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Review | Derleme

POTENTIAL USE OF QUANTUM IMAGING AND ARTIFICIAL INTELLIGENCE TECHNOLOGIES IN NEUROSURGERY

NÖROŞİRÜRJİDE KUANTUM GÖRÜNTÜLEME VE YAPAY ZEKÂ TEKNOLOJİLERİNİN POTANSİYEL KULLANIMI

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ABSTRACT

This study examines the current status and potential future areas of use of artificial intelligence and quantum technologies in neurosurgery within a conceptual framework. Artificial intelligence is widely used, especially in the analysis of imaging data, surgical planning and intraoperative decision support systems, and is rapidly being integrated into clinical practices. Quantum imaging technologies, on the other hand, attract attention with their capacity to provide higher resolution and lower radiation dose, but are currently limited to experimental and pilot studies.

The study reveals that artificial intelligence and quantum technologies have complementary properties in neurosurgery; it shows that hybrid approaches such as quantum artificial intelligence can increase clinical success by increasing accuracy, speed and predictive capacity in diagnosis and treatment processes. In addition, it is emphasized that elements such as ethical responsibilities, user education and interdisciplinary collaboration are of critical importance in the clinical integration of these technologies. As a result, artificial intelligence and quantum technologies are seen as important tools that will shape the future surgical practices in neurosurgery.

Keywords: Neurosurgery, artificial intelligence, quantum imaging.

ÖZ

Bu çalışma, nöroşirürjide yapay zekâ ve kuantum teknolojilerinin mevcut durumunu ve gelecekteki potansiyel kullanım alanlarını kavramsal bir çerçevede incelemektedir. Yapay zekâ, özellikle görüntüleme verilerinin analizinde, cerrahi planlama ve intraoperatif karar destek sistemlerinde yaygın olarak kullanılmakta ve klinik uygulamalara hızla entegre olmaktadır. Kuantum görüntüleme teknolojileri ise, daha yüksek çözünürlük ve daha düşük radyasyon dozu sağlama kapasitesiyle dikkat çekmekle birlikte, henüz deneysel ve pilot düzeyde çalışmalarla sınırlandırılmıştır.

Çalışma, yapay zekâ ve kuantum teknolojilerinin nöroşirürjide birbirini tamamlayıcı özelliklere sahip olduğunu ortaya koymakta; kuantum yapay zekâ gibi hibrit yaklaşımların, tanı ve tedavi süreçlerinde doğruluk, hız ve öngörü kapasitesini artırarak klinik başarıyı yükseltebileceğini göstermektedir. Ayrıca, bu teknolojilerin klinik entegrasyonunda etik sorumluluklar, kullanıcı eğitimi ve disiplinler arası iş birliği gibi unsurların kritik önemde olduğu vurgulanmaktadır. Sonuç olarak, yapay zekâ ve kuantum teknolojileri nöroşirürjide geleceğin cerrahi uygulamalarını şekillendirecek önemli araçlar olarak görülmektedir.

Anahtar Kelimeler: Nörosirürji, yapay zekâ, kuantum görüntüleme.

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Introduction

Neurosurgery is a medical specialty involving complex surgical interventions targeting the central nervous system, characterized by high risk and requiring precision. One of the most critical determinants of surgical success is the quality of imaging before and during the procedure. Conventional imaging techniques, such as magnetic resonance imaging (MRI), computed tomography (CT), and positron emission tomography (PET), have long been widely used in neurosurgery; however, limitations in resolution and temporal accuracy in these systems have increased the need for more advanced technologies.[1]

In response to this need, quantum imaging techniques, which have emerged in recent years, hold revolutionary potential in neurosurgery. Based on principles such as quantum entanglement, squeezing, and superposition, these techniques utilize photons to provide higher contrast and resolution, while also enabling more accurate and lower-dose imaging of biological tissues.[2] Especially when dealing with complex structures like neural tissue, the impact of quantum imaging systems on early diagnosis and surgical precision is expected to become clearer in the near future.[3]

Moreover, the increasing role of artificial intelligence (AI) systems alongside quantum technologies in neurosurgery is noteworthy. Deep learning and machine learning algorithms enhance clinical decision support systems in areas such as tumor segmentation, aneurysm detection, and surgical risk assessment, thereby reducing error rates.[4,5] The combination of quantum computing and AI has led to the emergence of a new discipline called "quantum artificial intelligence" (Quantum AI), which provides a theoretical framework that may enable faster, more accurate, and more predictable interventions in neurosurgical procedures.[6]

This study aims to systematically review the current literature on the potential applications of quantum imaging techniques and artificial intelligence in the field of neurosurgery. Within this context, both the fundamental principles of technological advancements and their clinical applicability will be discussed. Furthermore, innovative approaches that may arise from the integration of these two fields in the future will be highlighted.

The Transformation of Imaging Technologies in Neurosurgery

Neurosurgery is a specialized field encompassing high-risk surgical interventions performed on the central nervous system, one of the most complex and delicate structures of the human body. In procedures involving the brain, spinal cord, and peripheral nervous system, imaging technologies undoubtedly constitute a fundamental determinant of surgical success. High-resolution, low-risk, and reliable visualization methods are required at every stage—from diagnosis to treatment, from surgical planning to intraoperative guidance.[7] In line with this need, the primary imaging techniques traditionally employed in neurosurgical applications have been computed tomography (CT), magnetic resonance imaging (MRI), and positron emission tomography (PET). These methods have long served as essential tools for surgeons in evaluating anatomical structures and guiding operations.[8]

However, conventional imaging systems may prove insufficient, particularly for detailed analysis and three-dimensional modeling of highly complex neural network structures. While methods such as MRI offer advantages in soft tissue resolution, they are limited by spatial resolution, imaging time, susceptibility to motion artifacts, and contrast accuracy.[9] Techniques like PET and CT, on the other hand, carry disadvantages such as ionizing radiation exposure and low tissue contrast. These fundamental limitations increase the risk of errors in surgical planning and intraoperative decision-making and complicate early-stage diagnosis of neurological diseases.[10, 11]

Increasing technological demands in neurosurgical practice have revealed the need for systems capable of real-time, low-dose, non-invasive imaging of biological tissues at micrometer resolution. At this point, innovative approaches that go beyond conventional methods are expected not only to improve imaging quality but also to be integrable into surgery, supported by analytical and predictive systems.

In this context, the transformation of imaging systems encompasses not only a hardware-based evolution but also the integration of imaging data with digital processing and decision support mechanisms. In particular, the development of artificial intelligence (AI) and quantum-based imaging systems stand out as two primary drivers of this transformation.[12] Deep learning algorithms increase clinical value in image data analysis, tumor segmentation, anatomical structure classification, and surgical targeting, while quantum imaging systems promise higher resolution and accuracy through next-generation photonic technologies that operate beyond classical physical principles.[2, 5]

Overall, the transformation of imaging technologies in neurosurgery holds the potential not only for improved visualization but also for creating a more holistic surgical ecosystem. This transformation aims to integrate next-generation systems that complement rather than replace conventional technologies, offering significant gains in accuracy, speed, and patient safety in neurosurgical practice.[4]

Fundamental Principles and Clinical Potential of Quantum Imaging Systems

Quantum imaging is a next-generation technology that transcends classical physical principles by utilizing the quantum properties of photons. This approach, based particularly on quantum mechanical phenomena such as entanglement, squeezing, and superposition, enables imaging of biological tissues with higher resolution and lower energy exposure.[2] While conventional imaging systems must balance image quality with radiation dose, quantum imaging enhances contrast without disrupting this balance and simultaneously reduces the risk of biological damage.[13] One of the most common applications in quantum imaging involves the use of correlated photon pairs obtained through quantum entanglement. In this method, changes experienced by one photon as it passes through biological tissue are measured via its entangled partner, allowing for less invasive and more sensitive imaging.[14] Consequently, high-resolution images can be obtained even at low light levels, offering significant advantages in complex and light-sensitive areas such as neural tissues.

When considered specifically in the context of neurosurgery, the potential of quantum imaging technologies is particularly striking. Quantum imaging surpasses the resolution limits of conventional methods by providing a new paradigm for structural and functional mapping of brain tissue, tracking signal transmission pathways between neurons, and identifying microvascular structures.[3] Especially in real-time intraoperative applications, these systems could provide surgeons with greater control and precision, playing a critical role in delineating cancerous tissue margins or detecting delicate structures such as aneurysms.15 Although the use of quantum technologies in biomedicine is still at an early stage, research in this area has accelerated. Initiatives such as the European Union's Quantum Flagship and US-based quantum bioimaging programs are accelerating the integration of these technologies into healthcare applications. Moreover, quantum sensors enable the detection of electromagnetic fields at the nanosecond scale, allowing for more detailed modeling of brain activity.[16]

Despite these advances, the clinical integration of quantum imaging systems still involves various technical and logistical challenges. The sensitivity of quantum hardware, costs, and the requirement to operate under specific conditions pose barriers to the routine use of these systems in hospital environments. Nevertheless, despite these challenges, quantum imaging holds transformative potential for diagnostic and therapeutic approaches in neurosurgery and many other fields of biomedicine.[17]

The Role of Artificial Intelligence Applications in Neurosurgery

Artificial intelligence (AI) has recently become a major driver of transformation in medicine and health sciences, becoming an integral part of decision support processes, particularly in specialties requiring high precision. In fields such as neurosurgery, which demand microscopic-level detail, the algorithmic analysis capacity offered by AI technologies enhances diagnostic accuracy, optimizes surgical planning, and minimizes human errors.[18] Deep learning, machine learning, and image processing techniques are actively used in numerous areas ranging from image analysis and anatomical segmentation to risk classification and prognosis prediction.

AI algorithms contribute significantly to the analysis of neuroimaging data, especially magnetic resonance imaging (MRI) and computed tomography (CT). Tasks that traditionally require long processing times using conventional methods—such as tumor boundary detection, identification of vascular anomalies like aneurysms, or early-stage prediction of neurodegenerative diseases—can be performed faster and more accurately with AI-assisted systems. These systems not only perform data-driven analysis but also learn from past data to model future probabilities.[19]

Another advantage of AI in neurosurgical planning is the integration of multidimensional clinical data to personalize surgical strategies. In this context, patient-specific anatomical data, physiological indicators, and pathological findings are combined to create decision support systems that strengthen the surgeon's clinical decision-making process. For example, in aggressive tumors such as glioblastoma, AI systems model disease progression, enabling restructuring of both treatment plans and operative routes.[20]

The use of AI systems during surgery is also increasingly widespread. Algorithms integrated with intraoperative imaging systems provide real-time guidance to the surgeon, facilitating visualization of critical elements such as nerve pathways, tumor margins, or vascular structures. Particularly in robot-assisted surgical systems, AI enhances movement precision and reduces tremors at a microscopic level.[21]

All these developments demonstrate that AI in neurosurgery has become not merely an auxiliary technology but an active component of the decision-making process. However, unresolved issues remain concerning ethics, safety, and regulation. Topics such as the reliability, explainability, and legal accountability of AI systems in clinical applications play a decisive role in the widespread adoption of these Technologies.[22]

Comparative Analysis of Artificial Intelligence and Quantum-Based Systems in Neurosurgery

In the field of neurosurgery, both artificial intelligence (AI) and quantum technologies have emerged as innovative tools developed to surpass the limitations of traditional methods. Although these two technological approaches are based on different principles, their shared goal is to enhance accuracy, speed, and personalization in diagnostic, therapeutic, and surgical processes. However, AI and quantum systems differ significantly in their areas of application, operational mechanisms, clinical integration challenges, and technical infrastructure requirements.[23,24]

AI technologies demonstrate strong performance particularly in image analysis and the processing of large datasets. Deep learning algorithms operate with high accuracy in tasks such as tumor delineation, lesion classification, and risk assessment in neuroimaging data, occasionally surpassing human performance.[25] AI algorithms integrated into clinical decision support systems are currently actively used and subject to specific regulations. Their greatest advantage lies in their ability to quickly adapt to existing infrastructures and continuously improve through learning from extensive data pools.[18]

In contrast, quantum technologies have the potential to provide microscopic-level precision in imaging biological tissues by transcending classical physical limits. Systems operating with photon-level components, leveraging features such as quantum entanglement and superposition, can offer higher resolution imaging at lower energy levels, particularly providing significant advantages in delicate structures such as neural tissue.[13] However, the clinical integration of quantum systems faces significant limitations regarding hardware complexity, cost, and physical operating conditions.[2]

From a clinical perspective, AI technologies currently hold an advantage over quantum systems in terms of "applicability." Regulations, user interfaces, training programs, and IT infrastructure facilitate the integration of AI algorithms. Quantum systems remain largely in the research phase and are implemented only at limited pilot project levels.[17]

Nevertheless, these two approaches are not mutually exclusive but rather possess complementary potential. Research in the field of "quantum artificial intelligence" (QAI) aims to integrate the computational power of quantum computing with AI algorithms, creating new synergy in areas such as neurosurgery that require high resolution and high speed.[26]

Current Clinical Applications and Experimental Initiatives

Artificial intelligence (AI) and quantum technologies, in addition to offering significant theoretical potential, have recently begun to be tested in various pilot applications within clinical and semi-clinical settings. These initiatives in the field of neurosurgery are of great importance for demonstrating the integration of technologies into practice and their interaction with real patient data. In this context, AI-based decision support systems have entered routine use, while quantum-based technologies are still primarily in experimental and prototype stages.[27]

The most common clinical application of AI-assisted systems is observed in image analysis-based applications. For example, advanced imaging platforms developed by companies such as Brainlab and Surgical Theater operate integrated with AI algorithms, providing surgeons with three-dimensional virtual planning and intraoperative guidance during neurosurgical procedures. These systems are actively utilized, especially in delicate interventions such as tumor resection, assisting in tumor margin delineation, preservation of brain functional areas, and vascular structure analysis.[28]

Another example found in the clinical literature is the use of deep learning algorithms for preoperative risk stratification. A model developed at Johns Hopkins University predicts postoperative complication probabilities in glioma patients, providing personalized risk management. Such examples demonstrate that AI is effectively used not only in imaging but also in patient management and surgical decision-making processes.[29]

Regarding quantum technologies, although direct clinical use remains limited, prototype-level applications have been implemented in some research centers. For instance, a project conducted in collaboration between Massachusetts General Hospital (MGH) and Harvard University tested quantum entanglement-based biological imaging systems for low-dose, high-contrast imaging of neural tissues.[21] Similarly, quantum signal processing algorithms developed under the IBM Q project have been reported to offer more efficient results compared to classical algorithms in compressing and analyzing neuroimaging data.[30]

Moreover, experimental studies under the European Union–supported Human Brain Project aim to develop hybrid platforms combining quantum computing and AI for advanced applications such as neurological structure modeling, brain simulations, and virtual neurosurgical planning. Although these projects have not yet entered clinical practice, they provide preliminary evidence suggesting that quantum-assisted systems could be used across multiple domains, from preoperative simulations to intraoperative guidance.[31]

In summary, AI systems currently stand out as more mature, regulation-compliant, and field-integrated technologies, whereas quantum technologies remain in developmental stages with high future potential as experimental tools. However, the combined use of these two technologies, especially in hybrid systems, holds an exceptionally high capacity to transform neurosurgical applications.

Integration of Quantum Artificial Intelligence: Future Perspectives

The integration of quantum computing and artificial intelligence technologies has recently emerged as an interdisciplinary field extensively discussed in the literature under the term "Quantum Artificial Intelligence" (QAI). This new paradigm offers alternatives to problems that classical computers cannot solve, particularly in biomedical domains requiring the processing of high-dimensional and complex datasets.[5] In a field like neurosurgery, which demands simultaneous evaluation of numerous variables and real-time decision-making, the speed and predictive potential provided by quantum AI present promising opportunities.

Quantum algorithms can reveal deeper relationships with fewer data compared to classical machine learning methods and can significantly reduce processing time in tasks such as pattern recognition, classification, and optimization.[32] This advantage is particularly relevant for analyzing high-resolution images encountered in neurosurgery, providing real-time surgical guidance and enabling personalized treatment planning. For instance, quantum neural network architectures theoretically possess the potential to perform prediction and classification tasks in seconds that might take hours on classical systems.[26]

Quantum AI integration contributes not only to processing speed but also to explainability. The "black box" nature of most classical deep learning models raises safety and ethical concerns in healthcare. In contrast, quantum-supported models are expected to generate more interpretable mathematical solutions in nonlinear multivariate systems, potentially rendering decision-making processes more transparent.[33]

From a clinical integration standpoint, quantum AI systems remain largely experimental, though some pilot applications have shown promising results. Quantum simulation platforms developed within projects such as IBM Q and Google Quantum AI are employed for modeling biological systems and testing clinical decision support systems. Nevertheless, their integration into high-risk clinical fields like neurosurgery is still limited due to hardware complexity, data security concerns, algorithm stability, and regulatory gaps.[24]

Nonetheless, the fusion of AI and quantum computing could pave the way for revolutionary transformations in neurosurgery in the future. Highly accurate predictive models may enable safer planning of minimally invasive surgeries and potentially facilitate fully automated surgical scenarios integrated with robotic systems. The success of these developments depends on effective multidisciplinary collaborations, ethical oversight mechanisms, and the advancement of open data–based system architectures.

Conclusion

Neurosurgery, as a medical discipline where high precision and rapid decision-making processes intersect, is among the fields most sensitive to technological advancements. In this context, recent progress particularly in artificial intelligence and quantum technologies has introduced a new dimension to imaging, diagnosis, and treatment applications in neurosurgery. Artificial intelligence has already begun to provide tangible contributions in image processing, decision support systems, and preoperative planning; especially through deep learning algorithms, enabling automatic recognition of anatomical structures and more precise evaluation of surgical risks. These developments enhance patient safety and improve surgical success rates in neurosurgery.

Although still in the experimental phase, quantum imaging emerges as an innovative approach with the potential to overcome the resolution and contrast limitations of conventional imaging technologies. Operating on fundamental principles such as quantum entanglement and superposition, these systems offer higher accuracy imaging with lower energy, potentially creating revolutionary impacts especially in delicate areas such as neural tissue. However, the clinical integration of quantum technologies involves multilayered challenges including cost, hardware complexity, infrastructure compatibility, and regulatory gaps.

As demonstrated in this study, artificial intelligence and quantum technologies should not be considered independent but rather complementary systems. Particularly, new-generation integrated structures known as quantum artificial intelligence enable faster and more meaningful analysis of multidimensional data, offering a potential new paradigm in both diagnostic and surgical processes in neurosurgery.

In conclusion, the integration of artificial intelligence and quantum-based technologies contributes to building a more predictable, personalized, and safer clinical future that goes beyond current neurosurgical applications. To facilitate the widespread adoption of these technologies, multidisciplinary research collaborations should be encouraged, ethical and legal frameworks clarified, and further studies conducted to establish clinical validity. The integration of scientific advancements into healthcare is not only a technological progression but also a direct investment in the quality of human life.

Conflicts of Interest

There is no conflict of interest between the authors.

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Author Contribution

All authors contributed equally to this work.

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