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MODERN DIAGNOSTIC METHODS USING NEUROIMAGING IN NEUROLOGY AND NEUROSURGERY

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The purpose of the study was to provide a comprehensive overview of current neuroimaging technologies in neurology and neurosurgery, with a focus on their diagnostic and therapeutic applications. This review explores the neuroimaging technologies currently in clinical use that form the basis of modern diagnosis and treatment of neurological and neurosurgical diseases. A systematic analysis of studies from 2020 to 2025, drawn from medical databases Scopus, Web of Science, PubMed, and Google Scholar, highlights the advantages of neuroimaging technologies, which provide detailed, safe, and non-invasive information about the structure and function of the brain and central nervous system. The authors stress that computed tomography, magnetic resonance imaging, functional MRI, and positron emission tomography have become integral to clinical practice in neurology and neurosurgery. CT provides rapid and accessible diagnostics for patients with emergencies such as traumatic brain injury or stroke, thanks to its ability to quickly detect intracranial haemorrhages, fractures, and other damage. MRI is the gold standard for assessing neurodegenerative diseases, tumours, strokes, and brain injuries, as it offers high sensitivity to soft tissues, allowing for accurate localisation of pathological changes. Functional MRI, which measures brain activity by detecting changes in blood flow, is an important tool for neurosurgical planning, especially for localising functional areas of the brain prior to surgery. PET, in turn, allows the detection of molecular changes in brain tissue, which is important for the early diagnosis of diseases such as brain cancer, Alzheimer's, and Parkinson's. The basic conclusion is that further neuroimaging development promises significant improvements in the accuracy of diagnosis and personalisation of treatment for patients with neurological diseases.

Key words: magnetic resonance imaging, computed tomography, positron emission tomography, neurodegenerative diseases, brain activity, neurology, neurosurgery, diagnostics, treatment.

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СУЧАСНІ НЕЙРОВІЗУАЛІЗАЦІЙНІ МЕТОДИ ДІАГНОСТИКИ В НЕВРОЛОГІЇ ТА НЕЙРОХІРУРГІЇ

Метою дослідження була комплексна оцінка сучасних технологій нейровізуалізації в неврології та нейрохірургії, з акцентом на їхньому діагностичному та клінічному застосуванні. У цьому огляді досліджено технології нейровізуалізації, які використовуються в сучасній клінічній практиці та є основою сучасної діагностики та лікування неврологічних та нейрохірургічних захворювань. Систематичний аналіз досліджень з 2020 по 2025 роки, взятих з медичних баз даних Scopus, Web of Science, PubMed and Google Scholar, підкреслює переваги нейровізуалізаційних технологій, оскільки вони надають детальну, безпечну та неінвазивну інформацію про структуру та функції мозку і центральної нервової системи. Автори наголошують на тому, що використання комп'ютерної та магнітно-резонансної томографії, функціональної МРТ та позитронно-емісійної томографії стало невід'ємною частиною клінічної практики в неврології та нейрохірургії. КТ забезпечує швидку і доступну діагностику для пацієнтів з екстреними випадками, такими як черепно-мозкові травми чи інсульти, завдяки здатності швидко виявляти внутрішньочерепні крововиливи, переломи та інші пошкодження. МРТ є золотим стандартом для оцінки нейродегенеративних захворювань, пухлин, інсультів та травм головного мозку, оскільки дає високу чутливість до м'яких тканин, дозволяючи точну локалізацію патологічних змін. Функціональна МРТ, що вимірює мозкову активність через зміни кровообігу, є важливим інструментом для нейрохірургічного планування, особливо в локалізації функціональних областей мозку до операції. ПЕТ, у свою чергу, дозволяє виявити молекулярні зміни в тканинах мозку, що важливо для ранньої діагностики раку мозку, хвороб Альцгеймер та Паркінсона. В якості провідного висновку автори прогнозують більшу суттєве покращення точності діагностики та персоналізації лікування пацієнтів з неврологічними захворюваннями в разі подальшого розвитку нейровізуалізації.

Ключові слова: магнітно-резонансна томографія, комп'ютерна томографія, позитронно-емісійна томографія, нейродегенеративні захворювання, мозкова активність, неврологія, нейрохірургія, діагностика, лікування.

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In the contemporary world, people have become more prone to the risk of both acute threat and life-threatening neurological pathologies and chronic progressive conditions that are acquired over time [23, 36, 39]. The cases of stroke, traumatic brain injury, and intracranial hemorrhage are urgent and demand diagnostic processes in a fast and accurate approach to inform timely and effective therapeutic intervention practices [37, 41]. Concurrently, chronic neurological diseases, such as neurodegenerative diseases, tumors, and epilepsy, develop latently, and they tend to have weak symptoms which can be enhanced as the illness deteriorates [4, 19, 29, 34]. Such clinical conditions are sensitive and require proper, timely diagnosis to best manage patients.

Neuroimaging plays a central role in addressing the numerous challenges in modern neurodiagnostics by providing comprehensive, non-invasive information on the anatomical and functional properties of the brain and the central nervous system (CNS) [43]. In the last few decades, neuroimaging technology has advanced, transforming the way patients with various neurological and neurosurgical conditions are diagnosed, treated, and followed up [24]. The development of imaging modalities chronologically, starting with the application of computed tomography (CT) to more advanced techniques of magnetic resonance imaging (MRI), functional MRI (fMRI), and positron emission tomography (PET), has given clinicians an unprecedented ability to visualize and quantify the structures and functions in the brain [9, 33]. These modalities have therefore become indispensable resources in daily clinical practice and research, offering careful assessments of brain structure, tissue integrity, metabolic activity, and neuronal connectivity.

In neurosurgery, neuroimaging is a vital part of preoperative planning and operative guidance as well as the reduction of iatrogenic damage to critical cortical and subcortical areas. For example, MRI and fMRI allow precise delineation of neoplastic lesions, eloquent functional areas, and epileptogenic foci, which informs resection design and minimizes postoperative neurological impairment [15, 17]. Neuroimaging is essential in providing the clinical diagnosis and longitudinal evaluation of a wide range of neurological disorders, such as cerebrovascular incidents, multiple sclerosis, Alzheimer's disease, and other neurodegenerative diseases [14, 31]. These methods can help with early pathological diagnosis, disease progression, and treatment effects, thereby enabling prompt, personalized interventions.

Even though neuroimaging technologies have developed significantly, much remains to be done. The rapid acceleration of innovation, the increasing complexity, and the cost of imaging methodologies frustrate the realization of universal accessibility and the standardization of imaging protocols across sites [7, 12, 13]. Furthermore, the adoption of emerging computational technologies, such as artificial intelligence (AI) and machine learning algorithms, into neuroimaging analysis presents both promising opportunities and significant challenges in validation, reliability, and meaningful integration into clinical practice [22, 27]. Based on this, it is essential to conduct a thorough assessment of the current state of neuroimaging in neurosurgery and neurology to summarize available data, shed light on unresolved issues, and determine the future direction of research and practice.

The purpose of the study was to provide a comprehensive overview of current neuroimaging technologies in neurology and neurosurgery, with a focus on their diagnostic and therapeutic applications.

Materials and methods. To achieve the goal of the review, a thorough analysis of the international scientific literature indexed in major databases, including Scopus, Web of Science, PubMed, and Google Scholar, was conducted, covering English-language articles published from 2020 to 2025. The last search query was performed on February 11, 2025.

A meticulous, strategic search process was employed for each database, using a broad range of keywords relevant to neuroimaging and appropriate Boolean operators (e.g., AND, OR).

For explanation. When searching for scientific literature in a Scopus database the following verbatim search query was used: “neuroimaging”, “functional MRI”, “magnetic resonance spectroscopy”, “positron emission tomography”, “computed tomography”, “neurosurgery”, “neurology”, “brain tumor resection planning”, “epilepsy neuroimaging”, “stroke imaging”, “neuroplasticity imaging”, “artificial intelligence in neuroimaging”, “multi-modal neuroimaging”, “neurovascular malformation imaging”, “intraoperative imaging in neurosurgery”, “dementia imaging in neuroscience”, and “image-guided neurosurgery”.

Similar search strategies were subsequently used in other databases – Web of Science, PubMed, and Google Scholar. This extensive collection of keywords ensured a comprehensive search that captured the latest advancements in both the clinical applications of neuroimaging and the cutting-edge technological innovations driving neurosurgery and neurology.

The inclusion criteria for the review were strictly defined to ensure the inclusion of high-quality, relevant studies. Only original research articles, systematic reviews, and meta-analyses published in peer-reviewed journals were considered for inclusion. Emphasis was placed on studies published in English, which were prioritized for their broader accessibility and relevance to the international scientific community. Studies published in Ukrainian were also included to reflect regional contributions to the field.

The exclusion criteria were equally important. Conference abstracts, editorials, and non-peer-reviewed articles were excluded due to their limited rigor and relevance to the review’s goals. Only studies that provided substantial insights into the application of neuroimaging methods in clinical settings-such as diagnostics, surgical planning, and disease monitoring in neurosurgery and neurology, were retained for inclusion.

As this is a review article based on publicly available literature, ethical approval was not required. The study protocol was performed in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. Hence, a total of 446 articles were selected. After removing duplicates and those not meeting the inclusion criteria, a portion was selected for full-text review. Therefore, 43 manuscripts were included (Table 1).

Table 1

Simplified PRISMA Flow

Stage	Description	Number of Records/Studies
1. Identified	Total number of records identified through database searching and other sources	446
2. Duplicates Removed	Number of records removed before screening (e.g., duplicates)	49
3. Screened (Title/Abstract)	Number of records screened after duplicates were removed	397
4. Assessed for Eligibility (Full-text)	Number of full-text articles assessed for eligibility against the inclusion/exclusion criteria	94
5. Included in Review	Total number of primary studies finally included in the systematic review	43

Neuroimaging is part of modern medicine, especially in such branches as neurosurgery and neurology [20]. The modalities help clinicians obtain exhaustive anatomical and functional information on the brain and central nervous system, thereby enabling accurate diagnostic assessments, careful treatment planning, and surgical procedures. This has significantly changed the management paradigm in patients with neurological and neurosurgical conditions, as neuroimaging technologies provide safe, non-invasive images that enhance diagnostic efficacy and, in turn, improve the accuracy of therapeutic interventions.

Computed tomography is a standard and readily accessible neuroimaging modality that allows visualisation of intracranial structures using X-ray radiation [32]. Since becoming a part of the clinical protocols, CT has significantly altered the diagnostics of traumatic brain injury, cerebrovascular accident, intracranial haematoma, and other acute neurological conditions. This method has thus been developed as the standard of reference for the rapid and efficient examination of patients in emergency cases, where time is a critical factor. In the case of traumatic brain injury, CT allows one to identify focal lesions that require immediate neurosurgical care.

Shao et al. (2024) emphasise the key role of computed tomography in the diagnosis of traumatic brain injuries [30]. They note that CT is the primary method for assessing patients with acute head trauma, as it allows for the rapid and accurate detection of injuries requiring urgent surgical intervention. Of particular importance is the ability of CT to detect haemorrhages (intracranial haemorrhages), mass effect, and changes in ventricular size and bone fractures. The article also emphasises that CT is an indispensable method for assessing secondary injuries, such as cerebral oedema, ischaemia, and brain herniation, which may occur after the initial injury. Importantly, CT is an extremely fast and accessible method with few contraindications, making it ideal for primary diagnosis in emergencies.

In the case of a stroke, CT is used to rule out haemorrhage (haemorrhagic stroke), which is an essential first step before starting treatment [16]. Akbarzadeh et al. (2021) note that neuroimaging plays a crucial role in diagnosing acute ischemic stroke [2]. The authors emphasize that imaging should be secured during the so-called golden hour to prevent irreversible brain damage. Computed tomography is often used for its expeditiousness and ability to identify intracranial haemorrhage; however, magnetic resonance imaging, particularly diffusion-weighted imaging, has high sensitivity for detecting early ischemic changes. The review also considers the use of CT angiography and MR angiography in the assessment of the cerebral vasculature, and the future development of ultrasonography in the monitoring of cerebral blood flow. Lastly, the authors discuss the growing importance of telemedicine- telestroke- to increase access to stroke care. Altogether, despite MRI being more accurate for diagnostics, CT is the first-line modality due to its availability and time efficiency.

Magnetic resonance imaging is one of the most significant and advanced techniques in neuroimaging, producing high-resolution images without ionising radiation [25]. The technique uses the interaction between hydrogen nuclei, which are abundant in human tissues, with externally applied magnetic fields, combined with radiofrequency pulses [11]. This basic mechanism enables us to obtain both anatomical and functional datasets, making it irreplaceable for accurate diagnosis and therapeutic planning across a wide range of neurological and neurosurgical pathologies.

MRI's wide range of applications stems from its high sensitivity to soft tissues, especially the brain and spinal cord. MRI is used in the identification and follow-up studies of neurodegenerative disorders (Alzheimer's disease, Parkinson's disease), neoplasms, cerebrovascular accidents, multiple sclerosis, and in the evaluation of pathologic sequelae after a cerebral trauma and surgical intervention [8]. The key-ness of MRI has been further enhanced by its ability to provide detailed information about structure and function, achieved through specialized methods such as functional MRI (fMRI) and magnetic resonance spectroscopy (MRS). As a result, MRI helps in neurosurgical planning by allowing precise localisation of eloquent cortical and subcortical regions, thereby playing an essential role in reducing perioperative neurological deficits [38]. MRI is widely used to assess the morphology and hemodynamic integrity of the cerebral vasculature in ischemic stroke and vascular pathologies such as aneurysms and arterial stenosis.

Hussain O. et al (2023) review the significance of CT and MRI in diagnosing spinal cord injuries (SCI) [10]. Spinal injuries often result in long-term morbidity, with timely diagnosis crucial for preventing further neurological damage. CT, especially multidetector CT (MDCT), is the first-line imaging modality for evaluating bone fractures and traumatic lesions, offering high sensitivity for detecting fractures and soft-tissue abnormalities such as disk herniations and hematomas. New technologies like dual-energy CT (DECT) and photon-counting CT are improving diagnostic accuracy, especially in patients with metal implants. MRI, considered the gold standard for SCI diagnosis, provides detailed information on soft tissues, ligament instability, disk herniation, and spinal cord damage. Key MRI sequences, such as T2 and STIR, are highly sensitive to edema and hemorrhage, aiding in prognosis and surgical decision-making. Diffusion Tensor Imaging (DTI) provides insights into spinal cord microstructure, though artifacts and time constraints limit its clinical use. Functional MRI (fMRI) and perfusion MRI are emerging tools that assess functional activity and blood flow in the spinal cord, potentially guiding recovery and therapeutic targets. In conclusion, authors say both CT and MRI play crucial roles in diagnosing spinal trauma, with advancements in imaging technologies enhancing their ability to assess injury severity and predict outcomes.

Chen Y. et al. (2025) investigated the haemodynamic properties of the non-stenotic middle cerebral artery (MCA) in patients with cerebral ischaemia using 4D-MRI, comparing these properties with those of healthy individuals [5]. They focused on three segments of the MCA-proximal, curved, and distal-and measured various haemodynamic parameters, including blood flow, peak velocity, wall shear stress (WSS), pressure, and energy loss (EL). The study found that haemodynamic distribution in the SMA was similar between the ischaemic and healthy groups. However, patients with anterior cerebral circulation ischaemia showed lower peak blood flow velocity, circumferential WSS, and EL compared to healthy control groups.

Notably, the curved segment of the MCA in ischaemic patients had the lowest peak blood flow velocity and WSS, which may contribute to cerebrovascular events. These results suggest that morphological changes in the middle cerebral artery may alter blood flow dynamics, potentially leading to the progression of ischaemic stroke. The study highlights how 4D-MR blood flow imaging can provide valuable information about haemodynamic changes associated with cerebral ischaemia, even in the absence of stenosis, offering potential biomarkers for early detection and treatment of stroke.

Functional magnetic resonance imaging (fMRI) is a powerful tool for studying brain function, particularly for assessing neural activity in real time [6]. The difference between fMRI and standard MRI is that fMRI allows the assessment not only of anatomical structures but also of functional processes in the brain during specific tasks or at rest. Functional MRI is based on the principle of measuring changes in cerebral blood flow accompanying neural activity [21]. When brain cells are activated, they require a greater supply of oxygen, which in turn leads to local changes in blood flow. This altered oxygen supply can be detected using fMRI, which allows the creation of maps of brain activity during various cognitive or sensory tasks.

This method is particularly useful in neurosurgery for mapping functional areas of the brain before surgery, allowing surgeons to avoid damaging critical functional areas such as motor and speech centres. In neurology, fMRI is used to study neuroplasticity, assess brain activity in patients with epilepsy, and investigate changes in brain activity in patients with Alzheimer's, Parkinson's, and other neurodegenerative diseases [39, 42].

Recent improvements in fMRI techniques, such as the use of multi-modal approaches or integration with other neuroimaging methods, have significantly increased the accuracy and reliability of the data obtained. Due to its high sensitivity to changes in brain activity, fMRI is becoming an indispensable tool for studying the relationship between brain functions and various pathological processes.

Li et al. (2022) provides an overview of the use of functional magnetic resonance imaging (fMRI) for analyzing brain activity, specifically focusing on the method of blood oxygen level-dependent (BOLD) contrast imaging [18]. The BOLD technique identifies active brain regions by measuring changes in blood oxygen levels during various tasks or stimuli. The article emphasizes that BOLD-based fMRI offers high spatial resolution, enabling precise localization of active brain regions. However, there are limitations, such as the delay between the stimulus and the brain's vascular response (1-2 sec) and the need to repeat the stimulus several times to reduce noise in the data. This repetition is crucial for comparing results across different groups of individuals or animals involved in the study. Examples of fMRI use in studying various behavioural responses, such as motor and emotional activity, are provided. These examples illustrate how brain activity changes in response to tasks and stimuli. A key aspect of the research is comparing brain activity during rest and after stimulation, as well as examining changes in brain activity in different age groups and individuals with various diseases. In conclusion, fMRI is a powerful tool for investigating brain activity across various conditions, but its use requires careful control of experimental parameters to ensure reliable, accurate results.

The systematic review by Abu Mhanna H. et al. (2025) focuses on the applications of functional magnetic resonance imaging in preoperative planning and treatment assessment of brain tumours [1]. Discusses both task-based fMRI (T-fMRI), which localizes brain function during specific tasks, and resting-state fMRI (Rs-fMRI), which measures functional connectivity during rest. RS-fMRI has gained attention for its ability to detect functional networks in the brain, even when anatomical landmarks are absent, and has been used to study attention, speech, and memory networks in patients with brain tumours. It is particularly useful in patients who are uncooperative or impaired, such as children, paralyzed patients, or those with mental health conditions.

The review examines the validation of fMRI using direct cortical stimulation (DCS), which is considered the gold standard for localizing functional brain areas during surgery. fMRI has shown good concordance with DCS in mapping motor and language regions, although challenges remain in accurately localizing language functions. The combination of fMRI with other non-invasive techniques, such as navigated transcranial magnetic stimulation (nTMS), has shown promise in improving the accuracy of language localization and functional mapping. Furthermore, the review explores the potential of personalized fMRI, which enables the identification of functional regions within or near tumours, aiding more precise surgical planning. This technique has shown clinical potential in detecting changes in brain function after tumour resection and monitoring tumour response to therapy. Advances in real-time fMRI technologies, such as TurboFIRE, are also being developed to enable neurosurgeons to make decisions during surgery based on live brain activity data. Emphasizes the importance of fMRI in enhancing the precision of brain tumor surgeries, improving patient outcomes, and advancing our understanding of brain function [27, 31]. The continued development and integration of fMRI into clinical practice hold promise for improving the diagnosis, treatment planning, and monitoring of brain tumors.

Positron emission tomography (PET) is an innovative neuroimaging method that allows imaging of molecular processes in brain tissues [28]. PET uses radioactive isotopes that are introduced into the body via radioactive labels attached to specific molecules (e.g., glucose or oxygen), allowing their distribution and metabolic activity to be measured in real time. One of the main advantages of PET is its ability to assess brain metabolic activity, making this method extremely important for detecting pathologies at an early stage. This is particularly important for diagnosing brain cancer, studying neurodegenerative diseases (such as Alzheimer's and Parkinson's), and detecting epilepsy.

Compared with other neuroimaging methods, such as CT or MRI, PET provides information not only about brain anatomy but also about its functional state [40]. This allows detection of molecular-level changes that may precede visible structural changes. PET is often used to assess the metabolic activity of brain tissue after strokes or brain injuries, as well as to plan surgical interventions for tumours, where it is necessary to clearly define tumour boundaries. Recently, PET has been integrated with other neuroimaging methods, particularly MRI, enabling high-accuracy mapping and assessment of brain function as part of a comprehensive research approach [43].

Lijun Xie et al. (2024) consider the use of PET for the diagnosis of neurodegenerative diseases such as Parkinson's disease (PD), Alzheimer's disease (AD), and drug addiction [40]. PET is an essential tool for detecting brain biomarkers, enabling not only early diagnosis but also disease differentiation based on molecular and metabolic changes in the brain. In particular, PET allows detection of amyloid plaques and neurofibrillary tangles in AD and dopamine pathway dysfunction in PD, particularly in the substantia nigra and striatum. The article highlights the role of PET in monitoring neurodegenerative processes and evaluating treatment efficacy. In particular, the latest PET agents, such as 18F-Florzolotau and 18F-THK5351, allow for a detailed study of tau protein accumulation, which is a characteristic feature of AD. However, despite its numerous advantages, PET has limitations, particularly in the specificity and sensitivity of some contrast agents. At the same time, the article suggests potential directions for improving PET methods, including the development of new agents and innovative approaches to better assess brain function and treatment effects in patients with neurodegenerative diseases.

Neuroimaging technologies have revolutionized the field of neurosurgery and neurology, enabling clinicians to obtain comprehensive, non-invasive insights into the brain's structure and function [3, 11, 35]. Methods such as computed tomography, magnetic resonance imaging, functional MRI, and positron emission tomography have significantly enhanced diagnostic accuracy, therapeutic planning, and surgical precision. CT, as a fast and accessible imaging modality, remains the gold standard for acute cases such as traumatic brain injuries and cerebrovascular events.

MRI, with its ability to offer high-resolution anatomical images and functional data, plays a critical role in the assessment of neurodegenerative diseases, tumours, and other neurological conditions. The advent of functional MRI has further expanded the capabilities of neuroimaging, allowed real-time monitoring of brain activity, and facilitated preoperative mapping of critical brain regions. PET, with its molecular imaging capabilities, enables early detection of pathological processes, offering invaluable insight into conditions such as Alzheimer's disease and brain tumors.

These imaging techniques, individually and in combination, have reshaped clinical practices by providing vital information that guides therapeutic decisions, enhances surgical outcomes, and supports ongoing patient monitoring. Despite their tremendous potential, challenges remain, such as issues related to standardization, accessibility, and the integration of new technologies into routine clinical practice. Nevertheless, the continued advancement of neuroimaging techniques, coupled with emerging innovations like artificial intelligence, promises to further enhance the precision and personalization of care in neurosurgery and neurology.

Conclusions

1. Neuroimaging technologies have significantly improved diagnosis, treatment, and surgical outcomes in neurology and neurosurgery.

2. Modern neuroimaging techniques such as CT, MRI, fMRI, and PET provide detailed information about the structure and function of the brain, which facilitates accurate treatment planning and reduces risks during forthcoming treatment.

3. Modern neuroimaging techniques significantly enhanced diagnostic accuracy, therapeutic planning, and surgical precision. One should consider CT to be the gold standard in conditions of brain traumatic injuries and cerebrovascular events.

4. Possible brain damage and its involvement in the neuropathological process can be detected by imaging even before the onset of neurological symptoms, which is of particular value from a prognostic point of view.

5. Despite their tremendous potential, challenges remain, such as issues related to standardization, accessibility, and the integration of new technologies into routine clinical practice.

6. Neuroimaging high-resolution technological capabilities in neurology and neurosurgery, and their non-invasive application are of great importance, which maximally expand their arsenal of applications in modern conditions.

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