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Research Article

Artificial Intelligence in Neurosurgery: Pre, Intra and Post Operation Applications

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Abstract

Background: Artificial intelligence (AI) and Machine Learning (ML) have recently forayed into human healthcare. There is a growing interaction of AI in several neurological and neurosurgical practices. The main goals of this study are to ascertain the different uses of AI in the elaborate field of Neurosurgery and elucidate its uses. Additionally the study also quantify the existing use of AI assisted robotic neurosurgery.

Materials and Methods: A literature review using keywords 'Artificial Intelligence' and 'Neurosurgery' was conducted. Data charting was done using a structured format as per the Joanna Briggs Institute (JBI) methodology for scoping reviews. The articles retrieved were segregated into various subheadings (pre, intra and post-operative) and a review based on each topic was conducted.

Results & Discussions: AI has the potential to expand surgeons' skill sets during pre-, intra-, and postoperative neurosurgery. AI has proved to be essential in the generation, processing, and storage of clinical and experimental data. Additionally, neurosurgery and AI can form a symbiotic connection in which neurosurgery helps AI push the frontiers of the field and AI helps neurosurgery to create more reliable and superior algorithms.

Conclusions: AI can reduce the healthcare costs and errors or delays in medical management. By enhancing diagnostic and prognostic outcomes in clinical treatment and assisting neurosurgeons with decision-making during surgical interventions to improve patient outcomes, AI complements neurosurgeons' skills in providing patients with the best interventional and non-interventional care possible. Further research, financing, and multidisciplinary collaboration is required for wider societal impact.

Keywords: Artificial Intelligence; Machine Learning; Neurosurgery

Introduction

"Artificial intelligence is defined as the theory and development of computer systems able to perform tasks that normally require human intelligence, such as speech recognition, visual perception, decision-making and translation between language" [1]. The advancement in modern medicine, increase in the number of patients and a limited number of neurosurgeons, the role of AI becomes accentuated. The instruments of AI and its subdomains are being integrated in various aspects of neurosurgery to improve clinical information translation enveloping diagnostics, surgery, patient management and prognosis etc [2]. AI was first described in 1950 but because of several limitations, it was not accepted in the field of medicine [3]. In the early 2000, many of these limitations had already been overcome and during this period the initial part called the Machine Learning (ML) was replaced by Deep Learning (DL). Computer vision also came into practice where the computer integrated the data through images and videos allowing AI to self-learn and also to decode complex algorithms. Through this, a new age of medicine has been initiated where AI can be applied for clinical practice through efficient risk assessment, accurate diagnosis and quality workflow efficiency [4].

In the field of neurosurgery, the use of AI is a promising advancement. In neurovascular procedures like stroke thrombectomy, carotid artery stenosis, endovascular coiling and also for the interventional techniques, the catheter control and attenuated support are provided by AI-enabled robotic equipment. AI is also making huge developments in the field of neuroradiology and through deep machine learning and connected neural networks, AI has proceeded to make an accurate identification of pathologies , analyzing the MRIs, clinical data, other radiological images and help in the diagnosis. AI plays an important role in assessing the element of surgical decision making and the outcome by compiling the cohort studies with the patient history. The AI-ML algorithms are used to understand the outcomes of various procedures like spinal cord surgery traumatic brain injury, movement disorders and hydrocephalus with a median accuracy of 94.5% [5]. AI has also been used to assess surgical site infection after spinal injuries with a positive predictive value of 92.56% and negative predictive value of 98.4% [6]. AI stands out as the finest alternative in terms of accuracy and cost-effectiveness in the current era of rising population, rising diseases, and declining resources. The present paper aims to discuss and highlight the different uses of AI in preoperative, intraoperative, and postoperative neurosurgery and elucidate its uses.

Materials and Methods

A literature search from Jan'2010 till Dec'2022 on the scope of AI in neurosurgical procedures. A total of 2386 articles were found using the databases Medline, Ebscohost, Pubmed, and Google Scholar. Articles were filtered and characterized into the preoperative, intraoperative, and postoperative phases and the outcomes were measured. Articles published before 2010 whose primary focus was not distinct were excluded from the study. The search algorithms with the keywords used were "Artificial Intelligence" AND "Neurosurgery" ; "Artificial Intelligence" AND "Brain Research" ; "AI" AND "Neurosurgery" ; "AI" AND "Preoperative phase" ; "AI" AND "Intraoperative Phase" ; "AI" AND "Postoperative phase" ; "Artificial Intelligence" AND "Neurosurgery" AND "Global Uses" ; "Recent Developments" AND "AI" AND "Neurosurgery". A data extraction parameter was developed to extract relevant data from the studies, including the author(s), year of publication, country, Navigation problem faced, Remarks and PubMed ID provided. Two independent reviewers extracted the data from the included studies. After the studies are selected, the data can be extracted and organised using a data charting form. Microsoft Endnote was used as a reference manager and citation tool for organization of all references.

Results

The initial search identified 2386 articles from electronic databases. As a result of our final screening, there were 38 articles out of which 12 articles were dedicated for AI used around the world, 8 articles for areas of the brain frequently operated with AI, 2 articles for role of AI in preoperative phase, 5 articles for role of AI in intraoperative phase, 3 articles for role of AI in postoperative phase, 8 articles for AI in research models of brain (Figure 1). In the preoperative, intraoperative, and postoperative phases, the extent of AI utilization was investigated. The recent advancement of AI has made its impact worldwide including various countries like China, India, Middle East and several others that are both developed and developing. The use of AI in China proved to be a beneficial tool to improve the efficacy and has had an impact in all fields of medicine including diagnostics, surgery, therapy and even traditional Chinese Medicine [7]. Neurosurgical advancement in AI including ML algorithms which can automatically recognise and analyze the medical text data of patients with Intra Cranial Hemorrhage [8]. A global study showed that the main barrier to integrating AI technologies in low and middle income countries' neurosurgical practice is a shortage of competent manpower, equipment and funds. The absence of expertise in this field highlights the lack of knowledge regarding AI in healthcare [9].

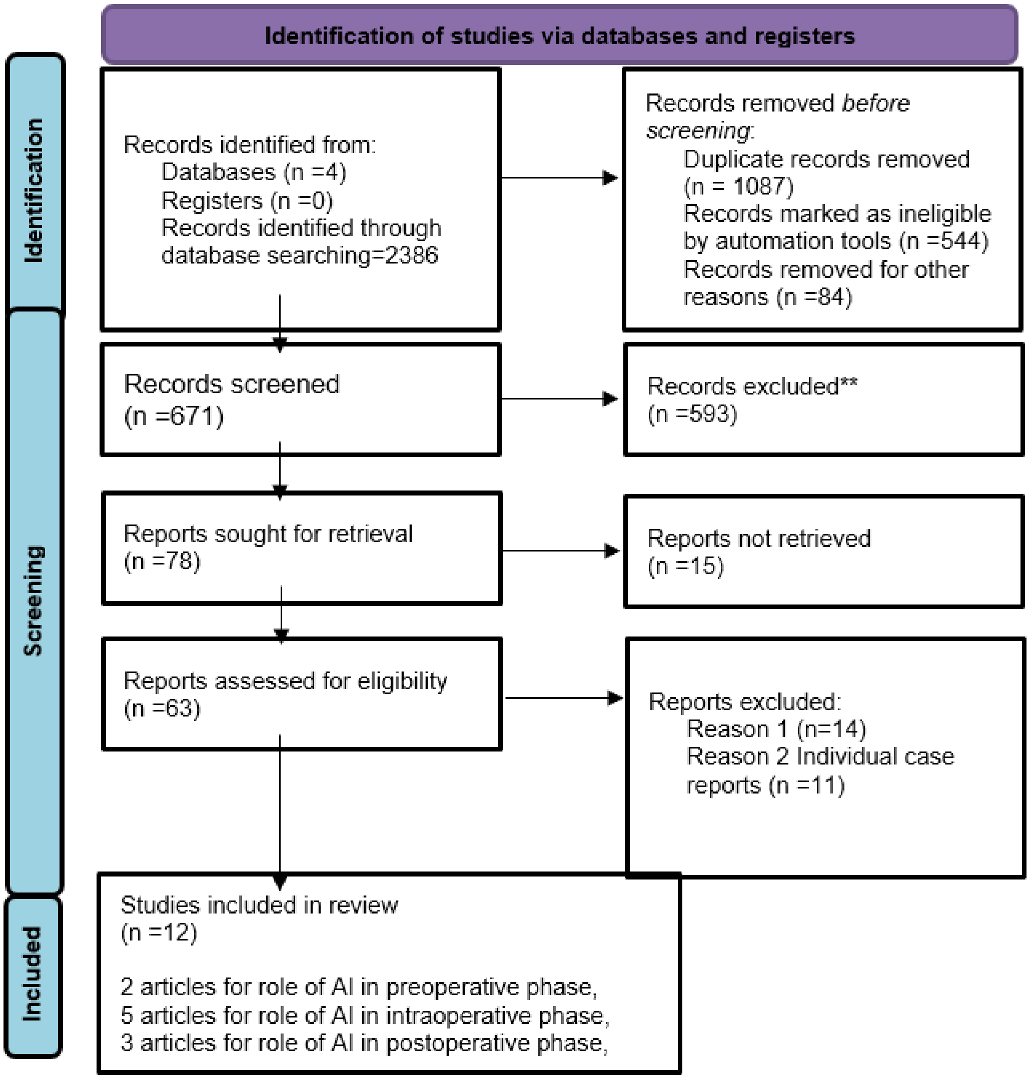

Figure 1: Study selection process according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flowchart. Reason 1- Subject not relevant to Neurosurgery. Reason 2- Individual case reports

*Consider, if feasible to do so, reporting the number of records identified from each database or register searched (rather than the total number across all databases/registers).**If automation tools were used, indicate how many records were excluded by a human and how many were excluded by automation tools.

Recent Developments of AI in Neurosurgery

Neurosurgery requires the right kind of data collection that will facilitate the treatment, care and rehabilitation of patients. Influence of AI in neurosurgery has been rising during the last decades. AI has helped neurosurgeons further develop their skills, which will improve the treatment process and make the surgeon's work easier. AI plays an important role in data collection, processing and storage. The use of artificial intelligence will reduce healthcare costs in neurosurgery and provide a higher quality neurosurgical service to the wider community. AI will enable the development of neurosurgery, and neurosurgery will help AI create new algorithms. Thus, this symphony has led to effective recent developments. Diagnostic problems were solved primarily by neuroimaging data and electroencephalography. While some studies addressed the planning of the preoperative process using image analysis, some studies attempted to predict outcomes of neurosurgical treatment. Research shows that AI/ ML can help solve clinical problems. In the majority of the studies AI/ML results were significantly more accurate than the conclusions made by clinical experts [8,10].

Comprehensive Analysis of Artificial Intelligence in Various Disease Models (Tables 1-4)

Study	Diagnostics	Accuracy Statistics	Intraoperative phase	Accuracy Statistics
Williams S et al 2021	Brain tumors identification with routine blood tests	96%sensitivity 74%specificity	Determination of the line between tumor and healthy tissues with HSI	-
	Blood fluorometric analysis to detect glioblastoma	92%accuracy	DL platforms with 3 convolutional layers for HSI analysis	Background identification-98%, Tumor identification-42
	Arrangement of the most convenient and useful sequence for MRI brain imaging	-	Raman scattering microscopy to determine the line between tumor and healthy tissues	97.5%sensitivity 98.5%specificity
	ML algorithm to detect IDH1 mutations in low-grade gliomas with MRI brain imaging	high accuracy	Intraoperational workflow phases and steps determination with endoscopic transsphenoidal pituitary adenoma resection video analysis	Phases determination-91% Steps determination-75%
	Determination of IDH1 mutation,1p/19q codeletion and MGMT Methylation Status	-	NeuroArm-surgical robot for microsurgeryimage-guidance	-
Mofatteh M et al, 2021	Segmentation of tumors	-	Label-free optical imaging to predict the tumor diagnosis in less than 150 seconds during the operation	95%
	Classification of tumors	86%		
	Glioma identification	-		
	Segmentation of gliomas and other brainstem tumors with MRI	-		
	Tumor diagnosis with CT	82.20%		
Dundar TT et al, 2022	MRI to find the best path for reaching the tumor and avoiding critical locations	-	Neuronavigation of the surgical path	-
Britz GW et al, 2019	Glioma identification using the MRI data	-	Operating microscopes with the ability to semiautomated change of positions	-
	Classification of tumors		AI models for intraoperative imaging	
	Segmentation of tumors		AI models to alert the surgeons about critical structures	
			CyberKnife for frameless stereotactic radiosurgery	

Table 1: AI for Neuro-oncology.

Paper	Diagnostics		Intraoperative phase
Bravo J et al , 2022)	● ML algorithms to determine the Aneurysm rupture status and risk for 5 years ● HeadXNet DLNN analysis ● NN model for <2 mm intracranial aneurysms detection ● AI model for prediction of SAH risk dependence from aneurysm's size ● DLNN for prediction of maturation of AVF /80+% accuracy/ ● DLNN for reconstruction of CTA ● AI-based 3D angiography as safer and reliable method for visualization of brain vessels ● DL algorithms(BioMind) to predict ICH expansion ● DL algorithms for determination of 3mL+ ICH ● ML algorithm for neoplastic and non-neoplastic ICH differentiation ● DL algorithm for differentiation of Moyamoya disease and atherosclerosis using T2-weighted images analysis		● Flow-driven endovascular navigation tool used to make deeper brain parts more approachable ● Steerable endovascular microcatheter for intracranial aneurysm treatment ● RVIRC for catheter and guidewire application for intracranial aneurysm treatment ● CorPath GRX robotic system modification for neurovascular catheterization ● CorPath GRX for CAS ● Magellan Robotic System for carotid artery stenting ● Force-sensing feedback framework for catheterization ● Robotics with three-dimensional preoperative imaging for catheterization
Wenchun Jiang et al, 2022	2D and 3D image processing		● Brain monitoring ● Detection of the changes of electrophysiological signals ● Nerve damage prevention ● Explanation of clinical importance of signal changes ● Help to decide on surgical strategies
Mofatteh M, 2021	● Vasospasm prediction after aneurysmal SAH	-	-
	● Prediction of brain tissue damage after acute ischaemic stroke	-	
	● Acute Ischemic Stroke diagnosis	56% accuracy	
	● Intracranial aneurysm diagnosis	90% accuracy	
Britz GW et al, 2019	● Acute Ischemic Stroke diagnosis ● Intracranial aneurysm diagnosis ● Vasospasm prediction after aneurysmal SAH ● Prediction of brain tissue damage after acute ischaemic stroke		-

Table 2: AI for endovascular diseases.

Paper	Diagnostics	Accuracy Statistics
Mofatteh M, 2021	Localisation of epileptogenic zone	-
	Candidate selection for epilepsy surgery	-
	Classification of epilepsy	60%
	Affected brain hemisphere lateralisation with MRI in TLE	95.8%
Britz GW et al, 2019	Localisation of epileptogenic zone	-
	Candidate selection for epilepsy surgery	

Table 3: AI for epilepsy.

Citation	Diagnostics	Intraoperative phase
Mofatteh M et al, 2021	Classification of lumbar disk degeneration	-
	Osteoporotic vertebral fracture classification based on pain level	
	Survival prediction of TBI patients	
Britz GW et al, 2019	-	MazorX for pedicle screw placement operation calculation and guidance

Table 4: AI for other diseases.

Role of AI in Preoperative Phase

In the preoperative phase of neurosurgical procedures, AI plays a big role in helping surgeons diagnose conditions, and come up with prognosis. Thus, it can assist in selecting the right treatment in individual cases. AI has been successfully used in the diagnosis of diseases such as epilepsy, brain tumors, autism, neurodegenerative diseases such as Alzheimer's Disease, Huntington Disease, and Parkinson's Disease. Studies have shown its remarkably high accuracy in diagnosing and characterizing brain tumors. By the help of ML (Machine learning), algorithms specialists have effectively predicted tumor grades, and detected metastatic progression with routine blood tests. Glioblastomas, meningiomas, pediatric posterior fossa tumors and other CNS tumors have also been demonstrated in such a way. In comparison with ML and AI, Deep Learning (DL) has become a more widely considered model for brain tumor classification. It is a subset of ML which simulates the human brain behavior with minimal human interference or handcrafted features. A prospering example of DL, Convolutional Neural Network or CNN suggests a segmentation-free method of brain tumor detection. The latest research of a 23-layer CNN indicated up to 97.8% and 100% prediction accuracy for multiclass brain tumor classification [11].

Although surgeons rely on their experience and knowledge, the position and boundaries of a tumor might occasionally be difficult to ascertain. This being said, AI can be more specific and less time-consuming as compared to human pathologists and surgeons. AI can detect precise abnormalities that are out of perception for even the most trained eyes and operate in the most delicate and inaccessible areas to the human hand. The WHO (World Health Organization) gradings state that Al diagnosis results outperform radiologists in many disease predictions. In the diagnosis of TLE (temporal lobe epilepsy), Al achieved a 95.8 % accuracy compared to physicians (66.7 %) using MRI data. TLE is the most common type among adult epilepsies. Another research on chondrosarcoma diagnosis in comparison between the ML and neurosurgeons has proven the above mentioned. The ML model has correctly diagnosed nine cases out of ten. Whereas the diagnostic accuracy of the neurosurgeons varied between 40% and 85% [12]. Besides the diagnostic aspect, AI and radiomic features also help with the effective prediction of chondroma treatment. This is considered in both pre- and post- operative phases of surgical appointment.

Role of AI in Intraoperative Phase

Countless patients suffer every year from mistakes made by a wide variety of medical personnel. From nurses to neurosurgeons. Errors can be varied - both during the diagnosis and during the operation. However, such errors can be avoided by the integrated use of AI [13]. AI is undoubtedly useful in neurosurgical interventions. It helps specialists prevent technical errors and makes it easier for surgical access. According to medical error statistics, individuals who need to have surgeries on their skulls are significantly more difficult to handle, and there are far more mistakes than when a pathology, injury, or other neurosurgical issue needs to be fixed elsewhere [13]. In these cases, a Markov Model is used - a type of deep learning in which an AI algorithm understands when the surgeon completes those manipulations that must be performed manually. After that, AI automatically takes on the execution of the next task, and after its completion, the neurosurgeon again resumes the operation. Such an approach to performing an operation greatly facilitates efficiency and reduces the risk of intraoperative errors.

AI can carry out a large number of different activities during the operation. For example, considering intraoperative tissue biopsy. Usually, during this procedure, the tissue must be sent to a laboratory, and analyzed by experts. AI facilitates this process by making real-time predictions of tumor diagnosis in less than 3 minutes. While a pathologist may need from half an hour to several hours [13]. The accuracy of such a study in the case of AI was seen to be as close to 100%, while the accuracy of the data obtained by doctors with this procedure was found to be much depreciated [14]. Another example is a model based on an ultra-precise neural network. This model is a unique model which allows surgeons to obtain high accuracy data on how much tissue needs to be resected so as not to damage the optic nerve during transnasal surgery. Henceforth, AI has proved to be immensely effective in surgical operations. It allows not only to most accurately diagnose patients, but also to perform all manipulations with particular accuracy and efficiency [13].

AI in Postoperative Phase

Similarly, in the postoperative phase of neurosurgical procedures, AI again plays a key role. It has a lot of functions, such as: predicting and mitigating the development of various post-operative complications, including adverse drug effects, thromboembolism, development of pressure ulcers, falls and hypoglycaemia. These complications severely affect patient outcomes. AI has the propensity to predict, manage and thus minimize the occurrence of these common post-operative issues.

AI-based integration into histological diagnosis of brain tumors may reduce the uses of traditional pathways. Firstly, AI has reduced the use of biopsy. Secondly, AI has helped speed up specimen analysis and increase the accuracy of grading. Thirdly, deep learning models have also helped us to categorize patients in previously unknown ways, which may impact on therapeutics and survival. Finally, the ability of AI-based programs to predict molecular and cellular markers in tumors have paved the way for highly tailored therapy for brain tumors, thus enhancing the effects of treatment, at the same time reducing harm to patients through side effects. Therefore, patient monitoring and drug administration post operatively in specially programmed ICU's lined by AI has shown astounding results and reduced post-op complication rate four fold.

Areas of the Brain Most Frequently Operated with AI

AI has the potential to advance neurosurgical training, research, and improve patient outcomes in different phases of operation such as pre-, intra-, and postoperative. Beside diagnostic function, AI also can improve surgeon performance and decrease neurosurgery-related mistakes during the intraoperative stage of the procedure. In this stage, the surgeon can employ robotic devices such as the Da Vinci, Robotic Stereotactic Assistance (ROSA) and SOCRATES Surgical System in order to reduce risks and enhance results [14] (Figure 2).

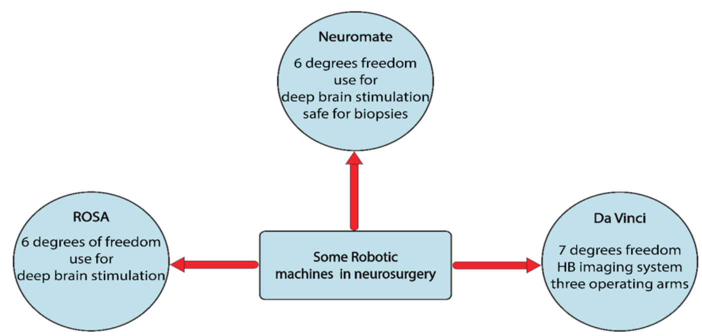

Figure 2: Major classifications of Robotic Machines in Neurosurgery with their degrees of freedom. i) ROSA ii) Neuromate iii) Da Vinci

Nevertheless, there isn't a completely autonomous interventional neurosurgery robot at the moment [15]. Currently, a variety of neurosurgical procedures are carried out using AI based robots and semi-autonomous equipment. For instance, ROSA robotic stereotactic assistance was used to implant bilateral subthalamic nucleus Deep Brain Stimulation (DBS) electrodes in Parkinson's disease patients [16]. Another illustration of how surgeons and robots can work together in the field of neurosurgery is the Transoral Robotic Surgery (TORS) approach to the skull base and sellar regions using the da Vinci Surgical System for manipulation of the pituitary gland and optic chiasm in cases of pituitary adenomas, cystic sellar masses, and so on [17-19]. Additionally, endovascular neurosurgery (for the treatment and diagnosis of intracranial aneurysms, intracranial hemorrhage and strokes) promises to revolutionize neurovascular services through the use of AI and robotics. Although AI is in its infancy stage and most of the cases above mentioned are cadaveric or 3-dimensional models studies, it seems to have a bright future in neurosurgery [20]. It was found that 4 areas of the brain are very frequently operated by AI: (i) Optic Chiasma, (ii) Subthalamic Nucleus, (iii) Cerebral Vascular Networks, and (iv) Pituitary gland.

Limitations of AI and Proposed Strategies for Overcoming

Security and privacy

Taking into consideration that extensive amounts of clinical data, it is obligatory to sufficiently train an algorithm to adequately respond to real-world clinical situations. This poses some security and operational challenges as it requires the sharing of data across institutions, cities and countries. It is a real possibility and fear amongst patients or clients as there is a risk of cyber hacking of their sensitive information, as well as data misuse by governing institutions that may negatively impact them [21]. There is also the problem of ownership of the data, would it be the clinician, the hospital, or the device company? [22] This poses a question as to how patient data will flow within the healthcare system, as well as to whom this data is made available [21]. Ethical and legal framework are necessitated to promote use of AI in the neurosurgical field.

Lack of explainability and adaptability

In a clinical setting, before the use of any process, device or drug there should be a thorough understanding of how it operates before use in a human. However, in the algorithm of current AI systems, the input-to-output processing mechanism is unknown. This results in issues related to biases, or decisions being made by AI which cannot be explained by humans. This lack of explainability is known as the "algorithmic black box" [22]. AI systems will also face a problem in adapting to unexpected situations, which is highly probable given the extensive variability in clinical presentation in real life. This is referred to as the "frame problem" wherein the AI system cannot cope with being presented with a data value it had not been trained in prior. Furthermore, AI systems are only capable of fulfilling a limited range of tasks and cannot fully replace the versatility of a human being. Furthering the range of tasks an AI system can undertake comes with greater complexity of integration of different algorithms, which could increase the potential for error [22].

Deskilling and distancing of physicians

The increased incidence of AI systems taking over in many aspects of clinical settings results in a reduced workload for healthcare workers. This can result in the stunting of the development of technical skills, a decrease in their clinical knowledge, reduced confidence in decision-making as well as over-reliance on these machines. In scenarios where there are technical errors in these machines, or trainees having to operate without the assistance of a senior, this deskilling and over-reliance on machines will pose a problem in providing adequate care for the patient [22]. Furthermore, the doctor-patient relationship as well as patient autonomy is likely to become more strained the more AI systems get involved in patient care, as this will result in the dialogue between doctor and patient ensuring patient understanding and consent to care being lessened [23].

Delimitations

Adapting regulations regarding data privacy and ownership

Mandating algorithmic transparency as well as setting guidelines regarding the application of AI systems before the sanctioning of such devices would be beneficial in a broader sense (Panesar et al., 2020). At the level of health workers and health organizations, being informed about new regulations and requirements in data protection and management is recommended [21]. This can be done through awareness raising as well as staff training to ensure a sufficient response to threats of a breach of confidentiality and privacy [22]. Providing patients or clients with informational modules about AI systems will let them have a better understanding of how their data will be handled [21]. A collective discussion should be held amongst the public (including the patient), clinicians and the developing company to come to an understanding of the ownership of the patient data. The range of expertise should include computer scientists, data experts and engineers as well [22].

Ensuring skill standards of healthcare workers

Developing training modules and having frequent assessments of the skill standards of practicing healthcare workers would ensure the maintenance of clinical skills even with the use of AI systems. Emphasis should be made on manual skills as well as reducing the use of automated machines in situations that do not require it. Healthcare workers should also be made aware of the working processes of the automated machines they use, and be provided with training for troubleshooting and routine maintenance of such machines [22].

Conclusion and Way Forward

The importance of artificial intelligence in medicine is expanding day by day, and neurosurgery, as a quickly emerging branch of medicine, cannot be excluded. There are already very promising statistics, that implementing AI in neurosurgery would help achieve better patient outcomes. AI in neurosurgery may help with pre-, intra-, and postoperative patient management, and outcome prediction, minimize the number of medical mistakes, and cut the overall cost of health care. Preoperative planning is crucial in many aspects of neurosurgical treatment; by implementing deep learning-based brain-tumor segmentation in neurooncology, neurosurgeons can successfully differentiate gliomas from healthy brain tissue [24]. This can improve the effectiveness of brain tumor resection and might help with boosting outcomes in neuro-oncology patients.

AI has been shown to have positive effects on selecting patients for pediatric epilepsy surgery [13]. Some surgical robots are successfully used in the operating room. It predicted that connecting AI with surgical robots will promote its work, improve intraoperative patient management and reduce some technical errors that humans can make. AI should not be considered a tool for replacing humans; instead, current advancements in AI technology may be used in a wholesome manner where humans and robots may collaborate to improve the quality of healthcare services. The neurosurgical community and neurosurgeons should embrace the application of AI and ML learning in routine clinical procedures. As a part of the medical community we can and should stimulate the utilization of AI in medicine. We can do this by deepening our knowledge of AI, doing more research, and by promoting it among undergraduate students. Further studies, funding, and cross-disciplinary cooperation are needed to broadly implement artificial intelligence in neurosurgery.

At the intersection of engineering, medicine, and neurology comes the multidisciplinary field of artificial intelligence. To provide patients the best results, neurosurgery may harness the power of AI. In the fields of pre-, intra-, and postoperative neurosurgery, AI has the potential to expand surgeons' skill sets. Through the acquisition, processing, and interpretation of images, the assignment of patients to the most appropriate surgeries, the improvement of intra-operative work, the provision of postoperative follow-up, and the facilitation of access to high-quality healthcare. Humans and machines can work collaboratively to harness the most recent technological advancements in AI to improve the quality of healthcare delivery [25]. For the treatment of disorders like Parkinson's disease, which is now managed by medicine and deep brain stimulation, the usage of AI can be further broadened.

In order to uphold ethical standards, the development of AI in neurosurgery needs to be carefully regulated and monitored. In the future, AI may open the door to personalized medicine. Additionally, AI in neurosurgery strives to develop quantitative models to predict health outcomes, prognosticate disease course, prevent illnesses, and reduce surgical complications as the collection of enormous amounts of clinical data increases by the day. AI has applications in both precision and customized medicine. Future broad adoption of AI in neurosurgery will need further study, funding, and interdisciplinary cooperation [26,27] (Table 5).

1. Can AI fully replace neurosurgeons and what would be its consequences?
2. It has shown that neurosurgery benefits from AI, but what are the cons?
3. How effective is AI in neurosurgery compared with other fields of medicine?
4. How long will it take until the full implementation of AI in neurosurgery?
5. Can the practice of AI use in other fields of science be considered in neurosurgical procedures, what are some of the ways?
6. Can AI be used equally in all types of neurosurgical procedures?
7. If the human factor is absent, will patients trust AI?
8. Will AI be as accurate in complex cases as in simple tasks?
9. Why the higher accuracy of AI compared to specialists in specific cases doesn't lead to their total replacement?
10. The role of IQ in neurosurgery. Does the lower IQ of AI-powered robotics limit their use in Neurosurgery??

Table 5: Unanswered research questions that may pave the way for future research.

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