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Review Article

The future of artificial intelligence in neurosurgery: A narrative review

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ABSTRACT

Background: Artificial intelligence (AI) and machine learning (ML) algorithms are on the tremendous rise for being incorporated into the field of neurosurgery. AI and ML algorithms are different from other technological advances as giving the capability for the computer to learn, reason, and problem-solving skills that a human inherits. This review summarizes the current use of AI in neurosurgery, the challenges that need to be addressed, and what the future holds.

Methods: A literature review was carried out with a focus on the use of AI in the field of neurosurgery and its future implication in neurosurgical research.

Results: The online literature on the use of AI in the field of neurosurgery shows the diversity of topics in terms of its current and future implications. The main areas that are being studied are diagnostic, outcomes, and treatment models.

Conclusion: Wonders of AI in the field of medicine and neurosurgery hold true, yet there are a lot of challenges that need to be addressed before its implications can be seen in the field of neurosurgery from patient privacy, to access to high-quality data and overreliance on surgeons on AI. The future of AI in neurosurgery is pointed toward a patient-centric approach, managing clinical tasks, and helping in diagnosing and preoperative assessment of the patients.

Keywords: Artificial intelligence, Health care, Machine learning, Neurosurgery, Operating room, Technology

INTRODUCTION

Neurosurgery is a complex field in terms of long hours and years of training and the high level of intelligence, decision-making skills, and surgical skills put all together. Neurosurgeons usually work in multidisciplinary teams involving other specialists from the anesthesiologists, neurologists, medical specialist nurses, and even medical students. The skill set required can be varied from compassion to having the stamina to work for long-standing hours, good eye and hand coordination, and manual dexterity.[54] Neurosurgeons usually go through a similar

pathway in training programs but the skill set can vary and can provide different patient outcomes. The patient outcomes in the case of neurosurgical diseases are based also on several other factors from the age of the patients, ethnicity, economic background, and national and international guidelines.[27] Quarter of the errors occurring in neurosurgery is the result of technical errors alone, so by intermingling the use of machine learning (ML), we can somewhat work on these errors shortly.[27,38] It has been estimated that preventable medical errors alone had led to the deaths of 98,000 Americans annually, with the surgical errors causing a major cost to the US economy while the ratio of neurosurgical errors is not known which makes the cost-effectiveness of the procedure opaque.[38]

With the recent advancement in technology, there has been a great emphasis on the use of artificial intelligence (AI) in health care and clinical practice as it can augment the data processing in larger amounts generated in the modern health-care system and provide clinically relevant results.[32] AI is a new field in computer science, and through ML, it gives the computer capability to learn, reason, and solve problems.[53] A recent study also predicts that ML algorithms have the potential for augmentation of clinical decision-making of clinicians in neurosurgical applications.[42] In the past decade alone, there has been a great interest shown in the use of AI in neurosurgery.[27] Modern diagnostic techniques produce large amounts of data that can be interpreted grossly by trained specialists and consultants but the quantitative analysis does require AI and ML as they can provide better results and patterns than observed by humans. The implications of AI in neurosurgical care are in the initial levels and their incorporation into daily clinical practice is yet to be established by working on limitations like the accessibility to high-quality data.[12] Although the emphasis, for now, is on the use of AI in neurosurgery as we can match AI with robotic surgery, it is assured that AI might find its way into the operating room (OR).[32] The use of advanced technology in the field of neurosurgery has always been on the rise, from using MRI and CT as diagnostic imaging modalities since they were first introduced, neurosurgeons all over the world are using cutting-edge technology for diagnosing and managing patients and to improve patient outcomes.[27]

The first ML approach used in the field of neurosurgery spans about a century ago, in a research published in 1900, that used artificial neural networks (ANNs) to develop structural databases. Since then, there has been great advancement in the field, while in the past 2–3 decades, we can see the implementation of AI and ML algorithms in clinical practice.[40] The AI and ML algorithms have been used in neurosurgical imaging like grading gliomas using convolutional neural networks,[57] the algorithms are also being used in pre-, intra-, and post-operative care, and yet, the future holds a lot of wonders in terms of its integration into routine clinical practice.[27] Neurosurgery can be a promising field in the case of the incorporation of AI and ML algorithms as the diagnostic and investigation produce a large amount of clinical data, radiological images, and MRI sequences; the ML algorithms can well interpret these high-quality data.[12]

With the higher demand for neurosurgeons due to the population growth, there has been a great emphasis on increasing the number of physicians,[27] but human power alone cannot solve the problems in health care as it requires more technology-based solutions shortly. While AI incorporation into clinical practice might seem like a computer taking the role of the physician with the preprogrammed decision, ML is an ever-evolving technology that uses huge amounts of data to come up with clinically relevant results with problem-solving and decision-making skills. Targeted cost-effective care is at the heart of future medicine and health care, reducing the cost of health with focused intervention and diagnostic techniques can reduce the unnecessary burden.[32] This literature review highlights the current and future implications of AI in neurosurgery.

DISCUSSION

AI and its implications in the field of surgery

With the other walks of life being increasingly automated, the fields of medicine and surgery have not been spared from technological revolution. From routine diagnostic and clinical investigations to laparoscopic and robotic surgeries, AI is being largely incorporated.[3] AI, being one of the technological breakthroughs of the modern world, enables the machines to imitate human problem-solving and decision-making capabilities by learning from extensive datasets and patterns of human activities. The core subfields of AI include ML, natural language processing (NLP), computer vision (CV), and ANNs.[18] ML, being one of the oldest fields of AI, enables machines to learn from experience and perform the tasks better, without being explicitly programmed. The super learning algorithm-based ML model performed better than benchmark logistic regression approach in predicting the patient-level outcomes of thyroidectomy and led to better, patient-specific, and informed treatment decisions as demonstrated by Seib *et al*.[41] NLP focuses on imparting computer systems the ability to understand human language in the form of written or spoken words. Thirukumaran *et al*. indicated that NLP-based models' prediction capabilities were comparable with the manual abstraction process and superior to the models that use administrative data only in identifying surgical site infections in the orthopedic surgery patients.[47] ANN, a biologically inspired subset of AI, which

concentrates on building computational models that mimic the working of interconnected neurons in the human brain. In a study by Chen *et al*., the success rate of facial feminization surgeries was assessed using neural networks designed for facial recognition, as evidenced by accurate gender typing and increased confidence in femininity.[11] CV, another crucial subset of AI, enables machines to extract and analyze visual data such as images or videos. With its utilization, the skill of the operating surgeon can be recorded and compared with peers. It can also identify potential areas of improvement, standardize procedural skills, and accurately predict the association of postoperative complications and operation time with surgeons' skill complexity.[24]

AI and neurosurgery

The history of AI in neurosurgery roots from the 1990s when the use of ML was first evidenced in the medical literature as ANNs were developed for structured datasets analysis and tasks' supervision. From the lesion detection on reconstructed SPECT scans and grading of astrocytic gliomas, ANNs were increasingly utilized and their outcomes were comparable to manual processing. By the end of the millennium, the well-trained AI algorithms continued to outperform the traditional clinical approaches for brain tumor diagnosis, tumor segmentation, and surgical risk assessment. Moreover, the digitalization of the health-care systems in the 2000s boosted the limits of AI systems by making extensive structured and unstructured datasets available for training and testing ML models. Throughout the 2010s, the AI-based programs further paved their way into neurosurgical care. The adoption trend of highly advanced contemporary models is going on, with many being reported to have unprecedented potential in revolutionizing neurosurgical practices. Moreover, the complex diagnostic and therapeutic modalities used in neurosurgery provide a vast amount of data that are ideally suited for ML models.[40]

The ratio of neurosurgeons to neurosurgical cases is low particularly in low-middle-income countries and the COVID-19 pandemic has further exposed the urgency to mitigate issues such as long working hours and physicians' burnouts in health-care setups.[1,45] Recently, MRI-compatible robotic arm, being remotely controlled by neurosurgeons, has successfully executed neurosurgical procedures, such as tumor biopsies and microsurgical dissection as discussed by Mattei *et al*.[26] Errors in neurosurgical procedures are often life threatening, common, and under reported. Neurosurgery comes third in the prevalence of wrong site or wrong level surgeries, after orthopedic and general surgery.[20] Although the implementation of various surgical safety checklists have reduced the incidence of such events, they have not completely abrogated them.[51] However, AI-based computational systems and robots have revolutionized the OR dynamics and have led to more efficient, safe, and invasive approaches in neurosurgical procedures.[37]

Human machine teaming and CV in neurosurgery

CV is a flourishing domain of AI technology that builds systems capable of extracting and interpreting data from visual inputs such as images and videos. Its application in monitoring team dynamics in OR has shown promising results.[22] Disruptions in procedural flow during surgeries can lead to surgical errors and, hence, increase the risk of complications. Teamwork or communication errors, technology and equipment failures, and training-related distractions are some of the possible causes of surgical workflow interruptions, with teamwork or communication failures at the top.[52] In a study by Khan *et al*., an advanced ML model was developed using SPR technology to efficiently recognize phases and steps of endoscopic trans-sphenoidal approach for pituitary adenoma resection. Despite the significant variations in recorded procedures in regard to video appearances, duration, and order of the steps, ML model was able to accurately identify steps (76% accuracy) and surgical phases (91% accuracy). This ML-based analysis of surgical workflow has a significant potential for reducing flow interruptions, maximizing the OR team coordination, and rating of operative videos for surgical education.[23] Considering the limited number of experts available for operative videos based skill assessment, Pangal *et al*. evaluated automated performance metrics' (APMs) capability to predict overall success rate, blood loss, and hemorrhage control in <1 min in endoscopic endonasal surgery for internal carotid artery vascular injury. The APMs were found to be more accurate predictors of surgeons' performance than their training status or prior experience.[33] With the rapidly advancing AI technologies, robots requiring minimal human supervision have led to reduced surgical site infections, precise tumor segmentation, reduced incision, and scar size and shorter recovery spans.[32] Although these ML powered devices can have unprecedented potential of pairing with human teammates, they do not necessarily possess human teamwork competencies such as communication, coordination, and adaptation.[39] Initial training with nonhuman models is one of the main hindrances in achieving human-like socioemotional attributes as indicated by Carroll *et al*.[10] The current AI research is focusing on imparting these transportable competencies to the machines and addressing their requirements to be effective teammates.[46]

Role of AI in pre- and post-operative management in neurosurgery

Despite recent advances in the field of neuroimaging, the precision of detecting tumor recurrence, small metastases, differentiating between tumors and infectious

foci, and management effects of MRI and other imaging modalities need to be refined further.[14] In a recent study, MRI histogram peaks were utilized to design AI algorithms that can accurately detect tumor volumes with more specificity, sensitivity, and a higher interoperator repeatability.[25] Radiomics combined with clinical indicators have been utilized to develop various ML models which can accurately predict molecular subgroups of medulloblastomas and skull base chondromas versus chondrosarcomas.[55,56] In another study, investigators have used texture analysis and other AI technologies to study necrosis as a treatment effect, distinction between benign and malignant tumors, disease progression, and number of metastases.[19]

Gross total resection of intra-axial brain tumors with minimal postoperative neurological deficits has always been the priority in the management of cerebrospinal tumors. Dundar *et al*. proposed a heuristic-based surgical path planning algorithm combined with Q-learning, a frequently used reinforcement learning AI model, to identify the appropriate skull entry points, optimal linear, and nonlinear pathways to ensure minimally invasive approach for tumor resection.[16] Moreover, a better delineation of each patient's anatomy by CV can help orient the neurosurgeons for complex procedures such as trans-sphenoidal pituitary resection, malignant neoplasm excision, and skull-base surgeries.[57] Hand tremors during microsurgeries lead to increased angle resection, more collateral damage, and, hence, a higher rate of complications. Different AI models have been incorporated in surgical education in the form of virtual reality and 3D simulators, to ensure sufficient, skill-oriented training of resident, and mid-career surgeons to augment their confidence and reduce hand tremors during the actual surgeries.[44]

Accurate prediction of early and late postoperative complications is areas of focus for neurosurgeons for stratification of patients into high- versus low-risk groups, postoperative management, and optimal allocation of limited health-care resources to ensure a cost efficient patient-centered care. van Niftrik *et al*. found that the gradient boosting ML algorithm was superior to conventional statistical methods in predicting early (within 24 h) postoperative complications.[49] As significant blood loss during complex spinal surgeries is strongly associated with longer surgery duration, greater morbidity, and mortality, Durand *et al*. proposed the use of conditional inference tree analysis, a ML algorithm, for accurate prediction of peri- and post-operative transfusion in patients undergoing surgery for adult spinal deformity.[17] In a study by Paliwal *et al*., four supervised ML algorithms predicted (90% accuracy) the 6-month clinical outcomes of flow diverter (FD) treatment for occlusion of intracranial aneurysm. The inappropriate occlusion by FDs can lead to thromboembolism and rupture.[30]

Role of AI in intraoperative performance and safety in neurosurgery

Neurosurgical patients are attended by large health-care teams ranging from neurosurgeons, radiologists, anesthesiologists to technicians, nurses, and other staff, exposing them to a wide variety of errors. Most of the errors are preventable and can lead to better patient outcomes. Researchers have found that patients' ASA scores correlated significantly with medical errors. Moreover, error rate was higher in cranial surgeries as compared to spinal cases possibly because of patients with a higher perioperative morbidity requiring complex, long duration procedures.[6] Padoy and Hager proposed Hidden Markov model, a type of deep learning algorithm which identifies the completion of manual subtask, performs the next automated task seamlessly and then transfers the control back to surgeon for the next manual step, hence leading to overall increase in surgical performance.[29]

Intraoperative brain shifts inflict a significant challenge on the neurosurgeons during high-risk operations such as skull base or posterior fossa tumor resections. Tonutti *et al*. employed ANNs and support vector regression combined with complex finite elements method, to determine resulting deformation for each node in brain tumor mesh and found that the positional on-screen errors with these models were <0.4–0.5 mm and 0.2 mm, respectively, in contrast to average error of not <2 mm with commercially available AI applications. The superiority of these ML approaches over the existing deformation models holds a great deal for the image-guided neurosurgical procedures and can potentially be applied to predict any type of soft-tissue deformations.[41,48] Recently, Cakmakci *et al*., using a random forest model, accurately determined the metabolic profile of intraoperatively resected tissue, detected residual neoplastic tissue in excision cavity, and guided the surgeon to perform maximal resection.[9] Finally, Qiao *et al*. found that convolutional neural network-based model can predict the extent to which tumor resection should be proceeded in endoscopic transnasal surgery with a comparable human accuracy of 87.4%, thus preventing optic nerve injury and reducing surgeons' cognitive workload.[36]

Challenges faced by AI in neurosurgery

AI has shown wonders in medicine and healthcare, and its future in the field of neurosurgery is promising in many respects, but still some setbacks need to be addressed and discussed before using it in daily routine practice.[27] One of the most crucial factors that are concerning in terms of its use in daily clinical practice is patient privacy.[4,35] AI algorithms training and generation of sequence require large amounts of data. The patient privacy policy does not make the data quite feasible which can halt the long-term advancement of AI in neurosurgical care. Hence, overprotection in terms of

patient privacy can lead to lesser advancement in the long run.[15] The more clean data the ML algorithms receive, the more likely they are to come up with results that are clinically significant, successful implementation of the data is required for training the ML algorithms.

Another concern for the use of AI in neurosurgery is the overreliance of the neurosurgeons which might lead them not to learn the surgical skills and master the techniques. Whereas, the hardware and software malfunctions are inevitable and carry the risk of misdiagnosis if not solved in time.[27] Transparency is another concern, as the health-care provider should know the logistics behind how the machine produced the results so they can know if the reasoning is sound enough to be trusted. If the health-care providers are not sure of how the machine came up with the result, they are less likely to be integrated into clinical practice.[28]

One of the concerns in the use of AI in any field is that it might replace humans. While in terms of neurosurgery, the outcomes should be patient centric and the use of AI should be weighed on the benefits versus the risk, it can provide to the patients. The use of technology and AI in health care is not to replace humans but to work in an environment that can lessen the burden and help in clinical decision-making for neurosurgeons. A study conducted by Palmisciano *et al*. who showed that most patients and their relatives have found the use of AI in neurosurgery acceptable, while most of the patients and their relatives wanted the neurosurgeon to remain in control.[31] Implementation of a new technology is costly initially and might be of concern to put the AI into clinical practice. While the initial data processing of machine algorithms setups might seem costly at first, but, they can be cost effective in the long run and can reduce the cost of unnecessary diagnostic testing.[27]

Future of AI in neurosurgery

Technological advances in the various fields of medicine make it crucial that these automation and advanced ML tools be incorporated into the field of neurosurgery. The neurosurgical field and the neurosurgeons should harness the power of the use of AI and ML learning into daily clinical practices and also introduce these models in the use of intraoperative and postoperative care.[27] The training of AI models in the future generation of doctors in undergraduate and postgraduate students should be started at an early stage so they should be familiar with the recent advancement in the technology and how they are being incorporated into clinical practice. A study conducted involving undergraduate students from three different medical schools assessing the knowledge of AI in radiology suggested that 68% of the students were unaware of the technology involved.[34]

The use of AI in future neurosurgery can be more individualized toward patient-centered care in the near future as recent studies have suggested that AI models can predict individual postoperative complications in patients undergoing anterior cervical discectomy and fusion using ML.[2] AI is thought to push the boundaries of a larger amount of clinical tasks performed by humans, reduce the number of medical errors, and lower the cost of health care in general. While the future of AI and ML is to currently integrate these into daily clinical practice, it is also estimated that interlinking AI with surgical robotics AI might find its way into the OR. Incorporating AI into clinical practice is not quite exclusive so the promises of AI in the field of medicine and neurosurgery are yet to be tested and looked at whether the benefits outweigh the risks.[32] AI is yet to enter the premises of the OR, whereas surgical robotics have already augmented human surgical skills and combining them with AI in the future will do wonders in the OR.[43]

Preoperative planning in neurosurgical care is important in many respects, while its automation in neurosurgical patients has shown benefits in identifying the epileptogenic zone and selecting optimal candidates for pediatric epilepsy surgery. Preoperative planning automation makes AI use quite reliable in the future as studies have shown that preoperative automation enhances the outcome in neuro-oncology patients.

Limitations and future recommendations

AI in health care has shown several advances in recent years and with the passage of time, doctors and robots might work side by side for patient betterment. However, AI being a disruptive technology has several drawbacks. It is hard for a patient to trust a robot with their surgery, and it is often suggested that a neurosurgeon has the ultimate control in the end.[31] Traditional neurosurgeons usually discourage the use of AI during neurosurgical procedures. On the other hand, overreliance on AI would lead to discouragement of mastering surgical skills required by surgeons, especially neurosurgeons.[27] AI requires a vast dataset to function, thus posing the challenge to create a large number of clinically functional algorithms. This requires storage of large-scale information providing easy access to abusers putting patient privacy at risk. There are many ethical concerns as well; while it is controversial to record patient data, if a misdiagnosis happens due to AI, moral and legal issues need to be addressed.[5] The "black box dilemma" is where both the users and the consumers do not possess understanding of how the computer generates results, thus lacking transparency in AI systems.[50] Another thing to consider is no matter how advanced AI gets, it does not possess human consciousness to take responsible and informed decisions.[13]

It is recommended to verify and certify AI-based systems for the safety of the patient, and also, AI system failures on patients must be minimized. Another future challenge is to annotate targets, such as sometimes, it is difficult

for even the neurosurgeons to recognize the anatomical structures. AI should be trained to learn such difficult anatomy alongside other technology. This would improve the accuracy for difficult targets.[5] Vast amount of data in a training set majorly consists of standard cases, cases with anatomical abnormalities are a concerning future challenge. In endovascular procedures, AI is limited due to the lack of haptic feedback.[7] AI can be used extensively for surgeries with advancing age, but a clinician's endorsement is still required.[8] Doctors would be required to train in computer sciences to be able to analyze and better use the data and the AI systems.[21]

CONCLUSION

The integration of AI into health care has created a paradigm shift; this would be the new normal for the future surgeons, whereby doctors work alongside scientists and engineers to create better tools and techniques for medical care and research. AI has its limitations and challenges which can be overcome by careful monitoring and constant development of better algorithms to overcome failure rates. AI is more of a tool for a neurosurgeon than a replacement. Workspaces should be augmented and not refined. Advances in AI can help integrate data-driven fields like genomics along with surgery for the creation of personalized treatments and precision public health.[8] It is important for future clinicians to be up to date on advances in health care and be able to integrate them in their procedures to show improved outcomes.

Declaration of patient consent

Patient's consent not required as there are no patients in this study.

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Conflicts of interest

There are no conflicts of interest.

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