DOI: 10.7860/JCDR/2025/78125.21518

Review Article

Surgery Section

Artificial Intelligence in Neurosurgery: Enhancing Diagnosis, Treatment and Patient Outcomes: A Narrative Review

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ABSTRACT

Neurosurgery is experiencing the impact of Artificial Intelligence (AI) in the form of improved diagnostic efficiency, procedural dexterity, and postsurgical management. This narrative review aims to discuss the numerous engagements of AI in the broad subdisciplinary areas of neurosurgery, such as neuro-oncology, functional neurosurgery, vascular neurosurgery, spinal neurosurgery, and Traumatic Brain Injury (TBI) care. The article pays particular attention to the application of machine learning algorithms and topic modeling for more accurate tumour grading, potential prediction of surgical outcomes for each patient and more appropriate patient stratification. Through early diagnosis in diagnostic imaging and individualised treatment regimens, technology—particularly AI—provides decisive information for constructive, real-time intraoperative data analysis. Additionally, the extension of AI applications in the telemedicine system helps to increase the availability of specialised care in relevant areas. While it is important to appreciate the risk of dependency on technology, this does not eliminate the potential for integrating such AI tools with surgical knowledge to continue improving patient care and outcomes. Current and future trends in the practical application of AI in neurosurgery include deep machine learning for neurosurgical planning and individualised patient data/targeted therapy. In general, AI plays an important role in enhancing neurosurgery while optimising the quality and outcomes of patient care.

Keywords: Automation, Brainmapping, Diagnostics, Imaging, Innovation

INTRODUCTION

The application of computer systems to improve the accuracy and effectiveness of neurosurgical treatments—including diagnostic imaging, preoperative planning, intraoperative procedures, postoperative care and neurointensive care—falls under the umbrella of AI in neurosurgery [1]. The use of AI in healthcare has the potential to enhance clinicians' diagnostic and decision-making skills. AI can identify significant components in intricate and data-intensive fields such as patient selection, diagnosis, therapy and outcome prediction [2]. The enormous volume of clinical data collected in contemporary healthcare settings can be quickly and thoroughly analysed using AI techniques, something that would be challenging for humans to achieve [3].

Furthermore, AI may find its way into the operating room and enable more precise procedures with fewer errors, especially when paired with surgical robotics and other adjuncts like image guidance [4]. AI can assist neurosurgeons in diagnosing conditions, selecting patients for the best course of therapy and supporting patients in making informed decisions during the preoperative stage of the procedure [5]. Preoperative planning can thus be improved to lower associated costs and enhance patient care. AI has the potential to improve surgeon performance and reduce surgical error rates during the intraoperative phase of neurosurgery [6].

Scientists have developed a label-free optical imaging approach that allows for automatic diagnosis prediction. AI has applications in the intraoperative phase of neurosurgery [7]. AI-based tumour diagnosis techniques exceed traditional histology processes, predicting tumour diagnoses with an overall accuracy of 95% in less than 150 seconds [7]. In postoperative care, AI can track data for improved recovery and aftercare, predict prognosis and identify potential postoperative complications [8]. Compared to other applications such as preoperative planning and image interpretation, surgeons and surgical teams are less comfortable with the use of AI in postoperative care and follow-up for neurosurgery [8,9]. The concern that AI could eventually replace clinicians in the medical field has been raised as one of the key issues. Over-reliance on AI in neurosurgery may lead to unfavourable primary and secondary outcomes. At a fundamental level, faults in equipment and software can result in errors during surgical techniques; additionally, misinterpretations of laboratory reports, clinical findings and image scans can lead to incorrect diagnoses [3]. On a secondary note, an over-reliance on AI in surgical treatments may hinder doctors from developing the skills necessary to achieve proficiency in their field [3,10].

The Role of AI and Topic Modeling in Enhancing Diagnosis and Prognosis in Neuro-oncology

Neuro-oncology, functional neurosurgery, vascular neurosurgery, spinal neurosurgery and surgery for TBI are among the fields of neurosurgery where AI techniques can be applied [11]. AI and topic models such as Latent Dirichlet Allocation (LDA) and Additive Regularisation of Topic Models (ARTM) have revolutionised the assessment of medical data in neuro-oncology, particularly in tumour grading, molecular diagnostics and imaging [11,12]. These algorithms allow the AI system to learn about the patterns between large datasets, such as Magnetic Resonance Imaging (MRI) scans and molecular information, enabling non invasive tumour grading and molecular diagnosis based on features linking imaging with tumour grade or genetic mutations, respectively [12,13].

In AI models, LDA and ARTM are used to segment brain structures, enhancing the accuracy of volumetric measurements that are vital for surgical planning and treatment evaluation [11]. In particular, two of the most promising procedures—namely conversation analysis and the generation of profiles for specific patients—are based on topic modeling assisted by AI [14]. Furthermore, the method of topic modeling is indispensable for identifying complicating factors and estimating treatment outcomes in neuro-oncology [12,15]. AI tools such as LDA and ARTM utilise historical patient information and data from multiple modalities to identify risks and predict patient outcomes related to interventions such as surgery or chemotherapy [16]. This aids clinicians in decision-making, thereby creating better profiles for treating patients with glioblastoma and other complex illnesses with higher precision [17]. Thus, AI is gradually extending its role to become an essential tool in enhancing diagnosis, patient stratification and prognosis in neuro-oncology [11,12,15].

The Growing Role of AI in Functional Neurosurgery: Advancements in Epilepsy and Parkinson's Disease (PD) Treatment

The role of AI has been significantly increasing in functional neurosurgery, particularly in the treatment of diseases such as epilepsy and PD [18,19]. In epilepsy, AI assists in diagnosing the condition by processing large volumes of data, including EEGs and imaging studies, to identify areas of the brain that exhibit abnormal activity during a seizure [18,20]. Machine learning and deep learning can also be employed in the design of AI models for treatment prognosis, which take population characteristics into account to assess the probability of surgical success [21,22]. Furthermore, various applications are enhancing seizure identification and forecasting through AI, ultimately improving patient welfare through continual assessment and timely alerts regarding impending seizures [20].

In the context of PD, AI is poised to transform how doctors diagnose the condition by analysing motor symptoms and brain imaging to detect the earliest signs of PD [19]. Machine learning algorithms can accurately learn the movement dysfunction features that distinguish PD from other neurodegenerative disorders [19,23]. This not only enhances the early detection of symptoms but also facilitates more individualised treatment options. Consequently, AI is now contributing to more accurate diagnoses, improved surgical planning and more precise predictions of surgical outcomes in functional neurosurgery, benefiting patients with epilepsy and PD [20,23]. The role of AI in functional neurosurgery for epilepsy and PD is summarised in [Table/Fig-1] [2,17-21].

Aspect	Epilepsy	Parkinson's Disease (PD)
Diagnosis	AI processes EEGs and imaging data to identify abnormal brain activity during seizures [17,19]	AI detects early signs by analysing motor symptoms and brain imaging [18]
Treatment prognosis	AI uses machine learning for predicting treatment success and identifies population factors [2,20]	Machine learning improves early detection and provides more individualised treatment [18,21]
Seizure identification and forecasting	AI applications enhance seizure detection and forecasting, improving patient welfare [19]	-
Surgical planning and outcome prediction	-	AI helps in accurate diagnoses, surgical planning and outcome determination [19,21]

[Table/Fig-1]: The role of AI in functional neurosurgery for epilepsy and Parkinson's Disease (PD) [2,17-21].
AI: Artificial intelligence; EEG: Electroencephalograms

AI Integration in Vascular Neurosurgery: Enhancing Diagnosis and Treatment

In vascular neurosurgery, there has been progress in integrating AI to enhance the diagnostic and therapeutic aspects of challenging cerebrovascular diseases [24]. A variety of AI models are utilised in diagnosing aneurysms, complementing deep learning and clustering models to identify aneurysms and categorise them based on parameters such as size, shape and position, thereby increasing overall risk stratification [4,25]. Machine learning algorithms can also estimate the prognosis of aneurysm rupture, aiding clinicians in deciding whether surgical intervention is necessary based on imaging findings and individual patient factors [25,26]. Moreover, AI facilitates the estimation of recovery rates, potential for surgery and likely complications in cases of ruptured aneurysms using historical data [26].

Beyond aneurysms, AI is applied to diagnose and treat other vascular pathologies, including Moyamoya disease, arteriovenous fistulas and cerebral carotid stenosis [27]. The diagnostic imaging data for these conditions, as well as the probable complications, are evaluated by AI-implemented systems [8]. For example, machine learning approaches can estimate the likelihood and potential outcomes of treating Arteriovenous Malformation (AVM) by processing relevant patient and treatment parameters [28]. Similarly, in cases of intracranial haemorrhage, AI-based segmentation tools are employed to quantify haemorrhage volumes and identify the extent of bleeding from imaging data in a fraction of the time required by conventional methods, thus improving outcome prediction [25,28]. AI tools enhance a surgeon's accuracy in planning and add value to patient care, ultimately increasing the efficiency of vascular neurosurgical operations [4,11].

AI in Spinal Neurosurgery: Advancing Diagnosis and Treatment Outcomes

Neurosurgical applications for spinal diseases are increasingly incorporating AI, bringing new solutions to patient treatment [3,29]. One essential use is the non-invasive monitoring of intracranial pressure, where AI-based models utilise information derived from imaging and clinical data to determine pressure measurements without invasive techniques [30]. This approach not only facilitates information gathering and keeps patients safer and more comfortable but also aids in diagnosis [11]. Additionally, AI has an impact on hospital discharge planning; through various patient parameters, including recovery status and mobility levels, clinical staff are assisted in identifying the appropriate discharge plan to implement [31]. In the field of gait analysis, machine learning algorithms are used to assess patients' mobility patterns, refining the diagnosis of spinal-related conditions and informing treatment plans [11,29,31].

Moreover, AI assists in estimating potential unfavourable treatment outcomes by analysing specific characteristics in the patient's records processed by the program [8]. This helps surgeons develop strategies to mitigate the risks of adverse events [8,21]. Finally, AI-driven models are employed to predict treatment outcomes based on preoperative and intraoperative data, helping surgeons and patients prepare for the operation and postoperative recovery expectations [4]. Therefore, AI continues to revolutionise spinal neurosurgery through the optimisation of diagnoses, mechanical planning and improvements in patient success rates [8,10].

The Role of AI in Prognosis and Management of TBI Surgery

AI is becoming increasingly significant in TBI surgery, particularly in improving prognostic assessments [32]. Another area where AI is already making an impact is in the prognosis and risk of death assessment. By analysing data from multiple patients, including imaging and vital signs, AI systems can identify patterns that correlate with increased mortality, helping clinicians determine the most critical treatment strategies for TBI cases [32,33]. Currently, AI models also assist in analysing crucial physiological values, such as intracranial pressure, mean arterial blood pressure, cerebral perfusion pressure and autoregulation [26,28,30]. These tools enable continuous monitoring and timely feedback, enhancing the accuracy of treatment for TBI patients and reducing the incidence of secondary brain injuries [32,34].

In particular, AI assists in detecting loss of consciousness as a manifestation of TBI and in estimating the severity of TBI based on data from imaging, neurological examinations and patient history [33]. Advanced machine learning techniques can achieve better outcomes than traditional methods in differentiating the severity of injuries, allowing for timely interventions [24]. Furthermore, AI enables the anticipation of TBI outcomes based on preoperative, intraoperative and postoperative information [21]. It also assists clinicians in providing an individualised approach to treatment plan development, explicitly considering patient outcomes [22]. The integration of AI in the management of TBI surgery enhances diagnosis, monitoring and outcome prediction, thereby improving patient management and increasing survival rates [32]. The role of AI in the prognosis and management of TBI surgery is summarised in [Table/Fig-2] [2,20,22,24,26,28,30-32].

Aspect	Role of AI in TBI surgery
Prognosis and mortality risk assessment	AI analyses data such as imaging and vital signs to detect patterns associated with mortality risk, aiding clinicians in prioritising treatment options [30,31].
Monitoring of physiological values	AI helps monitor critical values like intracranial pressure, mean arterial blood pressure, cerebral perfusion pressure and autoregulation [24,26,28].
Detection of loss of consciousness	AI assists in identifying consciousness loss as a TBI symptom and estimates severity using imaging, neurological exams and patient history [31].
Severity differentiation	Machine learning improves accuracy in assessing TBI severity and optimises intervention timing [22].
Outcome prediction	AI predicts outcomes by analysing preoperative, intraoperative and postoperative data, aiding in individualised treatment planning [2,20].
Improved patient management	AI integration enhances diagnosis, monitoring and outcome prediction, ultimately improving patient management and survival rates [30,32].

[Table/Fig-2]: The role of AI in prognosis and management of Traumatic Brain Injury (TBI) surgery [2,20,22,24,26,28,30-32].
AI: Artificial intelligence; TBI: Traumatic brain injury

The Impact of AI on Personalised Neurorehabilitation

AI in neurorehabilitation is changing the way patients recover from stroke, TBI and spinal cord conditions [11,33,35]. These algorithms enable AI to adapt rehabilitation strategies tailored to each patient. AI systems utilise big data related to patients' mobility, neuroplasticity and rehabilitation to design exercises that mitigate the effects of various impairments [36,37]. Through built-in or wearable devices and sensors, AI technology delivers real-time status updates on the patient's condition, allowing therapists to adjust treatment plans based on current status, thereby enhancing the efficacy of the treatment [38].

Additionally, AI benefits neurorehabilitation by providing the foundation for robotic and Virtual Reality (VR) therapies [16,22]. AI-driven robotic systems assist patients in carrying out functional activities, including task-related repetitive movements as forms of therapy [5]. These systems use AI to modify exercises within VR environments according to the patient's performance level, generating motivation to regain strength [16,22]. Consequently, there is an enhancement in the models predicting patient outcomes as the AI system continuously acquires patient data, providing clinicians with better insights and yielding improved long-term results for neurological patients [8].

AI-driven Telemedicine: Transforming Neurosurgery Globally

AI-based telemedicine in neurosurgery is an innovative solution with significant potential for development, particularly in overcoming geographical barriers that can hinder patient access to care [19]. Remote consultations and diagnosis of neurological illnesses enable neurosurgeons to make appropriate assessments and vital diagnoses that could otherwise be challenging due to these barriers [39]. AI algorithms analyse diagnostic imaging and patient data, including texts, photos and videos, to diagnose conditions such as brain tumours, aneurysms and spinal cord injuries [11,17,19,25]. Telemedicine integrated with artificial intelligence technology can not only increase the accuracy of early diagnoses but also offer detailed treatment plans for patients, ensuring that each individual receives optimal care from anywhere in the world [40].

Moreover, there are opportunities to use reliable and effective AI-driven telemedicine tools for postoperative consciousness evaluation and rehabilitation of neurosurgical patients [19]. This enables continuous assessment of the effectiveness of the patient's rehabilitation phase, allowing for timely adjustments when necessary [24]. Wearable devices also assist AI in monitoring patients' vital signs, neurological responsiveness and movements. If any complications develop, the neurosurgeon can be alerted to address them promptly [36,38]. The integration of AI with telemedicine is especially beneficial in underprivileged areas where the availability of neurospecialists is limited. This implementation enhances the effectiveness of training programs and promotes access to neurospecialty care for all, ultimately democratising access to high-quality healthcare [16,40]. The role of AI-based telemedicine in neurosurgery is summarised in [Table/Fig-3] [10,15,16,18,22,23,34,36-38].

Aspect	Role of AI-based telemedicine in neurosurgery
Remote consultations and diagnosis	AI-enabled telemedicine allows neurosurgeons to remotely assess and diagnose neurological illnesses, overcoming geographical barriers [18,37].
Diagnostic imaging and data analysis	AI algorithms use diagnostic imaging, texts, photos and videos to diagnose conditions such as brain tumours, aneurysms, and spinal cord injuries [10,16,18,23].
Enhanced accuracy in diagnosis and treatment planning	Telemedicine with AI increases early diagnosis accuracy and provides detailed treatment plans, ensuring optimal care from anywhere in the world [38].
Postoperative monitoring and rehabilitation	AI-driven telemedicine tools enable continuous postoperative consciousness evaluation and rehabilitation assessment, allowing timely adjustments [18,22].
Wearable device Integration	Wearables monitor vital signs, neurological responsiveness, and movements, allowing neurosurgeons to address complications in real time [34,36].
Increased access to neurospecialty care	AI-integrated telemedicine supports underserved areas by providing access to neurospecialists and training for local healthcare providers [15,38].

[Table/Fig-3]: The role of AI-based telemedicine in neurosurgery [10,15,16,18,22, 23,34,36-38].
AI: Artificial intelligence

Future of AI in Neurosurgery: Enhancing Care and Precision

The neurosurgical applications of AI research are promising to change clinical practices and improve patient experiences in the future [4]. One promising development involves the creation of advanced machine learning algorithms aimed at analysing the vast amounts of data obtained from neuroimaging and electronic health records [16]. These algorithms are designed to detect nuances and connections that traditional analytical methods might overlook, providing timely and more accurate diagnoses of neurological disorders [39]. Moreover, the integration of AI with intraoperative imaging can offer neurosurgeons real-time guidance on how to enhance the accuracy of surgeries involving the brain and spine, while also reducing associated risks [41].

Another vital area of AI research focuses on applications built around the concepts of personalised medicine and predictive analytics [40]. By utilising AI to analyse genetic, clinical and lifestyle data, healthcare providers can create tailored treatment programs based on individual patient characteristics [15,21]. This approach can aid in therapeutic decisions, such as selecting the most suitable medication, appropriate forms of physical therapy, or the ideal exercise regimen to achieve optimal results from treatment [38]. Furthermore, predictive algorithms derived from AI can help anticipate postoperative complications, allowing for appropriate management plans [8].

Thus, as technology advances, the use of AI in neurosurgery promises not only more efficient treatment processes for surgeons but also meaningful involvement in treatment decision-making by patients themselves, facilitated by AI technology [9,16,24]. The future of AI in neurosurgery is summarised in [Table/Fig-4] [1,2,7,8,14,15,22,37-39].

Aspect	Future applications of AI in neurosurgery
Enhancement of clinical practices	AI research is poised to change clinical practices and improve patient experiences through advanced algorithms [1].
Machine learning and data analysis	Development of deeper machine learning algorithms for analysing neuroimaging and electronic health records data to provide accurate diagnoses [15,37].
Intraoperative imaging integration	Combining AI with intraoperative imaging can offer real-time guidance to improve surgical accuracy and reduce risks during brain and spine surgeries [39].
Personalised medicine	AI facilitates personalised treatment plans based on genetic, clinical and lifestyle data, optimising therapeutic approaches [2,14,38].
Predictive analytics	AI-driven predictive algorithms can help anticipate postoperative complications, allowing for tailored management strategies [7].
Patient involvement in treatment	Advances in AI technology promote efficient treatment processes and enhance patient engagement in decision-making [8,15,22].

[Table/Fig-4]: The future of AI in neurosurgery [1,2,7,8,14,15,22,37-39].
AI: Artificial intelligence

CONCLUSION(S)

In conclusion, the application of AI in neurosurgery represents a new model for enhancing diagnostic and treatment efficiency, as well as improving patient outcomes across all subfields of neurosurgery. Recent technological advances, particularly in applications of AI including machine learning algorithms and topic modeling, have great potential to improve and enhance the overall surgical plan before, during, and after procedures, thereby minimising postoperative complications and elevating patient care standards.

Of course, concerns about over-dependence on AI remain significant. However, fostering collaboration between AI systems and surgeons can enhance training, decision-making, and ultimately lead to better surgical outcomes. Lastly, ongoing research and implementation of AI in neurosurgery offer hopeful prospects for precision medicine and improved patient care, paving the way for a revolution in the field and clearly serving the interests of both clinicians and patients.

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PLAGIARISM CHECKING METHODS: [Jain H et al.]

- Plagiarism X-checker: Jan 18, 2025
- Manual Googling: Apr 17, 2025
- iThenticate Software: Apr 19, 2025 (10%)

ETYMOLOGY: Author Origin

EMENDATIONS: 5

AUTHOR DECLARATION:

- Financial or Other Competing Interests: None
- Was informed consent obtained from the subjects involved in the study? NA
- For any images presented appropriate consent has been obtained from the subjects. NA

Date of Submission: **Jan 16, 2025**
Date of Peer Review: **Mar 20, 2025**
Date of Acceptance: **Apr 22, 2025**
Date of Publishing: **Sep 01, 2025**