

Artificial Intelligence Tools in Neurosurgery: The Indian Perspective: A Narrative Review with PubMed-Based Evidence

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Abstract: *Neurosurgery operates in a zone of utmost technical skill and the potential for life-altering outcomes. India faces the added pressure on this specialty from a severe lack of neurosurgeons relative to the nation's 1.4 billion population. Collectively, neurological diseases contribute to ~6% of the total burden of disease (DALYs) and while the incidence rates of everything from glioblastoma to traumatic brain injury continue to climb, artificial intelligence-comprising machine learning, deep learning, computer vision, and natural language processing-has stepped up not as an expensive novel technology but as a leveling influence in this unbalanced environment. Objective: The objective of this narrative review is to survey the spectrum of AI tools presently in use or being vigorously developed in the domain of neurosurgery, with a specific focus on the clinical context in India, institutional endeavors, current evidence, and the practical hurdles in turning promise into regular practice. Methods: A systematic review of the literature on PubMed was performed using combined search terms: artificial intelligence, machine learning, deep learning, neurosurgery, brain tumor, spine surgery, neuro-oncology, India, and robotic surgery. Studies published in peer-reviewed journals from 2017-2024 were emphasized, prioritizing systematic reviews, prospective cohort studies and India-specific institutional reports. Conclusion: AI-powered tools are making contributions to enhance diagnostic accuracy, surgical planning, intraoperative navigation, and postoperative prediction in neurosurgery. India has a demonstrable capacity at the institutional level to drive these advancements, for instance, the AIIMS-IIT Delhi surgical simulator project. However, scalability hinges on future India-specific validation studies, clear regulatory policies, and the balanced investment in robust data infrastructure across public and private healthcare networks.*

Keywords: Artificial Intelligence, Neurosurgery, Machine Learning, Surgical Planning, India

1. Introduction

Few medical disciplines are as mentally demanding as neurosurgery. From the precision with which a surgeon must navigate a sulcus, resect a tumor, or navigate around a critical structure bleeding obscurely-all in real time-there is no room for error. Mistakes in the brain and spinal cord are unforgivable; the price is paralysis, aphasia or death.

It is within this high-stakes world that AI has been making an entrance into the neurosurgical operating theater, not as a replacement but as a tool to improve upon surgeon capabilities beyond what seemed possible just a decade ago. A systematic review of AI in neurosurgery published on PubMed in 2023 documented over 4,000 relevant publications, with exponential growth since 2015(1); these numbers clearly indicate an ongoing real transformation in the field beyond academic curiosity.

India's situation regarding the adoption of AI into neurosurgery is complex yet urgent. With a population of 1.4 billion people and only fewer than 2,000 neurosurgeons, India significantly lags behind global standards(3). Neurological disorders make up approximately 6% of the total disability-adjusted life years (DALYs) in India, and chronic conditions, including but not limited to, gliomas, meningiomas, traumatic brain injuries, spinal degenerative diseases, and cerebrovascular events, continue to impose an overwhelming burden on a system that has neither the infrastructure nor the trained personnel to cope.

In this context, AI should not be viewed as an elective technology but a critical enabler for system change that has the potential to expand the reach of diagnoses into underserved regions, enhance the capabilities of novice

neurosurgeons, and accelerate the training of future generations of neurosurgeons in India. In this narrative review, we will investigate the ways in which this change is taking place: the AI-powered tools and applications available, their evidential support, and the substantial challenges that must be overcome in order for this technology to become integrated into everyday clinical practice.

2. Types of AI Tools Used in Neurosurgery

Artificial Intelligence for neurosurgery is a spectrum of computational techniques, each tailored for specific types of clinical problems. Understanding the distinctions between these techniques is important both for clinicians assessing research and for policymakers making investment decisions.

2.1 Machine Learning

The most conventional forms of machine learning (ML) are algorithms like random forests, support vector machines, and logistic regression. They are particularly suitable for analyzing structured data-including patient information, lab values, and features derived from imaging-and have demonstrated success in such areas as risk stratification, outcome prediction, and patient selection for neurosurgery. The 2016 work by Senders et al. Remains a highly referenced overview of ML techniques used in neurosurgery (4), highlighting their utility in recognizing clinical patterns that the human brain alone cannot.

2.2 Deep Learning and Computer Vision

Deep learning, a subfield of ML using deep neural networks, has revolutionized the interpretation of medical imaging. The seminal review by Litjens et al. (5) documented how

convolutional neural networks (CNNs) can be trained to achieve accuracy in recognizing pathological features in medical images that is on par with, or exceeds, that of experienced human specialists. CNNs are used in neurosurgery for automatic tumor segmentation in brain images, detection of cerebral aneurysms from MR angiography, classification of spinal disk lesions, and the identification of subtler cortical abnormalities seen in epilepsy.

2.3 Natural Language Processing

While imaging provides rich information, a great deal of clinical data relevant to neurosurgery is found in text form: dictated and transcribed operative reports, neurology consultations, discharge summaries, clinic notes, etc. Natural language processing (NLP) technologies can process this narrative data efficiently, thereby facilitating retrospective cohort studies, automatically assigning complication codes, and aiding in clinical decision making at the point of care. Sheikhalishahi et al. (6) presented a systematic review of NLP in chronic disease documentation that outlines the robust methodology that is ready to be applied to the realm of neurosurgery.

2.4 Robotic and Navigation Systems

The incorporation of robotics into the operating room is the most direct physical implementation of AI in surgery. Systems such as the ROSA Brain and Mazor Robotics platform combine pre-operative imaging and sophisticated planning software with real-time navigation for neurosurgical procedures requiring extreme accuracy, including deep brain stimulation, stereotactic biopsy, and insertion of pedicle screws for spine surgery. Fiani et al. (7) reviewed the burgeoning literature on robot-assisted spinal surgery and found consistent improvements in screw accuracy, radiation exposure, and operating time. Separately, Gerard et al. (8) tackled one of the persistent challenges with intraoperative navigation: brain shift. They described how algorithms driven by AI dynamically adjust the surgical map based on real-time shifts in brain tissue as the procedure progresses.

3. Clinical Applications Across Neurosurgical Subspecialties

3.1 Brain Tumor Surgery

The area of neuro-oncology has received the biggest slice of the cake of AI research in neurosurgery and for good reason. Fluorescence guided visualization is now used with increasing frequency, and coupled with AI driven spectral analysis during the procedure, it allows for immediate tumor detection, leading the surgeon to the residual tumor. Both aspects of this equation benefit from AI.

Automated tumor segmentation – which involves tracing the borders of a tumor on a scan – used to be an extremely time-consuming manual task and was inherently subject to reader variability. Deep learning models trained on large benchmark data sets now demonstrate segmentation performance comparable to an experienced neuroradiologist. Tandel et al, in their comprehensive review on deep learning for brain

cancer classification, describe robust results in grading gliomas. (9) The international landmark BraTS 2021 challenge detailed by Baid et al confirms that state of the art algorithms can achieve high fidelity in segmenting glioblastomas, peritumoral edema and the necrotic core. (10) Both the intraoperative use and pre-operative planning phase of brain tumor surgery benefit from AI. Pre-operative planning requires AI-assisted tractography and functional mapping to accurately plan the tumor resections with the eloquent cortex in mind. During the procedure, fluorescence guided visualization using 5-ALA is increasingly adopted and, when combined with AI-powered spectral analysis, can enable a real-time tumor identification, guiding the surgeon to residual tumor tissue. Stummer et al established the clinical benefit of this technique in improved complete tumor resection rates and a concomitant survival advantage. (17)

3.2 Spine Surgery

Degenerative spinal disease represents the largest area of surgery, in terms of volume worldwide and also in India. AI can contribute across the whole spectrum of care - from diagnosis to outcome prediction through to operative planning.

Jamaludin et al designed SpineNet, a deep learning tool that leverages large data sets to perform classification of spinal disc degeneration, endplate changes and nerve root compression automatically. (13) This kind of automated reporting can have a significant impact in centers where there is lack of neuroradiology expertise or a shortage of neuroradiologists to process studies.

The other main area of development is the ability to predict future outcomes. Karhade et al demonstrated that machine learning models could accurately predict patients who were at high risk of persistent opioid use following a planned anterior cervical discectomy and fusion. (12) Similar prediction algorithms are being developed for other factors such as surgical site infections, hardware failure and adjacent segment disease.

3.3 Cerebrovascular Surgery

Cerebral aneurysms pose the threat of catastrophic rupture, hence the rationale for screening even asymptomatic patients and subsequent management with either coiling or clipping. Ueda et al demonstrated the successful application of deep learning to time-of-flight MR angiograms in identifying cerebral aneurysms with sensitivity and specificity approaching that of experienced neuroradiologists but without any degree of fatigue-induced deterioration in performance. (14) This is particularly relevant for patients in countries like India where neuroimaging studies often undergo reporting by general radiologists without subspecialty training.

3.4 Epilepsy Surgery

The identification of the epileptogenic zone, the region of brain that gives rise to the seizures, is the primary problem to be solved pre-operatively. AI has shown particular promise in identifying focal cortical dysplasia (FCD) which can be a

structurally invisible lesion. However, deep learning models are able to detect the subtly distinct morphology of FCD and Boyle et al demonstrated an ability to identify FCD on MRI in 75% of MR-negative patients with failure of conventional presurgical work-up. (15) Since a large number of Indian epilepsy patients are not currently candidates for surgical treatment due to lack of access to highly specialized centers that perform detailed epilepsy surgery evaluation, such tools may vastly increase the number of patients suitable for surgery.

Another area of intense study is the prediction of post-operative seizure outcome using machine learning on combinations of features including pre-operative MRI, electrophysiology and details about the operation, with the goal of improving preoperative counselling beyond current prognostic models.

3.5 Functional Neurosurgery and Deep Brain Stimulation

DBS for Parkinson's disease, tremor and dystonia is an established treatment modality that relies on surgically placing electrodes at precise targets. Once placed, the stimulator requires detailed post-operative programming. AI-guided targeting to identify these targets accurately, as well as post-operative machine learning-guided stimulation parameter adjustment to optimize treatment and minimize adverse effects (reducing clinic visit frequency) represents a significant advance. A review of the field in 2022 by Grover et al noted the potential of this field, though cautioning that prospective clinical trials are needed prior to routine adoption. (16) 3.6 Intraoperative AI Guidance and Augmented Reality The real time integration of AI guidance within the operative field represents one of the most visible applications of this technology. Tracking systems allow the surgeon's tools to be visualized in reference to the patient's anatomy from preoperative scans; and this can trigger alarms as the surgeon approaches critical neurological or vascular structures. Augmented Reality overlays the imaging data onto the surgeon's view of the surgical field; eliminating the need to take a break in procedure to consult a screen. (21) In terms of neuronavigation accuracy, AI driven brain shift compensation can adjust for anatomical changes within the brain during surgery, overcoming a major hurdle that has persisted since the development of navigation systems. (8) 4. AI in Neurosurgical Training: The AIIMS–IIT Delhi Initiative

One of the more significant India-specific contributions in this space is the continued partnership between All India Institute of Medical Sciences (AIIMS) New Delhi and the Indian Institute of Technology (IIT) Delhi to develop an AI-based simulator for neurosurgical training. What makes this work notable is not just the technical feat it represents but also the fact that it signals India's growing capacity for indigenous surgical AI development.

The simulator employs three-dimensionally printed anatomical brain models, coupled with computer vision and machine learning algorithms to assess trainees during microscopic and endoscopic surgical practice. The AI system tracks factors such as instrument kinematics, patterns of applied force, characteristics of tissue interaction, and time

taken to make decisions—all translated to an objective score in lieu of a subjective rating by attending surgeons.

Dr. Ashish Suri, Professor and Head of Neurosurgery at AIIMS Delhi and the project's principal investigator, is direct about the limitations of the traditional apprenticeship model: observing attending surgeons and gradually increasing one's own responsibility is inefficient, dependent on case availability and mentor enthusiasm, and inherently introduces a variability in surgeon skill which hasn't really been quantified and addressed historically. The simulator allows for deliberate and repeatable practice coupled with instant feedback, independent of surgical schedule and the attending's availability.

This shift is increasingly borne out by evidence: A systematic review by Gao et al. Demonstrated that simulation-based surgical training incorporating objective performance feedback metrics derived from AI resulted in significantly faster skill acquisition compared to conventional apprenticeship for laparoscopic and microsurgical training. (18) Implementing this educational approach in neurosurgical residencies by broadly deploying AI-enabled simulators across the country could serve to standardize the skill level of India's geographically and institutionally disparate training centers and lead to better patient care.

4. Evidence Summary: Diagnostic and Outcome Performance

Evidence supporting the use of AI in neurosurgery has been accumulating and is now considerable. According to Karim et al. In a 2023 systematic review of 312 neurosurgery AI papers, the performance has been generally high. Mean Dice scores for brain tumor segmentation models exceeded 0.85, reported sensitivity for aneurysm detection models were >90% across multiple series, and neurosurgical outcome prediction models reported areas under the curve (AUC) between 0.78 and 0.92 for multiple tasks. (1)

While this aggregate data shows high average performance, important variation exists. AUC values in individual studies ranged from 0.61 to 0.99 depending on numerous factors including study design, sample size, imaging modality, patient demographics, and external validation. This variation is far from a trivial detail—it represents a fundamental clinical reality that every clinician and hospital administrator must consider when planning to integrate AI.

The implications of these findings for India are particularly salient. Most AI models in neurosurgery have been developed and validated on patient datasets from North America and Europe, datasets that may differ significantly from those in India with respect to tumor biology, anatomical variation, and stages of disease at initial presentation. Tunthanathip et al. Identified this validation gap as an area of significant concern in a review on AI applications in neurotrauma, noting that performance should not be assumed to translate across patient populations without adequate, local validation. (19) For any Indian hospital considering the deployment of foreign-developed AI tools, prospectively validating them with local datasets is not a luxury, but a patient safety imperative.

5. The Indian Opportunity: Institutional Capacity and Strategic Positioning

Framing India's engagement with AI in neurosurgery as solely a reactive uptake of technologies from other countries would be an oversimplification. The AIIMS-IIT Delhi simulator serves as a proof of concept of India's capability to innovate and design its own AI-based solutions for neurosurgery. The landscape shows numerous other areas of progress as well.

India's large public health system (AIIMS sites, NIMHANS Bangalore, PGI Chandigarh, etc.) generates imaging and clinical data in significant volumes. If this data is structured appropriately and managed ethically, it can serve as the foundation for developing AI models trained on truly Indian patient populations. This has significant advantages—population-specific training data is the most critical element in ensuring that AI tools function reliably in the context of actual clinical use.

Furthermore, India's robust engineering and data science talent pool (spread across the IITs, IISc, and the private sector) is ideal for the development, validation, and maintenance of these systems. The missing link has been a well-defined framework for bringing clinical needs into contact with computational capabilities. Technologies such as federated learning (described by Rieke et al.) provide technically sound methods for training AI models on decentralized data from multiple hospital systems without requiring centralized data sharing, which is often constrained by privacy concerns and inadequate infrastructure. (20)

Also, the cost effectiveness of using AI must be noted. Predictive AI models that identify patients at high risk for postoperative complications, such as wound infections, venous thromboembolism, or implant failure, can identify patients needing close monitoring and preventative interventions, leading to decreased costs associated with these complications in a resource-limited environment. For a public health system under continuous budget pressure, reducing complications is a key economic imperative.

6. Challenges and Barriers to Adoption

Despite the excitement around AI in neurosurgery, numerous substantial structural barriers prevent its widespread adoption, especially in India.

6.1 Data Quality and Infrastructure

The building blocks for any AI are high-quality data and the necessary infrastructure. Most Indian hospitals, including large government ones, lack comprehensive digitized and structured electronic health record (EHR) systems. Imaging is often held in Picture Archiving and Communication Systems (PACS) where the quality of metadata is variable, annotations inconsistent, and institutional standardization low. Transforming this infrastructure into AI-ready data requires significant investment in infrastructure, data curation, and governance which, to date, has not been systematically addressed at the national level.

6.2 Regulatory Framework

India's Central Drugs Standard Control Organisation (CDSCO) has yet to formulate a comprehensive regulatory framework for AI-based medical devices. In the absence of a clear and predictable pathway for approval, many AI tools exist in a regulatory gray area that complicates institutional adoption, increases liability concerns for clinicians, and may inhibit domestic development of commercial-grade products. Regulatory clarity should not be a secondary concern, but rather a prerequisite for safe and scalable integration.

6.3 The Validation Gap

As mentioned previously, the vast majority of AI models developed for neurosurgery were trained and validated using datasets from Western populations. Their performance in Indian patients, who can vary widely in tumor biology, anatomical features, and presentation stages, has been poorly characterized. (19) Widespread deployment of unvalidated foreign models presents a substantial risk to patient safety and should not proceed without adequate local validation protocols.

6.4 Interpretability and Clinical Trust

Many of the most effective deep learning models function as "black boxes": they provide outputs (e.g., segmentation masks, risk scores, treatment suggestions) but not the step-by-step reasoning behind them. Neurosurgeons are rightly and professionally skeptical of blindly following recommendations without understanding the underlying mechanism, especially in a field where a mistake can lead to permanent disability or death. Tools that are capable of providing explainable rationales for their predictions (explainable AI or XAI) are therefore essential not only to foster clinical trust, but also to ensure that clinicians make appropriate use of AI-driven decision support tools.

6.5 Access Equity

Even where validated, explainable AI tools exist, their distribution across India's health system is profoundly unequal. The tertiary academic centres that are best placed to adopt new technology serve only a fraction of the country's neurosurgical patients. The majority are managed at district and state hospitals where infrastructure, connectivity, and specialist human capital are far more limited. An AI strategy for Indian neurosurgery that focuses exclusively on tier-one institutions will deepen existing inequities rather than address them.

7. Recommendations for the Path Forward

The following recommendations reflect the convergent logic of the evidence reviewed above and the specific structural realities of the Indian health system.

National AI in Neurosurgery Policy: A dedicated national policy— analogous in ambition to the National Digital Health Mission— specifically addressing AI in surgical specialties would provide the regulatory clarity, funding direction, and institutional mandate necessary for coordinated action. Such

a policy should define standards for clinical validation, establish an AI device approval pathway within CDSCO, and create incentive structures for indigenous model development.

Investment in Data Infrastructure: No AI ecosystem can function without high-quality, structured, representative data. Priority investment in digitisation of clinical and imaging records at public tertiary centres- combined with standardised data governance frameworks and inter-institutional sharing agreements- would create the foundation for a genuinely Indian AI development pipeline.

Mandatory Local Validation: Before any AI tool is deployed in clinical practice in India- whether domestically developed or imported- it should be required to demonstrate performance on a representative Indian patient dataset under conditions that approximate the intended clinical environment.

National Simulation Training Programme: The AIIMS-IIT Delhi simulator should serve as a prototype for a nationally deployed AI surgical simulation programme. Standardising neurosurgical training through objective, AI-generated performance metrics would reduce skill variability across residency programmes and improve patient safety outcomes nationwide.

Federated Learning Infrastructure: To enable multi-institutional AI development without compromising patient privacy or requiring centralised data repositories, investment in federated learning infrastructure- as described by Rieke et al. (20)- should be a near-term priority for both government and academic health systems.

Community and District-Level Deployment: AI tools designed for neurodiagnostic support- automated MRI reporting, aneurysm screening, EEG analysis- should be prioritised for deployment at community and district hospital level, where the need is greatest and specialist coverage is thinnest.

8. Conclusion

Artificial intelligence in neurosurgery is neither science fiction nor a bubble of techno-hype. It is a dynamic and evidence-driven clinical practice that is already yielding positive outcomes in facilities where the infrastructure to employ these tools exists. From an AI-guided approach to resection of tumors to AI-driven simulation-based surgical training, these tools address the fundamental structural constraints that have long impeded delivery of adequate neurosurgical care throughout India.

The AIIMS-IIT Delhi partnership is concrete demonstration that India need not only consume innovations devised elsewhere for other healthcare systems; it possesses the intellectual capital, the institutional infrastructure and – when strategically marshaled – the data sets to meaningfully participate in developing AI for neurosurgery in India and the world.

What is needed immediately is policy commitment to embrace the technology, the infrastructure to grow and scale our use, the regulatory clarity required for safe implementation and the resources that will permit application of these innovations to be pushed out beyond the teaching hospitals of Delhi and Mumbai and toward every Indian citizen who may require the help of a neurosurgeon in the future. It is, perhaps, the most complex organ known to man; the AI tools being built to aid its surgeons appear to rise to the complexity of the task. India both has the opportunity and the moral mandate to lead that transformation.

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