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Review Article

The Role of AI in Neurosurgery

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Abstract:

Background:

The utilization of artificial intelligence (AI) and machine learning (ML) algorithms is experiencing a significant surge in their integration within the realm of neurosurgery. These AI and ML algorithms stand apart from other technological advancements due to their capacity to enable computers to acquire learning abilities, engage in reasoning, and employ problem-solving skills akin to those inherent in humans. This review provides an overview of the current application of AI in neurosurgery, highlights the challenges that require attention, and offers insights into what lies ahead in this field.

Methods:

We conducted a comprehensive literature review focusing on the utilization of AI in neurosurgery and its prospective impact on neurosurgical research.

Results:

The online literature pertaining to AI's use in neurosurgery reveals a broad spectrum of topics encompassing both current applications and future implications. Predominantly, research is concentrated in the areas of diagnostics, outcome prediction, and treatment models.

Conclusion:

The potential of AI in the field of medicine and neurosurgery is indeed remarkable; however, numerous challenges must be addressed before its widespread integration in neurosurgery becomes a reality. These challenges encompass issues such as patient privacy, access to high-quality data, and the risk of excessive dependence on AI by surgeons. The future of AI in neurosurgery is envisioned to revolve around a patient-centered approach, supporting clinical tasks, and aiding in patient diagnosis and preoperative assessment.

Introduction:

Artificial Intelligence (AI) has found its way into the realm of neurosurgery, significantly aiding in various aspects of patient care and surgical intervention. The foremost application lies in pre-operative planning where AI, through machine learning algorithms, facilitates enhanced image recognition and analysis, aiding in precise surgical planning and prediction of outcomes [1]. During surgery, AI assists in real-time image guidance, ensuring higher accuracy in instrument navigation and potentially reducing operative time. AI-driven robots, although in nascent stages, are anticipated to play a substantial role in executing intricate neurosurgical procedures with high precision [2]. Post-operatively, AI algorithms monitor patient recovery, predict complications, and assist in personalized patient management, thereby aiming to improve overall outcomes and reduce hospital stay [3]. Despite the promising potential, the integration of AI in neurosurgery presents challenges concerning data privacy, algorithm validation, and ethical considerations, necessitating a collaborative discourse among the neurosurgical community to address these issues and pave the way for a future where AI and neurosurgeons collaboratively elevate patient care standards.

The significance of Artificial Intelligence (AI) applications in neurosurgery is profound, providing a synergistic interface between technological innovation and clinical expertise to optimize patient care. Here's an elaborated insight into the various facets of AI applications in neurosurgery:

1.Pre-operative Planning:

- AI algorithms excel in image analysis and 3D reconstruction, aiding in meticulous surgical planning. They enhance the diagnostic accuracy by delineating pathological from normal structures, thus facilitating better pre-operative decision-making.

2.Intra-operative Assistance:

- During surgical procedures, AI augments real-time imaging and instrument navigation. It also holds promise in robotic assistance, which can potentially enhance surgical precision and reduce operative times. Moreover, AI can assist in intra-operative decision-making by providing real-time data analysis, thus potentially minimizing surgical risks [4]

3.Post-operative Monitoring:

- Post-operatively, AI aids in patient monitoring, early detection of complications, and personalized rehabilitation plans. It facilitates efficient clinical assessments which are crucial for timely interventions and improved patient outcomes1.

4.Clinical Research and Healthcare Access:

- AI significantly contributes to clinical research by automating data analysis, thus accelerating the pace of research in neurosurgery. Furthermore, AI can expand healthcare access by supporting tele-neurosurgery and remote patient monitoring, especially in underserved regions [5].

5.Advanced Imaging:

- Despite advancements in neuroimaging, the precise detection of tumor recurrence, differentiation between tumors and other pathological entities requires further refinement, a domain where AI has shown promise by enhancing the interpretative accuracy of imaging modalities.

6.Enhanced Prognostication:

- By analyzing vast datasets, AI can potentially improve prognostic accuracy, helping in better patient counseling and decision-making [6].

Discussion:

In an era marked by increasing automation across various domains, the field of medicine and surgery has not remained untouched by the technological revolution. AI has found substantial integration in routine diagnostic and clinical investigations, as well as in advanced surgical techniques such as laparoscopic and robotic surgeries [7]. AI, a remarkable technological breakthrough, empowers machines to emulate human problem-solving and decision-making abilities by learning from extensive datasets and patterns of human activities. Key subfields of AI encompass Machine Learning (ML), Natural Language Processing (NLP), Computer Vision (CV), and Artificial Neural Networks (ANNs) [8]. ML, one of the oldest branches of AI, enables machines to improve their performance in tasks through learning from experience without the need for explicit programming. Notably, Seib et al. demonstrated the superiority of a super learning algorithm-based ML model over traditional logistic regression in predicting patient-level outcomes of thyroidectomy, leading to more personalized and informed treatment decisions.

NLP focuses on enabling computer systems to comprehend human language, whether written or spoken. Thirukumaran et al. showed that NLP-based models exhibited prediction capabilities comparable to manual abstraction processes and outperformed models relying solely on administrative data in identifying surgical site infections among orthopedic surgery patients [9].

ANNs, inspired by biological neural networks, concentrate on creating computational models that mimic the interconnections of neurons in the human brain. Chen et al. assessed the success rate of facial feminization surgeries using neural networks designed for facial recognition, demonstrating accurate gender typing and increased confidence in femininity [10].

CV, another vital subset of AI, empowers machines to extract and analyze visual data from images or videos. It can be employed to record and compare the skills of operating surgeons with their peers, identify areas for improvement, standardize procedural skills, and predict the association of postoperative complications and operation time with the complexity of surgeons' skills [11].

AI and neurosurgery:

AI's involvement in neurosurgery traces back to the 1990s when ML was first applied in medical literature, with ANNs developed for structured dataset analysis and task supervision. ANNs proved increasingly useful in tasks such as lesion detection on reconstructed SPECT scans and grading of astrocytic gliomas. By the end of the millennium, well-trained AI algorithms consistently outperformed traditional clinical approaches in brain tumor diagnosis, tumor segmentation, and surgical risk assessment. The digitalization of healthcare systems in the 2000s provided extensive structured and unstructured datasets, further enhancing the capabilities of AI systems. Throughout the 2010s, AI-based programs continued to advance in neurosurgical care, with contemporary models showing unprecedented potential for revolutionizing neurosurgical practices, particularly given the wealth of data generated by complex diagnostic and therapeutic modalities in neurosurgery [12].

The shortage of neurosurgeons in comparison to neurosurgical cases, especially in low- and middle-income countries, has been exacerbated by the COVID-19 pandemic. Recent developments include the use of MRI-compatible robotic arms, remotely controlled by neurosurgeons, for procedures like tumor biopsies and microsurgical dissections [13]. Neurosurgical errors can be life-threatening, common, and underreported, with neurosurgery ranking third in the prevalence of wrong-site or wrong-level surgeries. While surgical safety checklists have reduced such incidents, they have not entirely eliminated them. AI-based computational systems and robots have transformed operating room dynamics, leading to more efficient, safe, and minimally invasive neurosurgical procedures [14].

Human-machine teaming and CV in neurosurgery:

CV, a burgeoning AI domain, focuses on developing systems capable of interpreting visual data from images and videos. Its application in monitoring team dynamics in the operating room has shown promise. Disruptions in surgical workflows during procedures can lead to errors and increased complication risks. Khan et al. developed an advanced ML model using SPR technology to efficiently recognize phases and steps of endoscopic trans-sphenoidal approaches for pituitary adenoma resection. This ML-based analysis of surgical workflow has significant potential for reducing interruptions, enhancing OR team coordination, and rating operative videos for surgical education . Automated performance metrics (APMs) have been evaluated for predicting surgeons' performance in endoscopic endonasal surgery for internal carotid artery vascular injury, outperforming training status or prior experience as predictors [33]. While ML-powered devices have great potential to collaborate with human teammates, they lack human teamwork competencies such as communication, coordination, and adaptation. Current AI research is focused on imbuing machines with these transferable competencies and addressing their requirements for effective teamwork [15].

Role of AI in pre- and post-operative management in neurosurgery:

Despite advancements in neuroimaging, there is room for improvement in detecting tumor recurrence, small metastases, distinguishing between tumors and infectious foci, and assessing the effects of MRI and other imaging modalities. Recent studies have leveraged MRI histogram peaks to design AI algorithms for more specific, sensitive, and repeatable tumor volume detection [25]. Radiomics, another emerging field, uses AI and ML techniques to extract and analyze data from medical images to inform diagnosis and prognosis. The prognostic value of radiomic features derived from multi-parametric MRI has been demonstrated in glioma patients, offering potential applications in treatment planning and surveillance [16].

AI can also play a crucial role in post-operative care. Identifying complications early is crucial for successful recovery. AI algorithms can monitor patients post-operatively, analyzing vital signs, lab results, and even patient-reported symptoms to detect complications promptly. Such systems can help reduce the burden on healthcare professionals and improve patient outcomes by ensuring timely interventions [17]. AI-powered chatbots or virtual assistants can assist patients in their recovery process by providing information, answering questions, and offering support, enhancing the overall patient experience [18].

Legal and ethical considerations in AI adoption:

The integration of AI into neurosurgery raises several legal and ethical concerns. Patient data privacy and security are paramount, with regulations like the Health Insurance Portability and Accountability Act (HIPAA) in the United States setting strict standards for the protection of health information. AI systems must adhere to these regulations and maintain the confidentiality of patient data [19].

Bias in AI algorithms is a significant ethical concern. If AI systems are trained on biased datasets, they can perpetuate and amplify existing biases, leading to disparities in healthcare outcomes. Efforts must be made to ensure that AI algorithms used in neurosurgery are fair and do not discriminate against any patient group [20].

Another ethical issue is transparency and accountability. Surgeons and healthcare institutions must have a clear understanding of how AI algorithms make decisions. Black-box AI systems that provide no insight into their decision-making process can be problematic. Ensuring transparency and accountability in AI systems is crucial for building trust in their use in neurosurgery [21].

The liability of AI in neurosurgery is another complex issue. If an AI system makes a wrong diagnosis or recommendation that leads to harm to a patient, who is held responsible? Is it the surgeon, the hospital, or the AI developer? Clarifying liability issues is essential to ensure that patients receive appropriate care and that healthcare providers are not unfairly burdened with legal responsibilities [22].

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