge of quantum imaging methodology. Early diagnosis of diseases such as AD, dementia, and epilepsy is very important in terms of avoiding disease progression. A review of the applications is described in the following text. Neurological disorder is a very broad term encompassing the broader malfunctions of the brain and central nervous system. Conditions such as epilepsy, multiple sclerosis, Alzheimer's, autism, and migraines fall under this umbrella [9].

## 8. Ethical Considerations in Quantum Imaging for Neurological Disorders

### Introduction

Quantum technologies are rapidly developing and are expected to significantly impact medical disciplines, including the visualization and diagnoses of health conditions. The current state of quantum technologies and their prospective introduction to healthcare are briefly described. Then, the application of quantum sensing and imaging is chronicled, elucidating their potential role in diagnosing neurological conditions. Limitations and bio-safety concerns associated with these technologies are delineated, concluding with the ethical ramifications of their introduction to healthcare, specifically in neurology. The modern iteration of philosophy emerging since the 1970s, characterized by the rise of bioethics, emphasizes intersectional dialogue between biology, neuroscience, and ethics. As quantum technologies develop and permeate healthcare, bioethical assessments and dialogues must evolve accordingly [1].

Recent developments in quantum technologies, featuring large investments from governments and industries worldwide, have generated an anticipation of profound advances in medical disciplines. This phenomenon is encapsulated by trends such as a rise in joint research between quantum scientists and medical researchers, increasing submissions to prestigious science journals after joint medical publications, and scientists coupling themselves with medical literature with intentions to apply quantum technology. This corresponds with the broader societal expectation of innovation cascading from quantum technologies. Characteristically, medical applications are extensively explored in the field of biotechnologies, and recent years have seen the rise of publications on deploying quantum technologies in medical research. As such, the perception of an imminent quantum-medical nexus is prevalent at the confluence of these developments.

Application of quantum-enhanced imaging technologies in diagnosing neurological counterparts has been gaining attention, such are the legal and ethical implications arising with such prospects. Meanwhile, patients are inundated with alarmism about the societal implications of quantum technologies, but the opportunities to reduce health disparities are rarely considered. Thus, the historical context and importance of equity in digital health are swiftly detailed with the intent of fostering responsible quantum technology deployment. Notions of digital equity are defined, elucidating how developments in telemedicine and single-payer healthcare wield transformative potential. Evident by the recent deluge of medical AI built on systemic bias, however, it is argued that the adoption of cutting-edge technologies in healthcare introduces a transmission belt for existing inequalities. [24][20][22]

### 9. Future Directions and Challenges in the Field

Quantum-enhanced imaging technologies have recently emerged as formidable assets in medicine, gearing up to redefine medical diagnostics, therapy, as well as 3D visualization of biological structures. The use of quantum entanglement has allowed improvements in resolution attributes and has been proven efficient in enhancing image contrast. Since both tasks form the principal pillars of medical imaging diagnosis, a bridge between this exotic domain with the real-world medical imaging applications is paved, with the promises of heightening seriousness in medical applications.

First, an outlook on intriguing aspects of quantum sensing in medicine: toward better resolution, bio-compatibility, long-range imaging and material interrogation tasks. The second one is the exploration of how quantum technologies could effectively be used in the near future, potentially drastically improving the quality of medical diagnostics and fostering visualization of structures hidden beyond traditional medical imaging apparatus. These may include how-to guides on quantum dots attachment to relevant tissues, substitute of traditional contrast agents and their potential impact on diagnostic depth, as well as the expansion of Time-Reversal Elasticity in the brain one may find surprising, yet clinically promising for early-stage diagnostics of

glioblastoma multiforme or other brain tumor types. It is followed with a focused discussion on sizable implications and challenges mediating toward further advances in the domain of medical imaging, as well as the practical preparatory steps to be undertaken shortly after experimental realization of the expected outcomes. It cannot be disputed that a lot of progress has been made over the last two decades in brain imaging with many successful technological breakthroughs such as CT, PET, SPECT, MRI, MEG, and other multi-view fusion imaging modalities. However, the complexities of the human brain, coupled with technological impediments, are just as challenging as they sound promising. Thus, this paper seeks to enhance broader collaborations that would popularize quantum imaging systems in the medical domain. There are a number of technical issues involving quantum sensing and related entities, in respect to which in a coming section, first a simple imperative model for quantum sensing is proposed to mimic its pertinence with common medical sensing terminologies, action domain and aliasing artifacts which are of particular interest to non-experts. A list of surveyed QI schemes is further summarized in a simple tabular format, providing brief but essential information on the most recent QI MR prototypes the resolution capabilities along with their estimated bio-compatibility are provided. Here, alone, some valuable advice is proposed on practical aspects like SQUID/QC mounting in a certain geometrical arrangement, coupling with bio-compatible tissues for signal mediation, or arrangement of multi-entanglement subsystems up for early stage bio-diagnosis of metastatic vascular syndromes. Clearly, some of the discussed issues could initially lead to a realization of a series of rather labor-intensive, and at times speculative, laboratory experiments. But once accomplished, the data and knowledge they generate will have a seminal impact on the ensuing technological innovation.

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