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Neural decoding with artificial intelligence for personalized robotic neurosurgery

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Abstract

Robotic neurosurgery has significantly advanced surgical precision and outcomes, with personalization becoming crucial in optimizing treatment for individual patients. The crucial aspect of personalization has become increasingly apparent in optimizing treatment for individual patients, allowing for tailored and precise interventions that can significantly improve patient care and recovery. This literature review explores the integration of neural decoding and artificial intelligence (AI) in personalized robotic neurosurgery, focusing on current techniques, applications, and future directions. Neural decoding, which interprets neural signals to guide surgical interventions, is examined alongside its limitations, including spatial resolution and invasiveness. The review highlights how AI and machine learning enhance neural decoding by improving pattern recognition and predictive capabilities, thus enabling real-time adaptations during surgery. Personalized robotic neurosurgery leverages advanced imaging and real-time data to tailor surgical approaches, improving precision and reducing complications. The integration of neural decoding and AI into robotic systems presents significant benefits, such as enhanced accuracy and personalized care, but also faces challenges related to technology integration, cost, and reliability. Future research should address these challenges by developing robust algorithms and expanding clinical applications. This review provides a comprehensive overview of how combining these technologies can advance personalized neurosurgical practices and improve patient outcomes.

Keywords- Robotic neurosurgery; Personalization; Neural decoding; Artificial intelligence; Machine learning

1. Introduction

Robotic neurosurgery represents a transformative approach to performing complex neurological procedures with enhanced precision, efficiency, and safety (1,2). The use of robotic systems in neurosurgery, such as the Robotic Stereotactic Assistance (ROSA) and the NeuroArm, has revolutionized surgical techniques by providing surgeons with greater accuracy and the ability to perform intricate maneuvers that were previously challenging or impossible (3). The incorporation of robotic systems in neurosurgical practice has enabled minimally invasive techniques that significantly reduce patient recovery times, decrease the risk of complications, and improve overall surgical outcomes (4,5). By utilizing robotic arms that can execute precise movements and operate with high levels of dexterity, neurosurgeons can navigate the intricate anatomy of the brain and spinal cord with greater confidence (6). These advancements are further enhanced by the integration of sophisticated imaging techniques and real-time feedback mechanisms that aid surgeons in visualizing and manipulating delicate brain structures during operations (4).

Personalization in neurosurgery is essential, as it tailor's treatment plans to individual patient needs, considering unique anatomical variations, specific disease characteristics, and patient preferences (7, 8, 9). Personalization is particularly vital in neurosurgery, where even minor deviations from a patient's unique anatomical structure can result in significant complications or suboptimal outcomes. For instance, the use of preoperative imaging, such as MRI or CT scans, allows surgeons to create patient-specific models that inform surgical strategies and techniques (7). By

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incorporating patient-specific data into surgical planning and execution, personalized approaches can lead to more effective interventions and improved postoperative results (10,4).

Neural decoding, combined with artificial intelligence (AI), plays a crucial role in advancing personalized robotic neurosurgery. Neural decoding refers to the process of interpreting neural signals to understand brain activity and intentions, allowing for improved interaction between robotic systems and neural function (11,12,13). AI-driven approaches enhance neural decoding by leveraging machine learning algorithms to analyze complex neural data, predict patient-specific responses, and optimize robotic systems' performance (14,15). Recent advancements in artificial intelligence (AI) have enabled more sophisticated neural decoding techniques that can learn from vast datasets and adapt to individual neural patterns (15). AI-driven approaches promise to enhance robotic neurosurgery by providing real-time insights into neural activity, enabling personalized interventions based on each patient's specific neural patterns and responses.

This literature review aims to explore the intersection of neural decoding, AI technologies, and personalized robotic neurosurgery. It will address the following research questions:

What are the current advancements in neural decoding techniques for neurosurgery? How can AI-driven approaches enhance these techniques for personalized applications? What are the potential clinical implications of integrating these technologies in robotic neurosurgery? By addressing these questions, this review seeks to provide a comprehensive overview of the current state of research and future directions in the field.

2. Neural Decoding for Neurosurgery

Neural decoding encompasses a variety of techniques aimed at interpreting the electrical activity of the brain. These techniques have significant applications in neurosurgery, where understanding neural signals can inform surgical decisions, improve outcomes, and even enhance postoperative rehabilitation (16,11). Electrocorticography (ECoG) is one such technique that involves recording electrical activity directly from the surface of the brain, providing high spatial and temporal resolution (17). ECoG has been utilized in various neurosurgical procedures, particularly in epilepsy surgery, where identifying seizure foci is critical for effective treatment (18). The ability to precisely localize and map brain function during surgery allows for more targeted interventions, reducing the likelihood of damage to healthy tissue.

Existing studies have demonstrated the efficacy of neural decoding in real-time applications during surgery. For instance, a study by (11) showcased how neural signals could be decoded to control robotic prosthetics, offering insights into potential applications in neurosurgery. Additionally, (19) explored the use of neural decoding to predict motor outcomes in patients undergoing deep brain stimulation for movement disorders. Such predictive capabilities can significantly enhance surgical planning and intraoperative decision-making, as they provide insights into how a patient's brain may respond to specific surgical interventions.

In addition to ECoG, other neural decoding techniques such as electroencephalography (EEG), functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG) (11,20). functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG) have been explored for their potential applications in neurosurgery. EEG measures electrical activity on the scalp, providing valuable information about brain function but with limited spatial resolution (21). fMRI allows for non-invasive imaging of brain activity by measuring blood flow changes associated with neural activity, while MEG provides high temporal resolution for tracking brain dynamics (22). It offers high spatial resolution and can identify brain regions associated with specific functions or responses, making it useful for preoperative planning and intraoperative monitoring (23,24). Both techniques have been utilized in preoperative planning to identify critical brain areas involved in specific functions, aiding in the surgical strategy for tumor resection or epilepsy treatment (25).

Despite the advantages of neural decoding, several limitations exist. For example, the spatial resolution of non-invasive methods like EEG is often insufficient for precise localization of neural activity, which can impact the accuracy of surgical planning and intervention (21,20). Furthermore, invasive techniques such as ECoG pose risks of complications, including infection and damage to brain tissue (26,27). Variability in neural signals can pose challenges in achieving consistent decoding accuracy (20). Factors such as noise, signal degradation, and the individual differences in brain anatomy and function can affect the reliability of decoding algorithms. Furthermore, the need for extensive training datasets complicates the generalization of neural decoding models across different patients and surgical contexts (28). Therefore, addressing these challenges is crucial for advancing the field and maximizing the potential benefits of neural decoding in neurosurgery. Addressing these limitations requires ongoing research to improve the accuracy, safety, and applicability of neural decoding techniques in neurosurgery (29). Overall, neural decoding techniques are becoming increasingly integrated into neurosurgical practices, providing valuable information that enhances surgical precision and outcomes. As these techniques continue to evolve, it will be essential to address the associated challenges to fully realize their potential in improving neurosurgical interventions.

Artificial intelligence and machine learning techniques are revolutionizing neural decoding, allowing for more sophisticated analyses of complex neural data (30). These AI-driven approaches enhance traditional decoding methods by leveraging large datasets to identify patterns and predict outcomes with higher accuracy. Machine learning algorithms, such as support vector machines (SVM), convolutional neural networks (CNN), and recurrent neural networks (RNN), have been applied to neural decoding tasks to improve pattern recognition and predictive capabilities (31,13). These algorithms can analyze large volumes of neural data to identify patterns associated with specific cognitive or motor tasks, facilitating more accurate interpretation of neural signals (20,32,33).

Deep learning, in particular, has emerged as a powerful tool for neural decoding due to its ability to automatically extract relevant features from raw data without extensive manual pre-processing (34). For example, convolutional neural networks (CNNs) have been employed to decode visual information from neural signals, demonstrating high accuracy in predicting perceptual experiences based on brain activity (35). The ability of deep learning models to generalize across different conditions and individuals is particularly beneficial in the context of neurosurgery, where variations in anatomy and pathology are common.

A review of existing studies reveals several successful applications of AI in neural decoding for neurosurgery. For instance, (36) demonstrated the potential of deep learning algorithms to improve the accuracy of seizure detection in patients with epilepsy, significantly aiding surgical planning. Similarly, researchers have utilized AI algorithms to analyze ECoG data for motor control applications, enabling patients to control robotic devices with their thoughts (11). These advancements highlight the transformative potential of AI in enhancing the capabilities of neural decoding and improving patient outcomes in neurosurgical contexts. AI-driven approaches have shown promise in improving the accuracy of neural decoding for neurosurgical applications. For example, CNNs have been used to analyze fMRI data and predict brain activity associated with different cognitive tasks, enabling more precise localization of brain regions involved in specific functions (25). Additionally, RNNs have been employed to analyze time-series neural data, providing insights into dynamic brain activity and enhancing the understanding of neural processes over time (35,32).

Feature extraction is a critical aspect of AI-driven neural decoding. This process involves identifying relevant characteristics of neural signals that contribute to accurate decoding outcomes. Advanced techniques such as wavelet transforms and time-frequency analysis have been employed to enhance feature extraction processes, ultimately improving the performance of neural decoding algorithms (37,31,20). Advances in feature extraction methods, such as wavelet transform and principal component analysis (PCA), have improved the ability to capture and analyze complex neural signals (32,13). Additionally, dimensionality reduction techniques, such as principal component analysis (PCA) and t-distributed stochastic neighbor embedding (t-SNE), have been utilized to simplify complex neural data while retaining essential information (38). Furthermore, the integration of AI with neural decoding has enabled the development of real-time neural decoding systems that can provide immediate feedback during neurosurgical procedures (12,9).

Moreover, classification techniques play a vital role in determining the efficacy of neural decoding. Researchers have explored various classification algorithms, including decision trees, random forests, and ensemble methods, to optimize performance (39). Each of these techniques offers unique advantages and may be more suitable for specific types of neural data or clinical applications. For instance, ensemble methods, which combine multiple classifiers, have been shown to enhance classification accuracy by leveraging the strengths of different algorithms (40). While AI-driven approaches offer significant advantages, challenges remain. The requirement for large, annotated datasets for training AI models can be a barrier to widespread adoption, particularly in specialized neurosurgical contexts (13,31,12). Additionally, the interpretability of AI models poses concerns, as complex algorithms may produce results that are difficult for clinicians to understand and trust (41). Addressing these issues is essential for the successful integration of AI-driven neural decoding in clinical practice. Ongoing research is focused on developing more robust algorithms, improving data acquisition methods, and ensuring the clinical applicability of AI-driven neural decoding techniques (8,9).

Furthermore, the ethical implications of AI-driven neural decoding must be considered. Issues related to patient consent, data privacy, and algorithmic bias can significantly impact the deployment of AI technologies in neurosurgery (42). Establishing transparent practices and regulatory frameworks will be crucial to ensuring that AI-driven neural decoding is utilized responsibly and equitably in clinical settings. AI-driven approaches for neural decoding are rapidly evolving and hold great promise for enhancing the precision and effectiveness of robotic neurosurgery. By improving the accuracy of neural signal interpretation and enabling personalized interventions, these technologies have the potential to transform the landscape of neurosurgical care.

3. Personalized Robotic Neurosurgery

Personalized medicine has emerged as a cornerstone of modern healthcare, offering tailored treatment strategies that consider individual patient characteristics (43). In the context of neurosurgery, personalized approaches are particularly vital due to the complex and varied nature of neurological conditions. Each patient's unique anatomy, disease progression, and treatment response necessitate customized surgical strategies to optimize outcomes and minimize risks (7). Personalized medicine aims to tailor healthcare interventions to individual patients based on their unique characteristics, and this principle is increasingly applied in neurosurgery. Personalized robotic neurosurgery leverages advanced imaging, genetic information, and real-time data to customize surgical approaches, thereby enhancing precision and optimizing outcomes (44,10). By integrating patient-specific data, surgeons can develop more accurate surgical plans that account for individual anatomical and functional variations, reducing the risk of complications and improving overall effectiveness (15,4).

Robotic neurosurgery plays a critical role in advancing personalized medicine by providing surgeons with precise control and enhanced visualization during procedures. The use of robotic systems such as the ROSA and NeuroArm, play a crucial role in personalized neurosurgery by providing precise control and adaptability during surgical procedures. These systems enable surgeons to perform intricate maneuvers with high accuracy, which is particularly beneficial for operations involving delicate brain regions (1,3). It also allows for the integration of patient-specific data, such as preoperative imaging and neural decoding results, into surgical planning (12). This integration enables surgeons to develop tailored approaches that account for individual anatomical variations and optimize surgical techniques for each patient (32,13).

One notable example of personalized robotic neurosurgery is the use of preoperative imaging data to create 3D models of a patient's brain. These models can be utilized in simulation environments to plan the surgical approach, allowing surgeons to visualize the relationship between critical structures and identify optimal entry points (8,12,40). Additionally, intraoperative imaging technologies, such as intraoperative MRI and fluoroscopy, can provide real-time feedback, enabling surgeons to adjust their techniques based on patient-specific anatomical considerations (45).

Moreover, the incorporation of neural decoding technologies into robotic systems enhances the personalization of neurosurgical interventions. By interpreting neural signals in real-time, surgeons can adapt their strategies based on the patient's responses during surgery. For instance, in cases of tumor resection, neural decoding can help identify critical functional areas of the brain, allowing surgeons to preserve essential functions while effectively removing pathological tissue (46).

Despite the advantages of personalized robotic neurosurgery, challenges remain in implementing these approaches on a broader scale. Variability in individual patient responses, the need for robust and reliable neural decoding algorithms, and the requirement for extensive training data can hinder the widespread adoption of personalized strategies (28,47,14). Additionally, the integration of advanced technologies into clinical workflows necessitates ongoing training and education for surgeons to ensure they can effectively utilize these systems in practice. Personalized robotic neurosurgery represents a promising advancement in neurosurgical care. By integrating patient-specific data and neural decoding technologies, surgeons can develop tailored strategies that enhance surgical precision and improve patient outcomes. As research and technology continue to evolve, the future of personalized neurosurgery holds great potential for transforming patient care.

The integration of neural decoding and AI technologies into personalized robotic neurosurgery represents a significant advancement in the field, with the potential to enhance surgical precision, improve outcomes, and revolutionize patient care (15). By combining real-time neural signal interpretation with AI-driven decision-making, surgeons can develop personalized treatment strategies that are tailored to each patient's unique neural patterns and anatomical features. (12,13)

Existing studies have explored various aspects of this integration, demonstrating the potential benefits of AI-driven neural decoding in robotic neurosurgery. For example, (48) examined the use of ML model to accurately differentiate skilled and less-skilled performance using EEG data recorded during a simulated surgery, explored the relative importance of each EEG bandwidth to expertise, and analyzed differences in EEG band powers between skilled and less-skilled individuals . This predictive capability can enable surgeons to make informed decisions during surgery, tailoring their approaches based on real-time feedback from the patient's neural activity. Research has shown that AI-driven neural decoding can improve the accuracy of brain-mapping procedures, allowing for more precise targeting of functional brain areas during surgery (8,9). Additionally, real-time neural decoding systems have been developed to provide immediate feedback during surgery, enabling dynamic adjustments based on the patient’s specific neuroanatomy and functional needs (12,13).

Moreover, the integration of AI-driven neural decoding with robotic systems allows for the development of adaptive surgical techniques. Robotic systems equipped with AI capabilities can adjust their movements and strategies based on the patient's neural responses, optimizing surgical interventions while minimizing risks (47). This adaptability is particularly valuable in complex procedures, where the surgical landscape may change dynamically based on the patient's condition.

Additionally, the incorporation of AI-driven neural decoding can enhance the precision of robotic systems. Advanced machine learning algorithms can analyze vast datasets to identify subtle patterns in neural signals that may indicate specific patient needs (28). By leveraging these insights, robotic systems can improve their performance, leading to more accurate and effective interventions.

However, the integration of neural decoding and AI in personalized robotic neurosurgery also presents several challenges. One of the primary challenges is the variability in neural signals among individuals, which can affect the accuracy and reliability of decoding algorithms (20). Factors such as differences in brain anatomy, pathology, and the presence of comorbid conditions can complicate the development of universally applicable models. To address this issue, extensive collaborations across institutions will be essential to develop comprehensive datasets that capture the diversity of neural signals across different populations (13)

Moreover, ethical considerations must be considered when integrating AI technologies into clinical practice. Issues related to patient consent, data privacy, and algorithmic transparency are paramount to ensuring trust between patients and healthcare providers (42). Establishing clear ethical guidelines and regulatory frameworks will be crucial for the responsible deployment of these technologies in clinical settings. The integration of neural decoding and AI technologies into personalized robotic neurosurgery offers promising advancements that can enhance surgical precision and improve patient outcomes. By leveraging real-time neural signal interpretation and adaptive robotic systems, surgeons can develop tailored treatment strategies that optimize interventions for individual patients. As research and technology continue to evolve, addressing the associated challenges and ethical considerations will be vital for realizing the full potential of these innovations in clinical practice.

4. Clinical Applications and Future Directions

The clinical applications of AI-driven neural decoding for personalized robotic neurosurgery are vast and hold significant promise for improving patient care. By enhancing surgical precision and tailoring interventions to individual patient needs, these technologies can address a range of neurological conditions, including tumors, epilepsy, and movement disorders (4,44).

One of the most promising applications lies in the field of tumor resection. AI-driven neural decoding can assist surgeons in identifying critical functional areas of the brain while excising tumors, thereby preserving essential neurological functions (46). Real-time feedback from neural signals can guide surgical decisions, allowing for more targeted interventions and minimizing complications associated with traditional approaches. (20,9)

Additionally, the integration of AI and neural decoding technologies can enhance the management of epilepsy. For patients with drug-resistant epilepsy, robotic systems equipped with neural decoding capabilities can accurately localize seizure foci, guiding the surgical resection of affected areas (36). This approach can significantly improve outcomes for individuals suffering from debilitating seizures, providing relief and improving their quality of life.

Looking ahead, future research directions in this field should focus on several key areas. First, efforts should be made to enhance the robustness and generalizability of neural decoding algorithms. This will involve collaboration among institutions to develop comprehensive datasets that reflect diverse patient populations and neural signals (13). Additionally, ongoing research should explore novel applications of AI-driven neural decoding in emerging fields such as neurorehabilitation, where these technologies can be utilized to optimize personalized rehabilitation strategies for patients recovering from neurological injuries. (8,40).

Furthermore, interdisciplinary collaborations among neurosurgeons, neuroscientists, and AI researchers will be essential to drive innovation and translate research findings into clinical practice. By fostering a collaborative environment, healthcare providers can develop practical solutions that address the unique challenges of personalized robotic neurosurgery.

The clinical applications of AI-driven neural decoding for personalized robotic neurosurgery are poised to transform the landscape of neurosurgical care. By enhancing surgical precision and tailoring interventions to individual patient needs, these technologies can improve outcomes for patients with various neurological conditions. Future research and collaboration will be vital to realizing the full potential of these advancements in clinical settings.

5. Challenges and Limitations

Despite the significant advancements in AI-driven neural decoding for personalized robotic neurosurgery, several challenges and limitations must be addressed to ensure successful implementation and patient outcomes. One of the primary challenges is the inherent variability of neural signals among individuals, which can affect the accuracy and reliability of neural decoding algorithms (20). Variability arises from differences in brain anatomy, pathology, and the presence of comorbid conditions, making it difficult to develop universally applicable models. (14,47)

Additionally, the requirement for large, high-quality datasets poses a significant barrier to the advancement of AI-driven approaches in this field (28). Many existing datasets may lack the necessary annotations or diversity to adequately train and validate AI models, limiting their applicability in real-world clinical settings. Collaborations across institutions to develop comprehensive databases will be crucial in overcoming this limitation (13). Ethical considerations also play a significant role in the development and implementation of AI-driven neural decoding technologies. Concerns regarding patient privacy, data security, and algorithmic transparency must be addressed to foster trust among patients and clinicians (42). Establishing clear ethical guidelines and regulatory frameworks will be essential for the responsible deployment of these technologies in clinical practice.

Moreover, the interpretability of AI models poses additional challenges. Complex algorithms may produce results that are difficult for clinicians to understand, potentially hindering their adoption in clinical settings (41). Developing explainable AI models that provide insights into their decision-making processes will be critical to ensuring that healthcare providers can trust and utilize these technologies effectively.

Finally, the integration of AI and neural decoding into clinical practice requires ongoing education and training for healthcare providers. As new technologies emerge, it is essential that neurosurgeons and other clinicians are equipped with the knowledge and skills to effectively incorporate these innovations into their practice (30). Continued professional development and training programs will be necessary to ensure that healthcare providers are prepared to navigate the complexities of personalized robotic neurosurgery.

Another limitation is the high cost associated with advanced robotic systems and AI technologies, which can limit accessibility and widespread adoption (8,40). Addressing these financial and logistical challenges is essential for making personalized robotic neurosurgery more accessible to a broader patient population.

Potential sources of bias and limitations in existing studies include small sample sizes, variability in data acquisition methods, and differences in study protocols (14,20). To address these issues, future research should focus on conducting larger, multi-center studies to validate findings and improve the generalizability of results (32,13).

The integration of AI-driven neural decoding for personalized robotic neurosurgery holds great promise, several challenges and limitations must be addressed. By focusing on variability in neural signals, dataset development, ethical considerations, model interpretability, and provider education, the field can advance toward realizing the full potential of these technologies in improving patient outcomes.

Abbreviations and their meanings

ROSA:	Robotic Stereotactic Assistance
NeuroArm:	A specialized robotic system for neurosurgery
MRI:	Magnetic Resonance Imaging
CT:	Computed Tomography

AI:	Artificial Intelligence
ECoG:	Electrocorticography
EEG:	Electroencephalography
fMRI:	Functional Magnetic Resonance Imaging
MEG:	Magnetoencephalography
SVM:	Support Vector Machine
CNN:	Convolutional Neural Network
RNN:	Recurrent Neural Network
PCA:	Principal Component Analysis
t-SNE:	t-distributed Stochastic Neighbor Embedding

6. Conclusion and Recommendation

In summary, the integration of neural decoding with AI technologies in personalized robotic neurosurgery represents a ground-breaking advancement in the field of neurosurgery. By enhancing the precision and effectiveness of surgical interventions, these technologies hold great promise for improving patient outcomes across a range of neurological conditions.

Neural decoding techniques provide valuable insights into brain activity, enabling surgeons to make informed decisions during procedures. The application of AI-driven approaches enhances the capabilities of neural decoding, allowing for real-time interpretation of neural signals and adaptive surgical strategies. The potential for personalized robotic neurosurgery to optimize treatment plans based on individual patient needs underscores the significance of this field in modern healthcare. While numerous advancements have been made, challenges remain in ensuring the widespread adoption of these technologies. Variability in neural signals, the need for comprehensive datasets, ethical considerations, and model interpretability are all factors that must be addressed for successful implementation. As research and technology continue to evolve, collaborative efforts among clinicians, researchers, and institutions will be essential in driving innovation and translating findings into clinical practice.

The future of personalized robotic neurosurgery is promising, with potential applications extending beyond traditional surgical interventions. As AI and neural decoding technologies advance, opportunities for novel applications in neurorehabilitation and postoperative care will emerge, further enhancing patient outcomes and quality of life (4,46). By embracing these innovations and addressing the associated challenges, the field of neurosurgery can continue to evolve and provide patients with the highest quality of care.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that there is no conflict of interest.

References

[1] Klodmann J, Schlenk C, Hellings-Kuß A, Bahls T, Unterhinninghofen R, Albu-Schäffer A, Hirzinger G. An introduction to robotically assisted surgical systems: current developments and focus areas of research. Current Robotics Reports. 2021 Sep;2(3):321-32.

[2] Mallela AN, Beiriger J, Gersey ZC, Shariff RK, Gonzalez SM, Agarwal N, González-Martínez JA, Abou-Al-Shaar H. Targeting the future: developing a training curriculum for robotic assisted neurosurgery. World neurosurgery. 2022 Nov 1;167:e770-7.

[3] Holland J, Kingston L, McCarthy C, Armstrong E, O'Dwyer P, Merz F, McConnell M. Service robots in the healthcare sector. Robotics. 2021 Mar 11;10(1):47.

[4] Runciman M, Darzi A, Mylonas GP. Soft robotics in minimally invasive surgery. Soft robotics. 2019 Aug 1;6(4):423-43.

[5] Alluri RK, Sivaganesan A, Vaishnav AS, Qureshi SA. Robotic guided minimally invasive spine surgery. InMinimally Invasive Spine Surgery-Advances and Innovations 2021 Apr 26. IntechOpen.

[6] Singh R, Wang K, Qureshi MB, Rangel IC, Brown NJ, Shahrestani S, Gottfried ON, Patel NP, Bydon M. Robotics in neurosurgery: current prevalence and future directions. Surgical Neurology International. 2022;13.

[7] Achrol AS, Steinberg GK. Personalized medicine in cerebrovascular neurosurgery: precision neurosurgical management of cerebral aneurysms and subarachnoid hemorrhage. Frontiers in Surgery. 2016 Jun 22; 3:34.

[8] Vezirska D, Milev M, Laleva L, Nakov V, Spiriev T. Three-dimensional printing in neurosurgery: a review of current indications and applications and a basic methodology for creating a three-dimensional printed model for the neurosurgical practice. Cureus. 2022 Dec;14(12).

[9] Kalani MY, Theodore N, editors. Personalized medicine and neurosurgery. Frontiers Media SA; 2017 Nov 22

[10] Fontana EJ, Benzinger T, Cobbs C, Henson J, Fouke SJ. The evolving role of neurological imaging in neuro-oncology. Journal of neuro-oncology. 2014 Sep; 119:491-502.

[11] Lebedev MA, Nicolelis MA. Brain–machine interfaces: past, present and future. TRENDS in Neurosciences. 2006 Sep 1;29(9):536-46.

[12] Madhavan K, Kolcun JP, Chieng LO, Wang MY. Augmented-reality integrated robotics in neurosurgery: are we there yet?. Neurosurgical focus. 2017 May 1;42(5):E3.

[13] Mattei TA, Rodriguez AH, Sambhara D, Mendel E. Current state-of-the-art and future perspectives of robotic technology in neurosurgery. Neurosurgical review. 2014 Jul; 37:357-66.

[14] Pangal DJ, Cote DJ, Ruzevick J, Yarovinsky B, Kugener G, Wrobel B, Ference EH, Swanson M, Hung AJ, Donoho DA, Giannotta S. Robotic and robot-assisted skull base neurosurgery: systematic review of current applications and future directions. Neurosurgical Focus. 2022 Jan 1;52(1): E15.

[15] Panesar SS, Kliot M, Parrish R, Fernandez-Miranda J, Cagle Y, Britz GW. Promises and perils of artificial intelligence in neurosurgery. Neurosurgery. 2020 Jul 1;87(1):33-44.

[16] Nicolelis MA, Lebedev MA. Principles of neural ensemble physiology underlying the operation of brain–machine interfaces. Nature reviews neuroscience. 2009 Jul;10(7):530-40.

[17] Serruya MD, Hatsopoulos NG, Paninski L, Fellows MR, Donoghue JP. Instant neural control of a movement signal. Nature. 2002 Mar 14;416(6877):141-2.

[18] Fukushima M, Chao ZC, Fujii N. Studying brain functions with mesoscopic measurements: Advances in electrocorticography for non-human primates. Current opinion in neurobiology. 2015 Jun 1; 32:124-31.

[19] Usman SM, Khalid S, Aslam MH. Epileptic seizures prediction using deep learning techniques. Ieee Access. 2020 Feb 27; 8:39998-40007.

[20] Mirchi N, Warsi NM, Zhang F, Wong SM, Suresh H, Mithani K, Erdman L, Ibrahim GM. Decoding intracranial EEG with machine learning: a systematic review. Frontiers in Human Neuroscience. 2022 Jun 27; 16:913777.

[21] Niedermeyer, E. (2011). Niedermeyer's electroencephalography: basic principles, clinical applications, and related fields. Lippincott Williams & Wilkins

[22] Hämäläinen M, Hari R, Ilmoniemi RJ, Knuutila J, Lounasmaa OV. Magnetoencephalography—theory, instrumentation, and applications to noninvasive studies of the working human brain. Reviews of modern Physics. 1993 Apr 1;65(2):413.

[23] Ogawa S, Tank DW, Menon R, Ellermann JM, Kim SG, Merkle H, Ugurbil K. Intrinsic signal changes accompanying sensory stimulation: functional brain mapping with magnetic resonance imaging. Proceedings of the National Academy of Sciences. 1992 Jul 1;89(13):5951-5.

[24] Buckner RL, Logan JM. Functional neuroimaging methods: PET and fMRI. Handbook of functional neuroimaging of cognition. 2001:27-48.

[25] Watanabe Y. PET/SPECT/MRI/fMRI studies in the myalgic encephalomyelitis/chronic fatigue syndrome. PET and SPECT in Psychiatry. 2021:985-1001

[26] Buzsaki G. Rhythms of the Brain. Oxford university press; 2006 Aug 3.

[27] Engel J, McDermott MP, Wiebe S, Langfitt JT, Stern JM, Dewar S, Sperling MR, Gardiner I, Erba G, Fried I, Jacobs M. Early surgical therapy for drug-resistant temporal lobe epilepsy: a randomized trial. Jama. 2012 Mar 7;307(9):922-30

[28] Panuccio G, Semprini M, Natale L, Buccelli S, Colombi I, Chiappalone M. Progress in Neuro-engineering for brain repair: New challenges and open issues. Brain and neuroscience advances. 2018 May 21; 2:2398212818776475

[29] Crone NE, Sinai A, Korzeniewska A. High-frequency gamma oscillations and human brain mapping with electrocorticography. Progress in brain research. 2006 Jan 1; 159:275-95.

[30] Kumar K, Kumar P, Deb D, Unguresan ML, Muresan V. Artificial intelligence and machine learning based intervention in medical infrastructure: a review and future trends. InHealthcare 2023 Jan 10 (Vol. 11, No. 2, p. 207). MDPI.

[31] Lotte F, Bougrain L, Cichocki A, Clerc M, Congedo M, Rakotomamonjy A, Yger F. A review of classification algorithms for EEG-based brain–computer interfaces: a 10 year update. Journal of neural engineering. 2018 Apr 16;15(3):031005.

[32] Saeidi M, Karwowski W, Farahani FV, Fiok K, Taiar R, Hancock PA, Al-Juaid A. Neural decoding of EEG signals with machine learning: a systematic review. Brain Sciences. 2021 Nov 18;11(11):1525

[33] Liu F, Meamardoost S, Gunawan R, Komiyama T, Mewes C, Zhang Y, Hwang E, Wang L. Deep learning for neural decoding in motor cortex. Journal of Neural Engineering. 2022 Sep 23;19(5):056021

[34] LeCun Y, Bottou L, Bengio Y, Haffner P. Gradient-based learning applied to document recognition. Proceedings of the IEEE. 1998 Nov;86(11):2278-324.

[35] Zhang, Y.J., Yu, Z.F., Liu, J.K. and Huang, T.J., 1997. Neural decoding of visual information across different neural recording modalities and approaches. Machine Intelligence Research

[36] Abbasi B, Goldenholz DM. Machine learning applications in epilepsy. Epilepsia. 2019 Oct;60(10):2037-47.

[37] Khosla A, Khandnor P, Chand T. A comparative analysis of signal processing and classification methods for different applications based on EEG signals. Biocybernetics and Biomedical Engineering. 2020 Apr 1;40(2):649-90.

[38] Van der Maaten L, Hinton G. Visualizing data using t-SNE. Journal of machine learning research. 2008 Nov 1;9(11).

[39] Kell DB, Samanta S, Swainston N. Deep learning and generative methods in cheminformatics and chemical biology: navigating small molecule space intelligently. Biochemical Journal. 2020 Dec 11;477(23):4559-80.

[40] Zhou ZH. Ensemble methods: foundations and algorithms. CRC press; 2012 Jun 6.

[41] Caruana R, Niculescu-Mizil A. An empirical comparison of supervised learning algorithms. InProceedings of the 23rd international conference on Machine learning 2006 Jun 25 (pp. 161-168).

[42] Dagi TF, Barker FG, Glass J. Machine learning and artificial intelligence in neurosurgery: status, prospects, and challenges. Neurosurgery. 2021 Aug 1;89(2):133-42.

[43] Collins FS, Varmus H. A new initiative on precision medicine. New England journal of medicine. 2015 Feb 26;372(9):793-5.

[44] Boutet A, Gramer R, Steele CJ, Elias GJ, Germann J, Maciel R, Kucharczyk W, Zrinzo L, Lozano AM, Fasano A. Neuroimaging technological advancements for targeting in functional neurosurgery. Current Neurology and Neuroscience Reports. 2019 Jul; 19:1-1

[45] Jolesz FA. Future perspectives for intraoperative MRI. Neurosurgery Clinics. 2005 Jan 1;16(1):201-13.

[46] Zhang H, Feng Y, Cheng L, Liu J, Li H, Jiang H. Application of diffusion tensor tractography in the surgical treatment of brain tumors located in functional areas. Oncology Letters. 2020 Jan 1;19(1):615-22.

[47] D'Angelo E, Antonietti A, Casali S, Casellato C, Garrido JA, Luque NR, Mapelli L, Masoli S, Pedrocchi A, Prestori F, Rizza MF. Modeling the cerebellar microcircuit: new strategies for a long-standing issue. Frontiers in cellular neuroscience. 2016 Jul 8; 10:176.

[48] Natheir S, Christie S, Yilmaz R, Winkler-Schwartz A, Bajunaid K, Sabbagh AJ, Werthner P, Fares J, Azarnoush H, Del Maestro R. Utilizing artificial intelligence and electroencephalography to assess expertise on a simulated neurosurgical task. Computers in Biology and Medicine. 2023 Jan 1; 152:106286