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Review

Neuroimaging Techniques in the Early Detection of Brain Tumors

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Abstract

This review examines the neuroimaging techniques essential for the early detection and management of brain tumors. The complexity and variability of brain tumors, whether benign or malignant, pose substantial diagnostic and treatment challenges. Accurate diagnosis heavily depends on imaging technologies such as magnetic resonance imaging (MRI), which offers detailed anatomical and functional information, and positron emission tomography (PET), which reveals metabolic processes. Additionally, emerging methods like functional magnetic resonance imaging (fMRI), single-photon emission computed tomography (SPECT), as well as advanced techniques such as diffuse optical imaging (DOI) and magnetoencephalography (MEG) are increasingly utilized to enhance detection capabilities. Despite the advancements, challenges remain in integrating these technologies for comprehensive tumor analysis. Future research directions should focus on refining multimodal imaging approaches, enhancing automated analysis with machine learning, and minimizing radiation exposure. Improved diagnostic precision and efficiency are essential for effective tumor management and treatment planning. This review highlights the need for ongoing advancements in imaging techniques and technology integration to improve early brain tumor detection and patient outcomes.

Keywords: *brain tumors, neuroimaging techniques, MRI, early detection, automated analysis*

Introduction

Brain tumors are abnormal growths that occur within brain tissue and can affect various brain functions. They can be benign or malignant, and their diagnosis and treatment can be complex. The location and classification of brain tumors are crucial for accurate diagnosis and treatment planning (1). Brain tumors represent one of the most prevalent and severe forms of cancer globally, comprising about 2% of all cancers and 13% of all cancer-related deaths (2).

Intracranial tumors pose a significant health challenge, with the annual incidence of primary and secondary central nervous system neoplasms ranging from 10 to 17 per 100,000 individuals (3). The primary histological types of brain tumors in adults include high-grade tumors such as gliomas, primary cerebral lymphomas, and medulloblastomas; low-grade tumors including meningiomas, acoustic neuromas, and neurofibromas; and secondary tumors, which are common malignancies that spread to the brain, such as lung cancer, breast cancer, stomach cancer, prostate cancer, thyroid cancer, colorectal cancer, melanoma, and kidney cancer.

The diagnosis and treatment of brain tumors depend on their size and severity, with accurate location and classification being crucial for determining the most suitable treatment approach (4). In recent years, diagnostic imaging techniques such as magnetic resonance imaging (MRI) have become essential for the diagnosis and management of brain tumors (5). MRI provides high-resolution images of the brain, allowing for detailed visualization of tumors and surrounding tissues. However, interpreting MRI images can be challenging due to the varying shapes, sizes, and locations of brain tumors, as well as their distinct characteristics based on type and severity. Consequently, there is increasing interest in developing automated methods for brain tumor detection and classification using MRI images to enhance diagnostic accuracy and efficiency (6). Automated techniques can also alleviate the workload on radiologists and clinicians, enabling them to focus on other aspects of patient care.

Image segmentation is a technique used to divide an image into distinct regions or segments based on attributes such as color, texture, or intensity, particularly in the context of medical MRI images. Segmentation can be employed to isolate and analyze various structures or anomalies, such as brain tumors, blood vessels, or lesions. Several methods are available for performing image segmentation, including thresholding, edge detection, region growing, and clustering. Each method has its advantages and limitations, and the choice of technique often depends on the specific application and image characteristics (1).

Overall, image segmentation is a vital technique for analyzing medical MRI images, especially for tasks like brain tumor detection and classification. However, further research is necessary to refine segmentation methods for various image types and structures, ensuring their accuracy and reliability for clinical applications (1). Recent advancements in neuroradiology have significantly improved the diagnosis of brain tumors (3).

Methodology

This study is based on a comprehensive literature search conducted on August 24, 2024, in the Medline and Cochrane databases, utilizing Medical Subject Headings (MeSH) and a combination of all available related terms, according to the database. To prevent missing any research, a manual search for publications was conducted through Google Scholar, using the reference lists of the previously listed papers as a starting point. We looked for valuable information in papers that discussed neuroimaging techniques in the early detection of brain tumors. There were no restrictions on date, language, participant age, or type of publication.

Discussion

Neuroimaging utilizes quantitative (computational) methods to examine the structure and function of the central nervous system, offering a scientific and non-invasive approach to studying the healthy brain. It is increasingly applied in quantitative research on brain disorders and psychiatric conditions. This interdisciplinary field integrates neuroscience, computer science, psychology, and statistics, and should not be confused with the medical specialty of neuroradiology (7).

Brain-imaging techniques

Computed axial tomography

Computed tomography (CT) or Computed Axial Tomography (CAT) scanning involves capturing a series of X-ray images of the head from various angles. Frequently used for the quick assessment of brain injuries, CT scanning utilizes a computer program to perform a numerical integration (known as the inverse Radon transform) on the collected X-ray data to quantify X-ray absorption in specific brain regions. The processed data is typically displayed as cross-sectional images of the brain (8).

MRI of the brain

MRI is frequently the preferred imaging technique for diagnosing and managing brain tumors because it provides detailed information about tumor type, location, size, anatomy, cellular structure, and vascular supply. This makes MRI an invaluable tool for the diagnosis, treatment, and monitoring of the disease (3). Thus, MRI is regarded as the preferred study for brain tumors. While the detailed physics of MRI are beyond the scope of this discussion, it is important to note that conventional MRI relies on three physical properties of tissue protons to generate signals. These signals are then visualized as areas of varying contrast, representing the anatomy and physiology of the organ under examination (3).

MRI employs magnetic fields and radio waves to generate high-resolution two- or three-dimensional images of brain structures, avoiding the use of ionizing radiation (X-rays) or radioactive tracers. The highest spatial resolution achieved for a complete, intact brain (postmortem) is 100 microns, as demonstrated by Massachusetts General Hospital (9).

Positron Emission Tomography

Positron emission tomography (PET), including brain PET, detects emissions from radioactively labelled metabolically active substances injected into the bloodstream. A computer processes this emission data to produce two- or three-dimensional images that depict the distribution of these substances in the brain (10). PET imaging leverages radioisotopes produced by cyclotrons to create radiotracers that highlight metabolic and neurotransmitter activities in the brain. Through the injection of these radiotracers and subsequent detection of emitted radioactivity, PET scanners generate detailed, color-coded images of brain activity. The technique's utility is significantly enhanced by the diverse range of available ligands, with Fludeoxyglucose (FDG) being one of the most prevalent, providing insights into glucose metabolism and various neurotransmitter functions. This capability makes PET a powerful tool for both clinical and research applications in neuroscience.

The major advantage of PET scanning lies in its ability to reveal blood flow, oxygen usage, and glucose metabolism within the brain's active tissues. These measurements offer valuable insights into brain function by reflecting activity levels across various regions. When PET scanning was first introduced, it outperformed other metabolic imaging methods with its superior resolution and rapid completion time, often as quick as 30 seconds. This enhanced resolution facilitated a more precise examination of brain areas activated by specific tasks. However, a notable limitation of PET scanning is its restriction to monitoring short-duration tasks due to the rapid decay of the radioactivity used in the imaging process (10). PET scanning, despite the advancement of fMRI technology, continues to be a crucial tool in neuroscience for functional brain imaging. Its ability to detect changes in brain metabolism makes it invaluable for diagnosing and monitoring various brain disorders, including tumors, epilepsy, and neurodegenerative diseases. PET is particularly beneficial in identifying early-stage dementia and planning surgical interventions for epilepsy, offering insights that are often not visible with other imaging modalities. Its capacity to reveal metabolic abnormalities remains a significant asset in both clinical and research settings (11). Although they are not commercially accessible for clinical usage, other radiotracers, including 11C-flumazenil, 11C-alpha-methyl-L-tryptophan, 11C-methionine, and 11C-cerfentanil, have also been used to detect seizure onset sites.

Cranial Ultrasound

Cranial ultrasound is employed for infants, as their open fontanelles provide acoustic access for imaging the brain. This technique offers the benefits of avoiding ionizing radiation and enabling bedside scanning. Nevertheless, because it lacks detailed soft-tissue resolution, MRI is typically favoured for diagnosing some conditions (12).

Single-Photon Emission Computed Tomography

Single-photon emission computed tomography (SPECT) is like PET, employing gamma ray-emitting radioisotopes and a gamma camera to gather data. This data is subsequently processed by a computer to generate two- or three-dimensional images of active brain regions (13). SPECT imaging offers valuable insights into cerebral blood flow by utilizing a radioactive tracer that highlights brain activity at the time of injection. This capability is particularly advantageous for epilepsy imaging, as it captures a momentary "snapshot" of blood flow even after a seizure has ended, provided the tracer was administered during the event. Despite its advantages, SPECT's resolution, approximately 1 cm, is lower compared to MRI. However, advancements in SPECT technology, such as Dual, Triple, and even 6 or 11 Detector Head systems, have enhanced resolution and reduced imaging time through improved tomographic reconstruction. Additionally, SPECT remains a useful tool for differentiating dementia-related diseases, with applications like the I-123-labeled Isoflupane (DaT scan) proving effective in distinguishing Parkinson's disease from other tremor-inducing conditions (14).

Functional Magnetic Resonance Imaging

Functional magnetic resonance imaging (fMRI) and arterial spin labeling (ASL) utilize the paramagnetic properties of oxygenated and deoxygenated haemoglobin to visualize changes in blood flow associated with neural activity. This technique generates detailed images that highlight brain regions activated during various tasks or while at rest, based on the oxygenation hypothesis, which links regional cerebral blood flow changes with neuronal activity. fMRI's ability to accommodate diverse stimuli and actions makes it a crucial tool for studying brain functions related to perception, thought, and action, with a spatial resolution of 2-3 millimetres. Although fMRI has supplanted PET in examining brain activation patterns, PET remains advantageous for identifying specific brain receptors or transporters using radiolabelled ligands. However, concerns about the validity of some statistical methods used in fMRI analysis underscore the need for careful interpretation of fMRI data (15). However, fMRI methods have significantly improved, achieving 72% to 90% accuracy in identifying which of a set of known images a participant is viewing, surpassing the chance level accuracy of 0.8% (16). Recent developments in psychiatry's machine learning field have made use of fMRI to create models that can differentiate between those who exhibit suicidal behaviour and those who do not. When paired with machine learning algorithms, these imaging investigations may be able to find novel neuroimaging indicators that allow for patient classification according to suicide risk, directing the creation of more individualized therapies and treatments (17).

Magnetoencephalography

Magnetoencephalography (MEG) is a sophisticated imaging technique that directly measures neural electrical activity by detecting the magnetic fields generated by the brain. Utilizing sensitive devices such as superconducting quantum interference devices (SQUIDs) or spin exchange relaxation-free (SERF) magnetometers, MEG offers exceptional temporal resolution, capturing dynamic neural processes with high precision. Although its spatial resolution is not as refined as methods like fMRI, MEG benefits from reduced distortion of magnetic fields by surrounding tissues compared to electroencephalography (EEG). Despite potential impacts from white matter anisotropy, especially for radial and deep sources, MEG remains robust in delivering accurate data on neural activity with minimal influence from skull anisotropy (18). It is likely that skull anisotropy also affects MEG, although to a lesser extent than EEG (19). MEG is utilized for various purposes, including aiding surgeons in localizing pathology, helping researchers understand brain function, and applications in neurofeedback, among others.

Benefits and concerns with neuroimaging methods

Since its introduction in the 1970s, CT scanning has become a widely adopted imaging technique thanks to its rapid acquisition capabilities. The speed of CT scans, typically completed in under a second, provides significant clinical advantages, especially in emergency settings. However, the higher radiation exposure associated with CT scans—ranging from 100 to 500 times greater than traditional x-rays—raises concerns regarding patient safety, particularly in relation to image resolution and long-term health effects (20, 21). This increased radiation exposure, especially in asymptomatic patients, raises concerns about potential long-term risks. fMRI is considered to carry minimal to moderate risk due to its non-invasive nature. Because it uses blood oxygenation level-dependent (BOLD) contrast, which is a physiological process that happens naturally, it is better than methods that make use of radioactive tracers (22). A significant concern with MRI, particularly fMRI, is its use with individuals who have medical implants or metallic objects in their bodies. The magnetic fields produced by fMRI can potentially interfere with medical devices or attract metallic items if not properly screened. The FDA classifies medical implants and devices based on their MRI compatibility into three categories: MR-safe (safe in all MRI environments), MR-unsafe (unsafe in any MRI environment), and MR-conditional (safe only under specific MRI conditions, with additional information required) (23).

PET scans use radioactive tracers injected into the bloodstream to visualize brain activity, contrasting with fMRI's use of intrinsic biological processes (22). Although PET scans involve radiation, the exposure is low, akin to environmental radiation over a year. The radioisotopes used in PET scans have short half-lives (~2 hours), ensuring brief exposure times. Despite these concerns, fMRI is often preferred over PET for imaging brain activity because it avoids radiation, offers superior temporal resolution, and is more widely available in medical settings. MEG and EEG also provide excellent temporal resolution, capturing brain activity at the millisecond level without exposing patients to radiation. EEG measures electrical signals from neurons, while MEG detects the magnetic fields generated by these electrical currents. Although MEG offers high temporal resolution, its use is limited by its excessive cost, often reaching millions of dollars, whereas EEG is more affordable and commonly used. Both MEG and EEG, however, have poor spatial resolution compared to fMRI (22).

Future directions

Future directions in neuroimaging for early brain tumor detection should focus on integrating advanced imaging modalities and improving machine learning algorithms for enhanced accuracy and early diagnosis. Efforts should be directed towards developing multimodal imaging approaches that combine the strengths of MRI, PET, fMRI, and other techniques to provide comprehensive insights into tumor characteristics and brain function. Enhancing image analysis through AI and machine learning can improve tumor detection and classification, reduce diagnostic errors, and streamline clinical workflows. Additionally, research should prioritize reducing patient exposure to radiation, improving imaging resolution and speed, and ensuring the accessibility of these technologies in diverse clinical settings. Collaborative efforts in these areas have the potential to significantly advance early brain tumor detection and management.

Conclusion

Advancements in neuroimaging, especially MRI and PET, play a pivotal role in the early detection of brain tumors, offering precise anatomical and metabolic insights. Emerging techniques like fMRI and Single SPECT further enhance diagnostic accuracy by providing more detailed assessments of

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brain function and activity. These innovations are critical in improving early diagnosis, guiding treatment decisions, and improving patient outcomes.

Disclosures

Author Contributions

The author has reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Ethics Statement

Not applicable

Consent for publications

Not applicable

Data Availability

All data is provided within the manuscript.

Conflict of interest

The authors declare no competing interest.

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