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Review Article

A review on advancements in neurosurgery through the integration of artificial intelligence: Current impact and future prospects

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Abstract

The use of artificial intelligence (AI) in neurosurgery has greatly improved clinical precision, safety, and efficiency. AI-driven innovations, such as image-guided navigation, robotic surgery, predictive analytics, and brain-computer interfaces, improve outcomes and allow for real-time, data-driven decisions. This study examines existing AI uses in neurosurgical operations, diagnostics, and postoperative care, as well as prospects such as real-time intraoperative decision-making, individualized neurosurgery planning, and autonomous surgical systems. Despite the potential, ethical, legal, and infrastructure difficulties persist. Continued multidisciplinary collaboration is required to realize AI's promise in neurosurgical developments fully.

Keywords: Artificial intelligence, Neurosurgery, Healthcare, Personalised medicine, Machine learning algorithms.

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1. Introduction

Neurosurgery is a clinical medicine discipline that generates a substantial amount of data because of the frequent usage of cutting-edge medical technology and information systems. These variables increase the likelihood that neurosurgery will successfully adapt to AI technology. AI is quickly transforming the field of brain injury care and neurosurgery. Its application in diagnostic imaging, surgical planning, intraoperative navigation, and postoperative monitoring has already shown substantial results. While hurdles remain in ethical implementation, validation, and data protection, the future of AI-assisted neurosurgery is bright and unstoppable. Multidisciplinary cooperation will be critical for the safe and successful implementation of AI technology in brain injury care. Neurosurgery, one of the most difficult and risky areas of medicine, necessitates accuracy and real-time decision-making. Historically, neurosurgical operations have depended on high-resolution imaging, skilled hand dexterity, and intraoperative navigation systems. However, the advent of artificial intelligence (AI) and machine learning (ML) has created transformational prospects for optimizing surgical planning, improving diagnostic accuracy, and assisting with intraoperative decision making.[1]

With recent technological advancements, there has been a strong emphasis on the application of artificial intelligence (AI) in health care and clinical practice because it can complement the huge volumes of data collected in the current health-care system and offer clinically useful outcomes.[2] AI is a new topic in computer science, and ML enables computers to learn, reason, and solve problems.[3] New research also suggests that ML algorithms might help physicians make better clinical decisions in neurosurgical applications.[1] Over the last decade, there has been a rise in interest in the application of artificial intelligence in neurosurgery.[4] Modern diagnostic procedures generate vast

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volumes of data that may be analyzed broadly by experienced professionals and advisors; nevertheless, quantitative analysis requires AI and ML since they can deliver better findings and patterns than humans. The implications of AI in neurosurgical treatment are in their early stages, and their integration into everyday clinical practice has yet to be demonstrated by addressing obstacles such as access to high-quality data.[5]

Although the emphasis is currently on the application of AI in neurosurgery since we can match AI with robotic surgery, AI will likely make its way into the operating room (OR).[2] The use of advanced technology in neurosurgery has always been on the rise; since the introduction of MRI and CT as diagnostic imaging modalities, neurosurgeons all over the world have used cutting-edge technology to diagnose and manage patients, as well as improve patient outcomes.[4] The inclusion of artificial intelligence into neurosurgery is driving a change away from traditional approaches and toward predictive, tailored, and precision-based therapies. This article presents a detailed review of AI in neurosurgery, including current uses, recent advances, and prospects. To develop an AI-based project in neurosurgery, it is necessary to analyze the present demand and implementation of these technologies, as well as to identify research areas that are potentially suitable for employing AI. This literature review tries to describe the difficulties in neurosurgery that AI technologies can tackle, as well as to highlight the areas where these technologies are needed.

With the increased need for neurosurgeons owing to population expansion, there has been a strong emphasis on expanding the number of physicians,[4] but human power alone cannot address the difficulties in health care, which will require more technology-based solutions shortly. While AI inclusion into clinical practice may appear to be a computer taking the position of the physician with preprogrammed decisions, machine learning (ML) is an ever-evolving technology that leverages massive quantities of data to provide clinically relevant findings with problem-solving and decision-making abilities. Targeted cost-effective treatment is at the heart of future medicine and health care; lowering health-care costs through focused intervention and diagnostic procedures can alleviate unneeded stress.[2] **Figure 1** below shows the impact of artificial intelligence on brain tumor patient outcomes likely to occur even before the patient reaches the operating table.

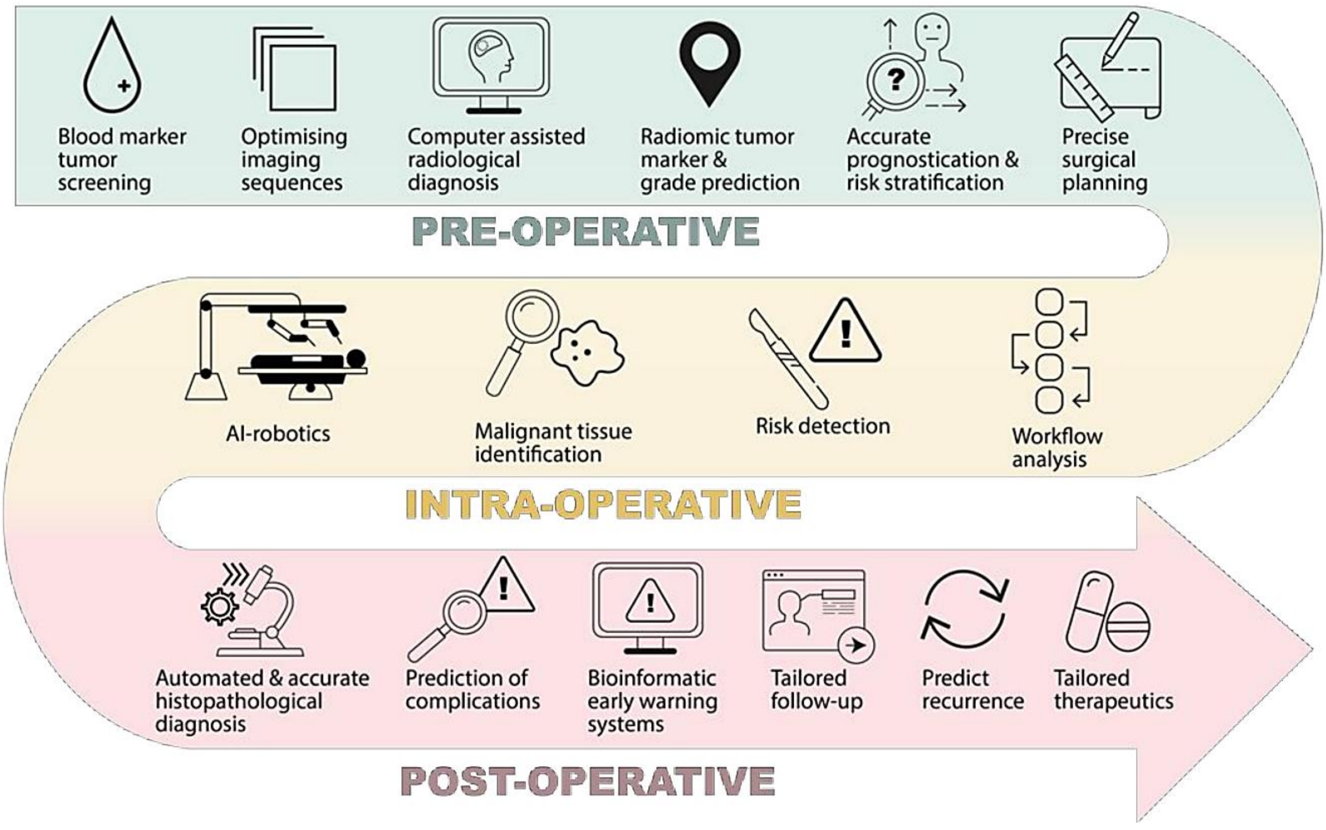

Figure 1: Potential clinical impacts of AI in the neurosurgical management of brain tumours, in the pre-operative, intra-operative, and post-operative phase[3]

2. Materials and Methods

A literature search was done utilizing PubMed, Scopus, IEEE Xplore, and Google Scholar for publications published between January 2015 and March 2024. The search phrases were "AI in neurosurgery," "artificial intelligence head injury," "robotic brain surgery," "machine learning in TBI," and "AI postoperative prognosis." Original research papers, clinical trials, meta-analyses, and reviews were included in the study, which focused on AI applications in the surgical care of brain injuries.

3. Discussion

Technically, artificial intelligence is a mathematical technique that automates the solution of an intellectual issue that was previously solved by a human. At the same time, the word AI refers to the area of computer science in which such solutions are produced. In the latter situation, AI refers to several mathematical and software technologies that mimic some aspects of human cognitive function.

How do Artificial Intelligence technologies work? AI's mathematical equipment enables the discovery and retention of distinct data patterns that humans cannot always explain. This method is known as machine learning (ML), which is the mathematical search for the optimal solutions to systems of equations. The ML method produces a mathematical model, which is a function containing independent variables (predictors) and parameters learned by ML. For example, many models employ the patient's age and illness severity as independent variables, with the model's output being a prediction of the treatment result (in numerical or categorical terms). ML "learns" the parameters of such a model using a vast quantity of representative data. The most promising features of AI technologies are their capacity to exploit the most accessible information (even if it is unstructured — photos or text) and identify complicated and essential patterns.

Neurosurgery is a clinical medicine discipline that generates a substantial amount of data because of the frequent usage of cutting-edge medical technology and information systems. These variables increase the likelihood that neurosurgery will successfully adapt to AI technology. To develop an AI-based project in neurosurgery, it is necessary to analyze the present demand and implementation of these technologies, as well as to identify research areas that are potentially suitable for employing AI. This literature review tries to describe the difficulties in neurosurgery that AI technologies can tackle, as well as to highlight the areas where these technologies are needed.

The history of AI in neurosurgery dates to the 1990s, when the usage of ML was first documented in the medical literature as ANNs were created for structured dataset analysis and job monitoring. From lesion detection on reconstructed SPECT scans to grading of astrocytic gliomas, ANNs were progressively used, with results equivalent to manual processing. By the end of the decade, well-trained AI algorithms will have outperformed traditional clinical procedures in brain tumor detection, tumor segmentation, and surgical risk assessment. Furthermore, the digitization of healthcare systems in the 2000s expanded the capabilities of AI systems by providing enormous structured and unstructured datasets for training and testing ML models. Throughout the 2010s, AI-based algorithms expanded their reach into neurosurgical treatment. The use of highly advanced modern models is on the rise, with several reportedly having extraordinary potential to revolutionize neurosurgery treatments. Furthermore, the complicated diagnostic and therapeutic techniques utilized in neurosurgery generate a large quantity of data that is well-suited for ML models.[6]

Despite recent breakthroughs in neuroimaging, the accuracy of identifying tumor recurrence, tiny metastases, distinguishing between tumors and infectious foci, and the treatment impacts of MRI and other imaging modalities requires further refinement.[7] In a recent work, MRI histogram peaks were used to develop AI algorithms capable of properly detecting tumor sizes with greater specificity, sensitivity, and intero-perator repeatability.[8] Radiomics, along with clinical signs, has been used to construct several machine learning models that can reliably identify molecular subgroups of medulloblastomas and skull base chondromas vs chondrosarcomas.[9,10] In another study, researchers employed texture analysis and other AI technologies to investigate necrosis as a therapy effect, the differentiation of benign and malignant tumours, disease progression, and the number of metastases.[11] **Figure 2** depicts the emerging applications of these machine learning technologies in neurosurgery.

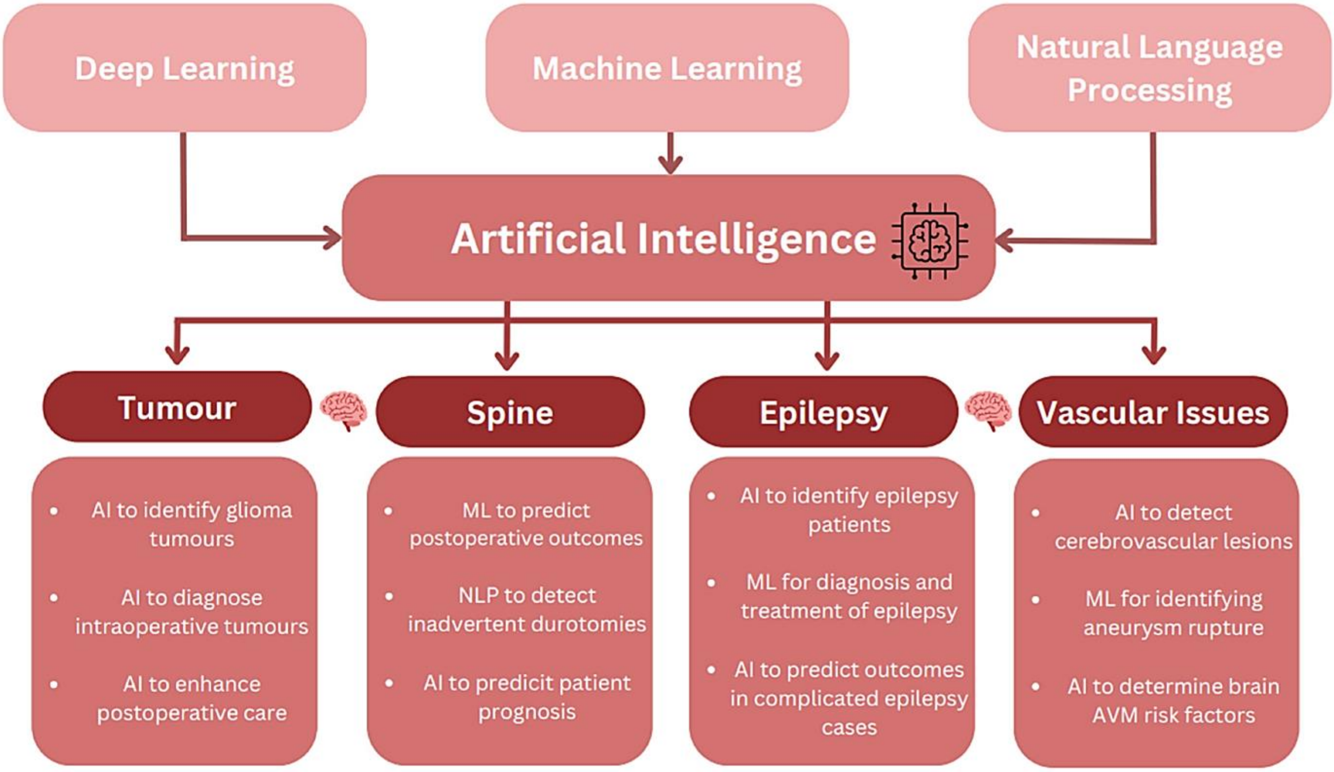

Figure 2: Potentials of AI in neurosurgery[12]

3.1. AI technologies for neurosurgery

1. Machine and deep learning: Machine learning (ML), a subset of artificial intelligence, allows computers to learn from data without explicit programming. Deep learning (DL), a more sophisticated subset, uses artificial neural networks to simulate human brain activity. These technologies are utilized in neurosurgery to perform tasks such as tumor segmentation, diagnosis, surgical simulation, and risk assessment.
2. Computer vision and imaging: AI-powered computer vision systems can assess preoperative and intraoperative pictures to aid with navigation. These techniques extract information from MRI, CT, and intraoperative ultrasound images to help with tumor margin detection and localization of important brain locations.[13]
3. Natural language processing (NLP): NLP is useful for analysing massive datasets such as electronic health records (EHRs), operation notes, and radiology reports. NLP systems can help identify patient groups, assess results, and automate documentation.[14]

3.2. Clinical applications

1. AI in preoperative planning: AI systems can evaluate neuroimaging data to automate the segmentation of brain tumours, aneurysms, and vascular abnormalities. For example, DL algorithms have shown remarkable accuracy in glioma segmentation, with Dice scores above 0.9 in some circumstances.[15] Predictive models help with risk stratification by evaluating comorbidities, imaging biomarkers, and genetic variables.
2. Image-guided neurosurgery: Artificial intelligence-powered platforms like augmented reality and intraoperative navigation devices are redefining accuracy in real time. Intraoperative feedback systems, such as Brainlab and Synaptive's Modus V, improve spatial awareness while lowering the risk of iatrogenic injury.[13]
3. Robotic-assisted neurosurgery: Deep brain stimulation (DBS), stereotactic biopsies, and spinal instrumentation are all performed with greater precision because of neurosurgical robotics and AI algorithms. The ROSA robot, for example, employs preoperative planning and AI to insert electrodes in DBS with sub-millimetre precision.[16]
4. Intraoperative decision support: Artificial intelligence systems can monitor physiological signs in real time (EEG, ICP, blood flow) and notify surgeons of crucial changes. Research is moving toward technologies that give intraoperative decision assistance, such as identifying surgical hazards, forecasting bleeding, and recommending resection borders.
5. Outcome prediction: AI can predict surgical outcomes, complications, and long-term functional recovery

based on perioperative data. A recent study found that ML models predicted 30-day postoperative problems in neurosurgical patients more accurately than conventional risk models.[17]

3.3. Integration of AI in brain tumor surgery

1. Automated tumor segmentation: AI allows for rapid and accurate 3D segmentation of brain tumors using MRI data. The BraTS challenge datasets have aided the creation of AI models that outperform conventional radiologists in some tasks.[15]
2. Histopathological classification: Deep learning models applied to histological slides can accurately diagnose glioma subtypes. AI-powered pathology solutions accelerate diagnosis and increase interobserver reliability.[18]
3. Predicting molecular markers: Using radiomics and imaging-based algorithms, AI can non-invasively predict the molecular state of gliomas (e.g., IDH mutation, MGMT methylation), assisting with treatment planning and prognosis.[19]

4. Prospects and Future Directions

As technology progresses in numerous disciplines of medicine, it is critical that these automation and sophisticated machine learning techniques be integrated into neurosurgery. The neurosurgical discipline and neurosurgeons should use the capabilities of AI and ML learning in everyday clinical practice and incorporate these models into intraoperative and postoperative treatment.[4] AI model training for the next generation of doctors in undergraduate and postgraduate students should begin early so that they are aware of recent technological advancements and how they are being integrated into clinical practice. **Figure 3** summarises the upcoming course of artificial intelligence in the field of neurosurgery.

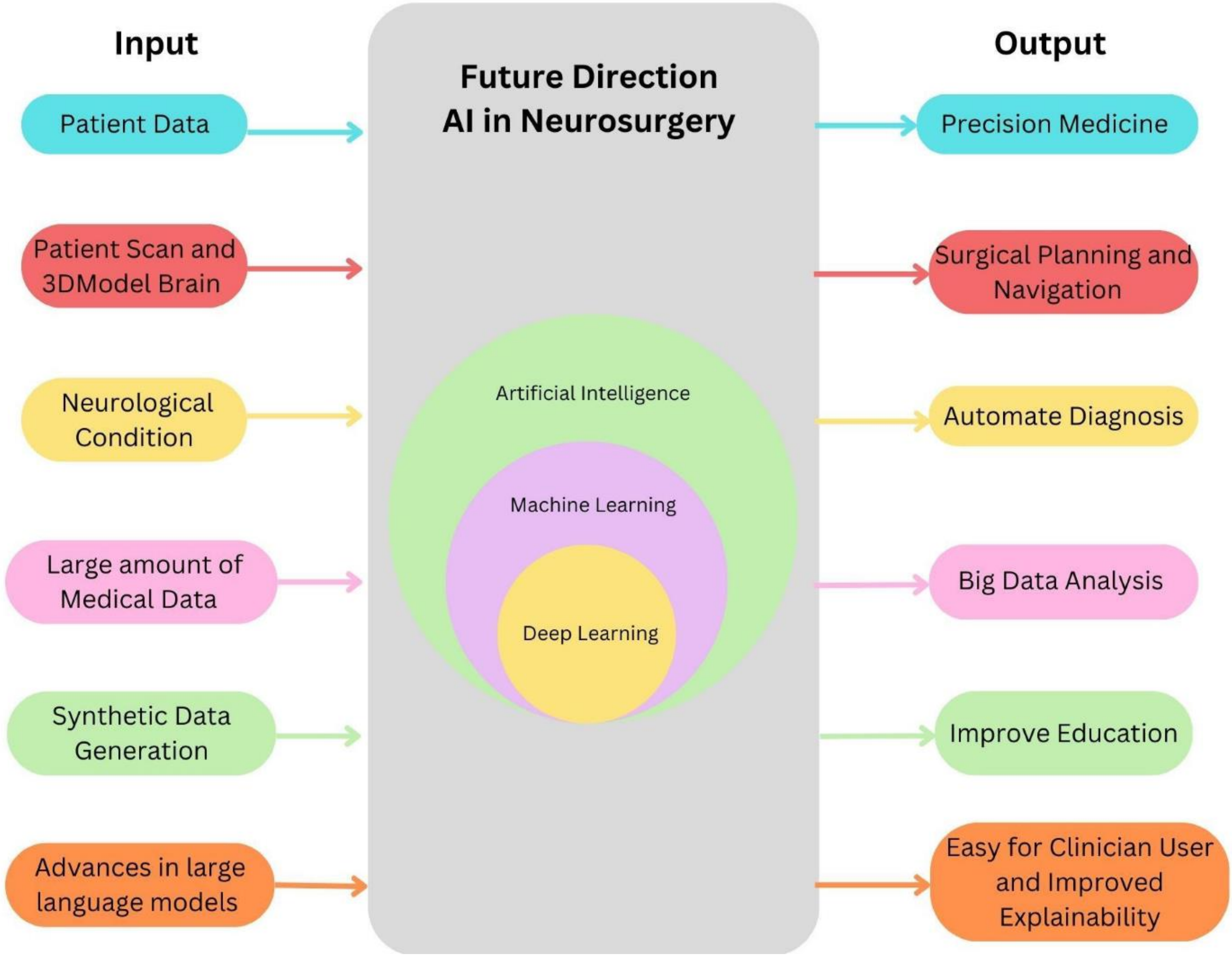

Figure 3: Course of artificial intelligence in neurosurgery[12]

1. Autonomous surgical systems: While existing AI systems mostly serve as decision-support aids, research is moving toward semi-autonomous and completely autonomous neurosurgery platforms. These technologies might potentially undertake activities, including suturing, resection planning, and navigation with little human intervention.[20]
2. Brain-computer interfaces (BCIs): Artificial intelligence (AI) is critical to the development of BCIs that restore motor or sensory functions in individuals with spinal cord injuries or neurodegenerative disorders. Elon Musk's Neuralink and BrainGate are pioneering real-time brain decoding to control external devices.[21]
3. Personalized neurosurgery: By combining genetics, radiomics, and phenomics, AI can adapt surgical and treatment strategies to the specific patient. Predictive models based on omics data will guide tumor resection extent, treatment options, and post-op care paths.
4. Augmented reality (AR) and Mixed reality (MR): In the future, neurosurgical operating rooms may utilize AI-integrated AR/MR headsets to overlay important structures on the patient's anatomy during operation. This visualization improves orientation and accuracy.[13]

4.1. Challenges and ethical considerations

AI has demonstrated miracles in medicine and healthcare, and its future in neurosurgery seems promising in many ways, but several drawbacks must be addressed and acknowledged before it is used in everyday, regular treatment.

1. Data privacy and security: AI systems require enormous datasets, which frequently contain sensitive health information. Ensuring compliance with privacy rules like HIPAA and GDPR is crucial.
2. Bias & generalizability: Many AI models are trained on data from specific populations or organizations, which might lead to biases when used generically. Model validation across varied populations is critical to generalizability.
3. Regulatory and legal concerns: As AI systems begin to make key choices, defining culpability in the case of a negative outcome becomes difficult. Regulatory rules must change to address this complexity.
4. Surgeon acceptance and training: The effectiveness of AI integration is dependent on clinician acceptance. Adequate training in AI tools and building trust in machine-generated suggestions are required for clinical use.

5. Results

The comprehensive review of literature and clinical studies revealed that artificial intelligence (AI) has profoundly impacted nearly every phase of neurosurgical care—from diagnosis and operative planning to intraoperative assistance and postoperative prognosis. AI-powered image processing algorithms demonstrated exceptional accuracy in the segmentation and classification of brain tumors, with deep learning models such as U-Net and nnU-Net achieving Dice similarity coefficients exceeding 0.90 in glioma segmentation tasks. Robotic-assisted systems, particularly in deep brain stimulation and spinal instrumentation, have significantly improved surgical precision and reduced operative time. Moreover, predictive analytics using machine learning algorithms outperformed traditional statistical models in forecasting postoperative complications and long-term functional outcomes. In intraoperative contexts, AI-supported navigation and real-time feedback mechanisms enhanced the safety of resections by minimizing damage to eloquent brain areas. Several studies also confirmed the feasibility of AI in automating histopathological classification and non-invasive prediction of genetic markers like IDH mutation and MGMT promoter methylation in gliomas. Collectively, these findings underscore the transformative potential of AI in optimizing surgical outcomes, reducing complications, and paving the way for more individualized and minimally invasive neurosurgical strategies. However, the variability in data quality, limited external validation, and regulatory gaps highlight the need for more robust clinical trials and interdisciplinary collaboration to translate AI innovations into routine practice.

6. Conclusion

In current scenario, traumatic brain injuries (TBIs) are a leading source of morbidity and mortality globally, accounting for about 30% of all injury-related deaths. These injuries frequently necessitate emergency surgical procedures to alleviate cerebral pressure, drain hematomas, and repair structural damage. Given the complexities of the human brain, such operations need extraordinary accuracy, rapid decision-making, and ongoing monitoring. Artificial intelligence is transforming neurosurgery by increasing precision, customizing care, and boosting results. AI technologies are becoming increasingly important in neurosurgical surgery, ranging from preoperative planning and intraoperative assistance to postoperative prognosis. Regardless of present limitations, sustained innovation, ethical monitoring, and multidisciplinary cooperation will ensure that AI's full potential is reached.

The future of neurosurgery will most certainly involve hybrid models of human skill and AI-powered help, resulting in remarkable advances in brain and spine care. Recent advances in artificial intelligence (AI) have resulted in unique tools and tactics that greatly improve neurosurgical workflows. From enhanced image analytics to robotic surgical equipment and predictive monitoring, artificial intelligence has the potential to improve patient outcomes, eliminate surgical mistakes, and optimize healthcare delivery.

AI in healthcare has made major advances, with physicians and machines possibly working together to improve patient outcomes. However, AI has significant disadvantages, including patient trust difficulties and ethical concerns. Traditional neurosurgeons frequently discourage the use of AI during surgeries, as overreliance may lead to a loss of surgical expertise. AI necessitates a massive dataset, which presents issues in developing therapeutically useful algorithms and storing enormous amounts of data, putting patient privacy at risk. The lack of transparency in AI systems, as well as the lack of human awareness for responsible decision-making, raises ethical concerns. Verification and certification of AI-based systems are advised to ensure patient safety and reduce system failure. Future problems include marking targets, understanding complex anatomy, and dealing with anatomical defects during endovascular treatments. AI can be employed extensively for procedures with advanced age; however, clinical approval is still necessary. To analyse and use data and AI systems more effectively, doctors must be schooled in computer science.

The integration of AI into health care has resulted in a paradigm change; this will be the new normal for future surgeons, in which doctors collaborate with scientists and engineers to develop better tools and approaches for medical treatment and research. AI has limitations and obstacles that may be solved via rigorous monitoring and the continuous development of new algorithms to reduce failure rates. AI serves as a tool for neurosurgeons rather than a substitute. Workspaces should be enhanced, not refined. AI advancements can aid in the integration of data-driven disciplines such as genetics and surgery to provide individualized therapies and precision public health. Future physicians must stay current on innovations in health care and be able to incorporate them into their practices to demonstrate improved outcomes.

7. Source of Funding

None.

8. Conflict of Interest

None.

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