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EMERGENCE OF ARTIFICIAL INTELLIGENCE IN NEUROSURGERY

Korina Tumir
University of Zagreb, School of Medicine
0009-0007-4798-8473

Abstract

Artificial intelligence (AI) is increasingly being utilized across various scientific disciplines, and medicine is no exception to this trend. It was envisioned as a tool to complement human cognitive abilities and in medicine that refers to processing a large volume of data, decision-making and ultimately enhancing the quality of care provided to patients. In the field of neurosurgery, AI, machine learning (ML) and deep learning (DL) show significant potential regarding differential diagnosis, pre-operative evaluation, improving surgical precision and post-operative care. Their use can be presented in four major sections of neurosurgery: vascular neurosurgery, functional neurosurgery, neurosurgical oncology, and spinal neurosurgery. Examples of the implementation of AI in the mentioned fields will be provided in this review article.

KEYWORDS: artificial intelligence, deep learning, machine learning, medicine, neurosurgery

INTRODUCTION

Artificial Intelligence (AI) has become a very popular topic in recent years, particularly due to its expanding applications in various fields. AI involves the use of computer systems to simulate human cognitive functions, enabling machines to perform tasks such as pattern recognition, data analysis, and decision-making. To comprehend AI's role in medicine, it is essential to distinguish its core components: Machine Learning (ML) and Deep Learning (DL) (Figure 1).[1]

Machine Learning, a subset of AI, focuses on recognizing patterns within data and can be broadly categorized into: supervised learning, unsupervised learning, and reinforcement learning (Figure 2).[1] Supervised learning uses labeled datasets to predict outcomes. Labeled datasets are datasets where each piece of input data is paired with a known output or "label". For example, a dataset of medical records might include features such as blood pressure, cholesterol levels, and age, with labels indicating whether the patient has a specific condition (e.g., diabetes). Unsupervised learning identifies hidden patterns or classification in data without labeled outcomes, helping discover patterns that may lead to new medical insight in complex datasets. In cancer research, unsupervised learning has been used to analyze genetic data and identify subtypes of cancer. For instance, in breast cancer, clustering has revealed molecular subtypes (e.g., HER2-positive, triple-negative), which now guide the choice of treatment and prognosis.[2] Reinforcement learning is a method where systems learn by trying different actions and receiving feedback on their performance. They use this feedback to improve over time, which makes them especially useful for solving complex problems in real-life situations.

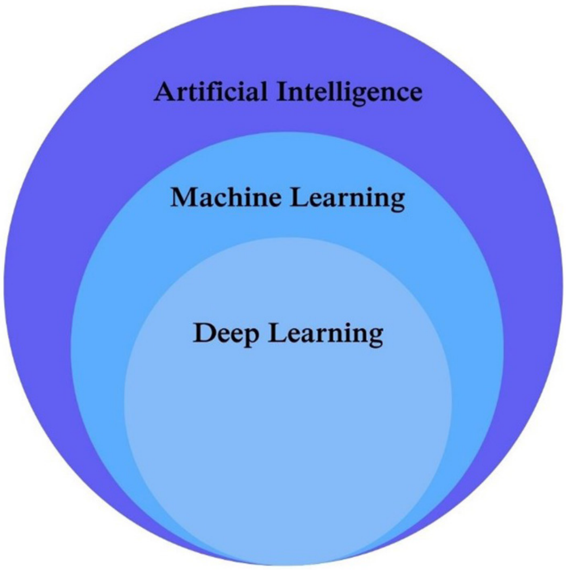

Figure 1. The relation between Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL).

Machine Learning is a subset of AI, and Deep Learning is a subset of ML, meaning they are both forms of AI.

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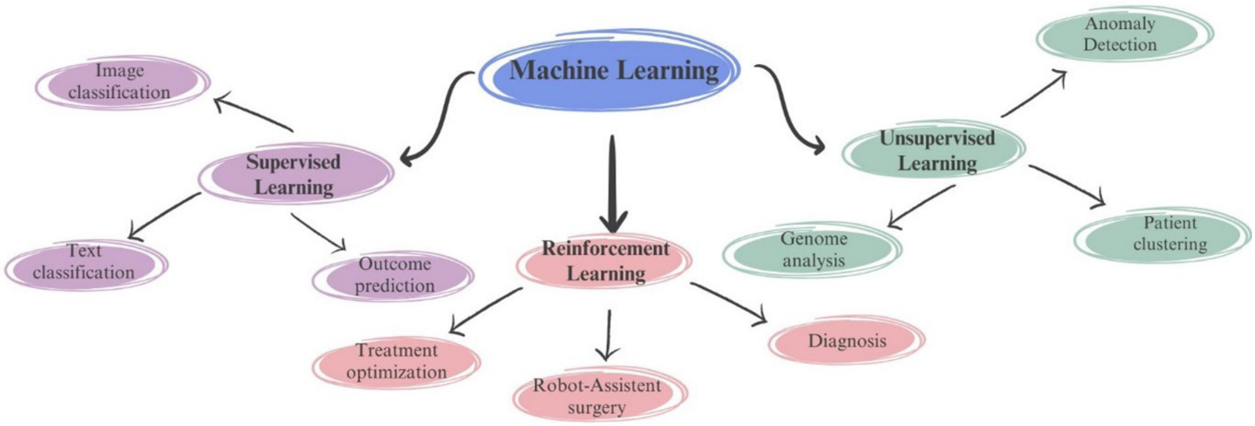

Figure 2. Types of Machine Learning.

The figure illustrates the three main types of Machine Learning—Supervised, Unsupervised, and Reinforcement Learning—along with examples of tasks they perform in various medical fields.

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Deep learning is an advanced subset of machine learning (ML) that uses Artificial Neural Networks (ANN) designed to simulate the way the human brain works.[3] These networks are composed of interconnected layers of nodes that process and identify complex patterns in data. By analyzing large amounts of data, deep learning systems can make more accurate predictions than traditional machine learning methods. An example of deep learning in action is its use in medical imaging, such as detecting tumors in MRI scans. By processing these images, it can highlight areas of concern that may be difficult for the human eye to detect, making them invaluable tools in diagnosing diseases like cancer at an early stage. In addition to image analysis, deep learning has also revolutionized Natural Language Processing (NLP), especially with the development of medical-specific large language models. These models are designed to process and interpret large volumes of text, making them ideal for analyzing clinical documents like patient histories, medical reports or research papers. By understanding and interpreting the nuances of medical language, these models can assist healthcare professionals in diagnosing conditions, predicting outcomes, and even personalizing treatment plans.

ARTIFICIAL INTELLIGENCE AND NEUROSURGERY

Neurosurgery is a demanding field of medicine and mastering it requires years of extensive training and a diverse skill set, including cognitive, decision-making, and surgical skills. Despite the expertise required, neurosurgical interventions do not always guarantee positive outcomes, with technical faults accounting for one-fourth of all errors in neurosurgery.[4] AI offers potential solutions to address such issues quickly, ultimately benefiting patients. It has been utilized for differential diagnosis, pre-operative evaluation, improving surgical precision and post-operative care. However, the increasing use of AI in neurosurgery brings challenges, including data quality, algorithm bias, and regulatory concerns. AI has begun transforming neurosurgical practices across several neurosurgical specialties: spinal neurosurgery, functional neurosurgery, vascular neurosurgery and neurosurgical oncology (Figure 3).[3,5]

SPINAL NEUROSURGERY

AI models, particularly DL, have shown promise in addressing several aspects of spinal surgery. Halliman et al. successfully used DL models for classifying low-grade and high-grade metastatic epidural spinal cord compression based on the Bilsky grading scale, showing 92– 98% agreement with radiologists.[6] Goedmakers et al. used DL models to predict adjacent segment disease in patients undergoing anterior cervical discectomy and fusion for cervical radiculopathy, demonstrating 95% accuracy compared to neuroradiologists' and neurosurgeons' 58% accuracy.[7] ML techniques have also been valuable in predicting adverse events following spinal surgeries, like predicting mortality and surgical outcomes. Karhade et al. predicted 30-day mortality following spinal metastasis surgery using various ML algorithms.[8] The models accurately identified preoperative prognostic markers such as albumin levels, alkaline phosphatase and functional status, showing the potential of ML algorithms in preoperative assessments and improving clinical decision-making.

Despite advancements in ML for spinal surgery, challenges such as data variability, model validation, and the need for large-scale prospective studies persist, with some models requiring further development to improve accuracy and applicability in predicting complex clinical outcomes and complications.

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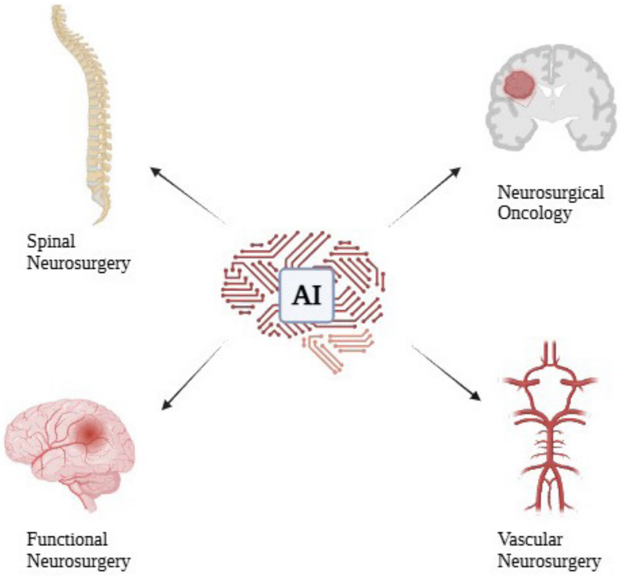

Figure 3. Artificial intelligence (AI) application in various neurosurgical fields.

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NEUROSURGICAL ONCOLOGY

A key aspect in oncological neurosurgery is surgical planning, where AI has been found to have an important role. For example, a tool created by Dundar et al. suggests the optimal points of entry into the skull and the best routes for minimally invasive tumor removal (Figure 4).[9] AI is also highly effective in predicting and grading gliomas. It uses imaging data, such as MRI scans, to distinguish between low-grade and high-grade gliomas with higher accuracy than traditional models (e.g. Svolos et al. reported 98% accuracy of an AI model compared to 80% accuracy of a traditional model).[10] Overall, AI is transforming neurosurgical oncology by improving diagnosis, surgical accuracy, and personalized care. These advancements are leading to better outcomes and providing new hope for patients with brain tumors.

FUNCTIONAL NEUROSURGERY

AI has been developed to quantitatively evaluate EEG data for epilepsy diagnosis. Varatharajah et al. observed changes in brain activity patterns in EEG findings between patients with temporal lobe epilepsy who, after a year following an anterior temporal lobectomy (ATL), were seizure-free and those who still had post-surgical seizures.[11] They found that patients with ongoing seizures showed a decrease in brain activity in the 10–25 Hz frequency range. The authors suggest that this variation is due to networks that generate temporal lobe seizures either inside or outside of the ATL borders. AI can also be used to predict the effectiveness of

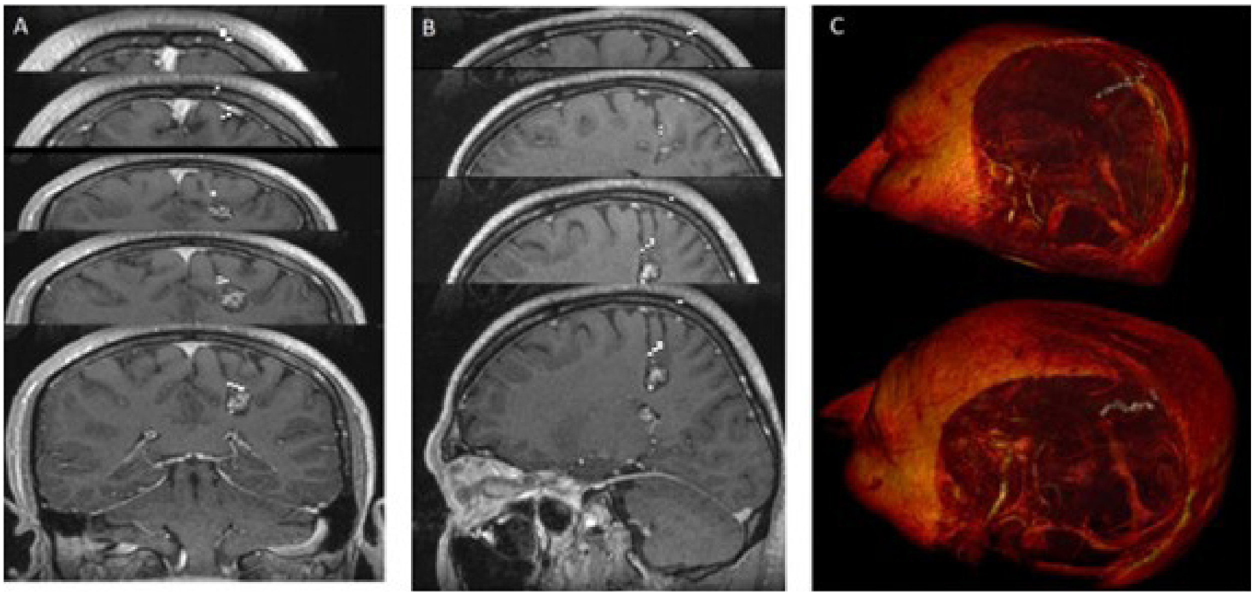

Figure 4. The most ideal cortico-tumoral approach recommended by Reinforcement Learning (RL).

Images were added one after another to show the nonlinear pathway. RL extracted the most optimal pathway by performing a random-onset point analysis of the entire intracranial area. Demonstration of the approach reaching the tumor from the base of the postcentral sulcus. (A) showing the pathway in coronal sections. (B) showing the pathway in sagittal sections. (C) showing the 3-dimensional pathway with image processing.

Source: Dundar TT, Yurtsever I, Pehlivanoglu MK, et al. Machine Learning-Based Surgical Planning for Neurosurgery: Artificial Intelligent Approaches to the Cranium. *Front Surg*. 2022;9. doi:10.3389/fsurg.2022.863633

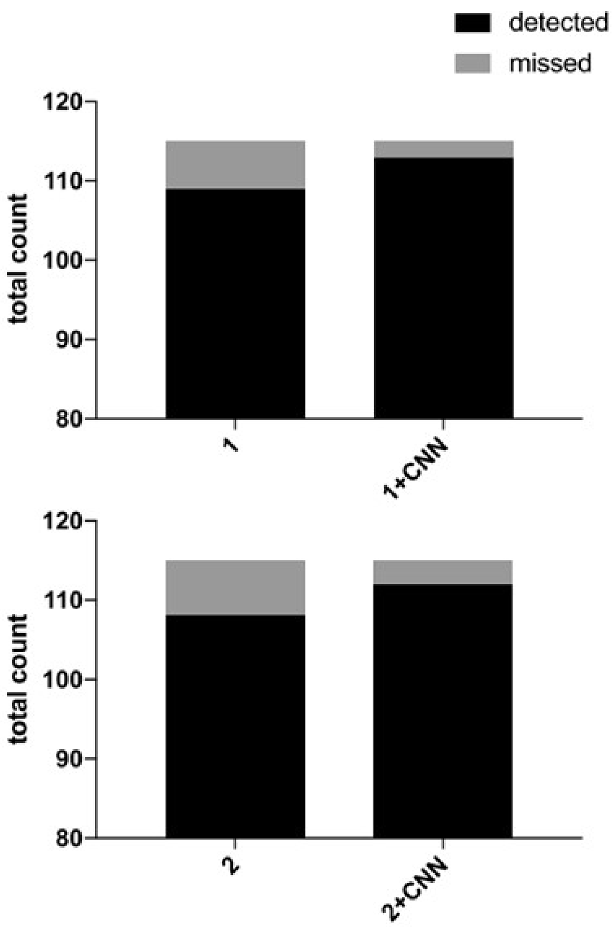

Figure 5. Diagnostic performance of human readers (upper reader 1, lower reader 2) regarding detected and missed aneurysms within the complete dataset (N= 115) with (1+CNN, 2+CNN) and without (1,2) combination of detections with the deep learning neural network—Convolutional Neural Networks (CNN).

Source: Faron A, Sichtermann T, Teichert N, et al. Performance of a Deep-Learning Neural Network to Detect Intracranial Aneurysms from 3D TOF-MRA Compared to Human Readers. *Clin Neuroradiol.* 2020;30(3):591-598. doi:10.1007/s00062-019 00809-w

surgical therapy for epilepsy. In the study by Cohen et al., an ML algorithm was employed to identify children early in their medical treatment who could benefit from early epilepsy surgery.[12] The researchers tested whether ML could identify candidates for epilepsy surgery as accurately as physicians, and even earlier. With F-measures between 0.71 and 0.82, the results showed that ML can help predict which children might benefit from surgery and reduce delays in referring them for treatment. The goal is to spare children from prolonged and unsuccessful conservative treatments by performing surgery earlier.

VASCULAR NEUROSURGERY

The primary use of AI in vascular neurosurgery is outcome and risk analysis. It has an important role in predicting and treating life-threatening conditions such as clinically symptomatic vasospasms after subarachnoid hemorrhage (SAH) in ruptured aneurysms, intracerebral hemorrhage and stroke.[3] Dumont et al. used ANN to predict the occurrence of vasospasms after aneurysmal SAH in the studied patient group with very high sensitivity (around 95%).[13] Also, Morey et al. used an algorithm to do a real-life experiment on ischemic stroke patients.[14] Randomized controlled trials have demonstrated the importance of time to endovascular therapy (EVT) in clinical outcomes in large vessel occlusion (LVO) acute ischemic stroke. A computer-aided triage system, Viz LVO, automatically identifies suspected LVO strokes on CTA imaging and rapidly triggers alerts, decreasing time-to-treatment.[14] The study showed that the algorithm led to quicker reperfusion and improved clinical results. The median initial door-to-neuroendovascular team notification time interval was significantly faster (25.0 min) as compared to the pre-Viz cohort (40.0 min). Furthermore, DL algorithms were shown to outperform radiologists in detecting intracranial aneurysms (Figure 5).[15] What is also important is predicting the stability of aneurysms, especially small ones, because the majority of ruptured intracranial aneurysms are classified as small intracranial aneurysms.[16] Liu et al. used ML to predict small aneurysm stability.[17] They identified key features like flatness and spherical disproportion to predict stability. The model showed good performance with a 94% accuracy.

CONCLUSION

Technological advancements are progressing rapidly and AI has the potential to improve many aspects of neurosurgical work: classifying diseases accurately, performing surgeries optimally, and providing good post-operative care. Recent studies have demonstrated high accuracy and precision across several fields of neurosurgery, bringing improvement in patient management and clinical outcomes. AI-based techniques, particularly ML and ANN, have already begun to outperform traditional statistical prediction models. Modern AI systems are now capable of detecting subtle, non-obvious patterns, enabling more insightful predictions about diseases and treatments. However, the full impact of AI on neurosurgery is still unpredictable, as its applications are in the early stages of development.

Despite all this advanced technology, one principle still remains: even the best AI models cannot fully represent an individual patient. While they could never replace the relationship between a doctor and a patient, they should be viewed as valuable supplementary tools.

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POJAVA UMJETNE INTELIGENCIJE U NEUROKIRURGIJI

Sažetak

Umjetna inteligencija sve se više koristi u različitim znanstvenim disciplinama, pa tako i u medicini. Zamišljena je kao alat koji će unaprijediti ljudske kognitivne sposobnosti, a u medicini se to konkretno odnosi na obradu velikih količina podataka, donošenje odluka i u konačnici na poboljšanje kvalitete skrbi koja se pruža pacijentima. U području neurokirurgije, umjetna inteligencija, strojno učenje i duboko učenje pokazuju značajan potencijal u diferencijalnoj dijagnostici, preoperativnoj evaluaciji, poboljšanju kirurške preciznosti i postoperativnoj skrbi. Njihova primjena može se prikazati u četiri velika područja neurokirurgije: vaskularnoj neurokirurgiji, funkcionalnoj neurokirurgiji, neurokirurškoj onkologiji i spinalnoj neurokirurgiji. Primjeri primjene umjetne inteligencije u navedenim područjima bit će predstavljeni u ovom preglednom članku.

KLJUČNE RIJEČI: duboko učenje, medicina, neurokirurgija, strojno učenje, umjetna inteligencija