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Applications of Artificial Intelligence in Neurosurgery

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Over the last decade, artificial intelligence has steadily begun to change neurosurgical practice. Tools that once seemed futuristic now assist in more accurate tumor diagnosis, confident surgical planning, and real-time intraoperative guidance. This review examines the current state of artificial intelligence applications in neurosurgery, highlighting proven benefits, remaining limitations, and the steps required for safe routine integration. Studies published between 2020 and 2025 in major databases were analyzed. Clear advantages include faster image analysis, improved outcome prediction, and enhanced surgical precision. However, challenges related to data privacy, algorithmic bias, and the "black-box" nature of many models persist. Addressing these issues will determine how widely these technologies are adopted in clinical practice.

Introduction

Artificial intelligence (AI) systems are integrated into multiple stages of neurosurgical care, from initial diagnosis and surgical planning to intraoperative navigation and postoperative monitoring (1,2). Machine-learning algorithms rapidly analyze MRI, predict complications, and suggest optimal trajectories for deep lesions (1). This review provides a concise, up-to-date overview of the most relevant and well-validated applications of artificial intelligence in neurosurgery, with emphasis on practical clinical impact (3,4).

Materials and Methods

A targeted literature search was performed for the period January 2020–December 2025 in PubMed, Scopus, and Web of Science. Combinations of the terms "machine learning", "artificial intelligence," "deep learning," and "neurosurgery" were used together with specific keywords including "intraoperative navigation," "image segmentation," "outcome prediction," and "robotic assistance." Only English-language original articles, systematic reviews, and case series with external validation or real-world implementation were included.

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Older landmark papers were cited when necessary for historical context (4).

Results

AI in Preoperative Diagnostics and Surgical Planning: Deep-learning models, particularly convolutional neural networks, now provide rapid and highly consistent segmentation of brain tumors, peritumoral edema, and critical white matter tracts. This automation reduces preoperative planning time (1,2). Predictive models that integrate imaging and clinical data improve estimation of tumor grade, molecular subtype, and postoperative seizure risk (5). Specific virtual-reality simulation platforms have become routine for complex skull-base and eloquent-area tumors, helping to minimize intraoperative surprises (1).

Intraoperative Assistance and Execution Augmented-reality systems overlay three-dimensional reconstructions directly onto the surgical field via microscope or exoscope, providing valuable anatomical guidance in distorted or re-operated fields (2,6). Robotic platforms equipped with artificial intelligence achieve sub-millimeter accuracy in deep-brain stimulation and stereotactic biopsies (3). Real-time tissue characterization using Raman spectroscopy or fluorescence data helps determine resection margins and has been shown to increase the extent of safe tumor removal in selected cases (5).

Postoperative Care and Outcome Prediction: continuous monitoring models that analyze vital signs, intracranial pressure, and early imaging changes can detect postoperative hemorrhage or hydrocephalus hours before deterioration (4,7). Longer-term predictive algorithms support individualized rehabilitation planning and estimation of seizure recurrence risk after epilepsy surgery or functional recovery after decompressive procedures (3).

Discussion

Artificial intelligence has automated many time-consuming tasks and reduced inter-observer variability in imaging analysis and surgical planning. Workflow efficiency has improved in many centers (1,2). Nevertheless, most algorithms are still trained on relatively homogeneous datasets, raising concerns about generalizability across different populations and resource-limited settings (6). The "black-box" problem remains a significant barrier to clinician trust; explainable artificial intelligence models that clarify decision-making processes are therefore essential (3,6). Data privacy, regulatory approval, and clear institutional liability frameworks must also be addressed. Interdisciplinary collaboration between data scientists, neurosurgeons, and ethicists will be critical for responsible implementation (7).

Conclusions

Artificial intelligence is already delivering measurable improvements in neurosurgical diagnostics, planning, intraoperative guidance, and postoperative care (1,2). The widespread adoption will require rigorous clinical validation, transparency, and thoughtful integration that preserves the central role of clinical judgment (5). When developed and applied responsibly, the technologies have the potential to enhance safety and personalize care for patients undergoing neurosurgical procedures (3,6).

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