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Review

The Role of Advanced Imaging in Neurosurgical Diagnosis

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Abstract

Neurosurgery as a specialty has developed at a rapid pace as a result of the continual advancements in neuroimaging modalities. With more sophisticated imaging options available to the modern neurosurgeon, diagnoses become more accurate and at a faster rate, allowing for greater surgical planning and precision. Herein, the authors review the current heavily used imaging modalities within neurosurgery, weighing their strengths and weaknesses, and provide a look into new advances and imaging options within the field. Of the many imaging modalities currently available to the practicing neurosurgeon, magnetic resonance imaging (MRI), computed tomography, positron emission tomography, and ultrasonography are used most heavily within the field for appropriate diagnosis of neuropathologies in question. For each, their strengths are weighed regarding appropriate capabilities in accurate diagnosis of cranial or spinal lesions. Reasoning for choosing one over the other for various pathologies is also reviewed. Current limitations of each is also assessed, providing insight for possible improvement for each. New advancements in imaging options are subsequently reviewed for best uses within neurosurgery, including the new utilization of FIESTA sequencing, glymphatic mapping, black-blood MRI, and functional MRI. The specialty of neurosurgery will continue to heavily rely on improvements within imaging options available for improved diagnosis and greater surgical outcomes for the patients treated. The synthesis of techniques provided herein may provide meaningful guidance for neurosurgeons in effectively diagnosing neurological pathologies while also helping guide future efforts in neuroimaging developments.

Keywords: advanced imaging, neurosurgery, magnetic resonance imaging, computed tomography, ultrasound, positron emission tomography

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1 INTRODUCTION

At the turn of the twentieth century, the ability to localize a neurologic lesion and determine the best operative approach relied solely on the surgeon's brain and clinical reasoning alone[1]. Since then, significant advancements have been made at an astounding pace, enhancing the technology and tools available to the modern neurosurgeon (Figure 1). Among these, advancements in neuroimaging have been demonstrated to be of particular importance, providing neurosurgeons with a greater wealth of information to inform diagnosis and subsequent management, selecting the appropriate patients and surgical targets, as well as optimal surgical approaches.2 Improvements in neuroimaging options have also been instrumental in improving patient care and reducing the morbidity and mortality from neurosurgical procedures while allowing for more reliable diagnoses and surgical decision-making within the specialty[2]. Similarly, the speed at which a neurosurgeon can now accurately diagnose and treat pathology continues to increase with new advancements in imaging modalities.

With these imaging advancements, the challenge thus becomes the appropriate utilization of the available imaging modalities, as needed, to produce the most effective efforts for patients. Herein, we summarize the current roles and advancements of heavily used imaging techniques in neurosurgery, including magnetic resonance imaging (MRI), computed tomography (CT), positron emission tomography (PET), and ultrasound. We also discuss emerging imaging modalities available to neurosurgeons for greater diagnostic capabilities, highlighting the future of imaging in neurosurgery.

2 MAGNETIC RESONANCE IMAGING

Magnetic Resonance Imaging (MRI) is an invaluable core tool in diagnosing cranial and spinal pathologies[3]. Considering the significant risk imposed with the biopsy of pathological tissue within these critical regions, current standards of care for intracranial/spinal disease involve a conventional MRI with the basic T1, T2, and FLAIR sequences[4]. These sequences, their merits, and pathologies well-visualized therein are discussed below and in Table 1.

2.1 T1 Pre-contrast

MRI imaging operates by administering a strong radiofrequency current into the body. Upon cessation of the radiofrequency field, the disequilibrated nuclei dissipate energy as they relax back to their preexcitation net magnetization vector[5]. Some tissues dissipate this energy quicker than others, and T1 imaging measures those differences in relaxation times between tissues[5]. For example, fat tissue reverts quickly to its preexcitation magnetization and is thus hyperintense in T1-weighted images[6]. Thus, the brain's white matter is brighter than gray matter on T1, and fluid is completely hypointense. Considering most intracranial pathologies are highly vascularized, they often present hypointense in T1-weighted imaging[7]. However, pathologies which include elevated concentrations of methemoglobin, melanin, lipid, protein, calcium, iron, copper, and manganese, have a shorter relaxation time and are therefore hyperintense[7]. Pathologies with concentrated methemoglobin include β-amyloid deposits, cavernous malformations, and cerebral venous thrombosis[7]. Melanin-containing lesions include metastatic melanoma, and lipid-dense lesions include lipomas, teratomas, dermoid cysts, and lipomatous ependymomas[7]. Protein-containing lesions such as colloid cysts, Rathke cleft cysts, and ectopic pituitary gland tissue may likewise be independently hyperdense, as will mineral-containing lesions[7].

Within the spine, non-contrast T1 imaging is commonly used in isolation or compounded with other MRI sequences, such as Short Tau Inversion Recovery (STIR), to assess bone marrow abnormalities[8]. For example, fatty marrow, Paget disease, bone marrow hemorrhage, melanoma, and other post-inflammatory focal marrow atrophy are all well-detected via T1-weighted non-contrast imaging.

2.2 T1 Post-contrast

Gadolinium-based contrast agents are commonly used to enhance brain or spine MRI imaging[9]. These contrast agents are composed of paramagnetic Gadolinium compounds, increasing MRI signal intensity by quickening the T1 relaxation rate and providing additional visual disparity between tissue types. Typical uses of T1 contrast imaging include the detection of inflammatory lesions, imaging of tumors, demyelination, and ischemic changes[7]. Furthermore, some contrast agents will bind specifically to specific tumor markers, which is particularly useful in visualizing intracranial tumor borders[10]. Radionecrosis following stereotactic radiosurgery and evidence of tumor recurrence is also often assessed using T1-post contrast[11].

Within the spine, T1-weighted post-gadolinium imaging provides enhanced visualization of enhancing primary or metastatic lesions within the spine and is otherwise helpful for spinal infection and vascular

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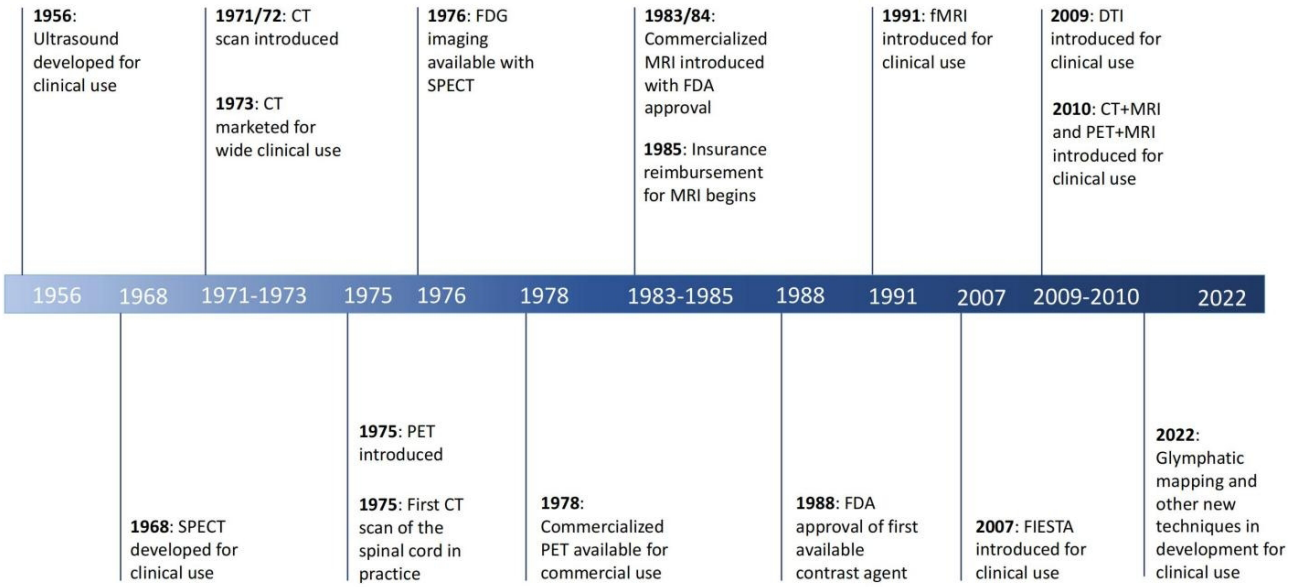

Figure 1. Timeline of imaging modality development and use in the neurosurgical specialty.

Table 1. Common Neuropathologies Diagnosed within Neurosurgery by MRI

MRI Modality	Cranial	Spine
T1 pre-contrast	β-amyloid deposits	Intraspinal lesions
	Vascular malformations	Fatty marrow changes
	Cerebral venous thrombosis	Vertebral body anatomy
	Metastatic disease	Infection
	Intracranial lesions	
	Mineral-laden structures	
T1-post contrast	Intracranial lesions	Vascular malformation
	Ischemic changes	Metastatic lesions
	Demyelination	Infection
	Radionecrosis	
	Tumor recurrence	
T2	Vascular malformations	Disc disease
	Intertumoral hemorrhage	Nerve root compression
	Thrombosed aneurysm	Stenosis
FLAIR	Multiple sclerosis	Multiple sclerosis
	Superficial lesions	Pathology near CSF
	Pathology near CSF	

Notes: MRI, Magnetic resonance imaging; FLAIR, Fluid-attenuated inversion recovery; CSF, Cerebral spinal fluid.

malformation detection[9,12]. However, some pathologies-especially those without increased vasculature-will persist as hypodense, despite the addition of contrast.

2.3 T2

As one of the basic pulse sequences of MRI, T2 is helpful as a broad-brush approach that is sensitive to many pathological states. In contrast to T1 imaging, fat tissue will be only moderately bright, whereas fluid will be hyperintense. Thus, intracranial pathology will likely be hyperintense upon T2 due to vascularization, and white matter will be darker than gray[13]. This can increase visualization of intertumoral hemorrhage[14]. Other pathologies of a vascular nature, such as cerebral hemorrhage, thrombosed aneurysm, arteriovenous malformation, cavernoma, and microhemorrhage, are also seen in T2-weighted images[14]. Unfortunately, T2 is limited by the signal produced by CSF with partial volume effects and flow artifacts which significantly inhibit periventricular and subcortical brain region

evaluation[15]. Within the spine, T2-weighted imaging is helpful in the detection and diagnosis of stenosis, nerve root compression, disc disease, or infection[16].

2.4 FLAIR

More recently developed, fluid-attenuated inversion recovery (FLAIR) has emerged as an adjunct or replacement sequence for traditional T2-weighted imaging and is more informative than T1 with contrast[17]. Producing strong T2 weighting while suppressing signals from cerebrospinal fluid, FLAIR allows strong visualization of lesions, such as cerebral cortical tumors, which lie close to CSF[18,19]. While FLAIR is particularly effective in evaluating supratentorial/superficial brain lesions, it has less diagnostic power for pathology in the posterior fossa or spinal cord[18,20]. However, due to the enhanced visualization of white matter, FLAIR of the head and spine is particularly effective in diagnosing multiple sclerosis[20-22].

2.5 Additional Sequences

Numerous additional MRI sequences have been developed and have their advantages within clinical practice. Particularly prevalent sequences include diffusion-weighted imaging and apparent diffusion coefficient sequences, which are often used to assess response to treatment and disease progression or detection of stroke or differentiation of brain tumors, respectively[23,24]. Additional MRI imaging sequences are being consistently introduced, continually improving spatial resolution and signal contrast[25]. Thus, there is likely more evolution to come regarding sequence choice in the assessment of intracranial and spinal disease with MRI imaging.

3 CT

Developed in the 1970s, CT has numerous applications within many areas of medicine; however, it is especially invaluable within neuropathological settings. This noninvasive diagnostic modality uses repeated X-rays and computer algorithms to produce images of body tissues. Compared with MRI, which records various hyperdensities per tissue as dependent upon the MRI sequence, CT is unidimensional as tissues with increased radiodensity will always present hyperdense. While MRI is considered superior to CT in the workup for intracranial abnormalities, CT is more commonly performed due to its widespread availability in acute care settings, shorter exam, and less expensive cost[26,27]. CT is also preferred over MRI to assess pathology involving the bony structures of the head and spine, such as for pathologic or traumatic fractures[26]. Intracranial pathologies commonly evaluated via CT and its variations include bone abnormalities, brain tumors, fluid collection, hemorrhage, hydrocephalus, stroke, trauma, and epilepsy[28]. Within the spine, CT offers excellent visualization of vertebral bodies, intervertebral discs, structural anomalies, and vascular malformations within the spine[29]. Soft spine tissues can also be enhanced on CT imaging with contrast[30]. A broad overview of the clinical uses of CT imaging in neurosurgery can be seen in Table 2.

3.1 CT Angiography

A specialized variant of CT is CT angiography (CTA) which augments traditional CT with intravenous contrast to produce images of blood vessels and tissues. Due to its ability to clearly track the course of blood products, CTA is often used as the first-line assessment of intracranial vasculature integrity, aneurysms, and hemorrhage[31]. Additionally, CTA may be used as radiographic support for diagnosing brain death following catastrophic brain injury[32]. The image reconstruction in CTA has developed to a diagnostic quality similar to MRI and can be used as a replacement for patients with metallic implants or other conditions which make them unfit for an MRI scan[33].

3.2 Perfusion CT

Like CTA, perfusion CT employs intravenous contrast to evaluate intracranial vasculature. However, CT perfusion is specially designed to test tissue perfusion status and is particularly useful in assessing the blood-brain barrier, acute stroke, thrombolytic injury, vasospasm, and the outcome of neuroendovascular therapies[34]. One of the particular advantages of perfusion CT is its ability to identify potentially salvageable tissue in the setting of acute ischemic stroke and can therefore predict the effectiveness of thrombolytic interventions and inform long-term outcomes following treatment[35].

3.3 Contraindications

It warrants observation that CT carries uniquely elevated risks compared to other imaging modalities as it imparts comparatively large doses of radiation. Such high radiation doses and the associated risks may preclude CT imaging within certain contexts, and the benefits of imaging have to be weighed against the dangers of radiation and intravenous contrast. For example, high-dose radiation in pregnant patients, particularly in the first trimester, has been associated with fetal developmental abnormalities[36]. Thus, CT imaging in pregnant patients must only be performed in critical situations and after carefully considering the risks. Additionally, the radiation of CT imaging use has been linked to the development of hematological and solid tumor cancers[37]. Thankfully, newer CT imaging techniques are being developed which use iterative reconstruction algorithms to acquire diagnostic-quality images while requiring diminished radiation doses for image acquisition[38].

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Table 2. Common Neuropathologies Diagnosed within Neurosurgery by CT

CT Modality	Cranial	Spine
General CT	Osseus pathologies/trauma	Vertebral body integrity
	Primary/secondary tumors	Disc disease
	Fluid collection	Structural anomalies
	Hemorrhage	Osseus trauma
	Stroke	
	Infection	
CT Angiography	Intracranial vasculature integrity	Vascular malformations
	Aneurysms	Carotid stenosis
	Intracranial hemorrhage	Anterior spinal artery syndrome
	Brain death assessment	Carotid artery dissection
Perfusion CT	Tissue perfusion status	
	Blood-brain barrier integrity	
	Acute stroke	
	Thrombolytic injury	
	Vasospasm	
	Outcomes of neuroendovascular therapies	

Notes: CT, Computed tomography.

Other adverse effects of CT imaging have also been reported due to the contrast agents used. Therefore, CT may likewise be contraindicated among patients with conditions such as allergies to the contrast agents, hyperthyroidism, pheochromocytoma, myasthenia gravis, metformin use, and chronic or acutely worsening renal disease[36].

4 PET

PET is a modern imaging technology often used to investigate neurological pathologies. It involves the intravenous administration of radioactive pharmaceutical compounds, which are systemically distributed and metabolized by cells. PET identifies metabolism variation by tissue types based on three-dimensional mapping of positron-emitting pharmaceuticals[39]. For neurosurgeons, PET is often used to create diagnostic images of regional cerebral functions such as blood flow, metabolism, and the binding of specific receptors[40]. Concomitantly, because of basic metabolic differences in neoplastic and non-neoplastic cells, PET is often used to discern cancerous masses from normal or inflamed tissue[41]. Within cancerous cells, radiolabeled FDG (fluorodeoxyglucose) is converted to FDG-6, which accumulates and undergoes no further metabolism[42]. This accumulation of radioactive compound can be quantified and used for a diagnosis.

Moreover, PET sometimes bears the capacity to inform the process of tumor classification for investigating neurosurgeons[43]. Aside from cases of neoplasia, PET is utilized to evaluate neurodegenerative diseases such as idiopathic normal pressure hydrocephalus and Parkinson's disease[44,45]. Additionally, its use extends to inflammatory diseases, such as Rasmussen's encephalitis and refractory epilepsy[46-48]. PET has applications beyond cranial imaging, as well. Some studies suggest that it might predict operative outcomes in cases of cervical spine stenosis[49]. Others implicate its possible combination with CT images in diagnosing surgical site spine infections when other imaging modalities prove inadequate[50,51]. As with intracranial tumors, masses of the spine are also regularly analyzed by way of PET. Of particular note, PET is a well-established imaging technique for investigating applications in epilepsy, neuro-oncology, and cerebrovascular disease, offering physiological data about brain metabolism (Table 3).

4.1 Applications

Epilepsy: Blood flow, metabolism, transport rates, the production of protein and DNA, and receptor density are just a few of the different physiological activities that may be seen and quantified using PET scans of the brain for diagnosis of epilepsy. PET radiotracers are made of positron-emitting isotopes, which produce paired gamma photons that the PET scanner detects via coincidence detection, giving PET millimeter-level spatial resolution. As a result, functional imaging data from PET are produced with a spatial resolution that is better than that of single-photon emission computerized tomography. Although several PET radiotracers are available to identify the epileptogenic focus, FDG is still the radiotracer for epilepsy most frequently utilized in clinical settings.

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Table 3. Common Neuropathologies Diagnosed within Neurosurgery by PET

PET Modality	Cranial	Spine
Radiolabeled FDG	Regional function assessment	Cervical spine stenosis
	Metabolic demand assessment	Surgical site infections
	Regional traumatic inflammation	All primary tumors of the spine
	Rasmussen's encephalitis	Spine metastases
	Refractory epilepsy	Spinal cord infections
	Idiopathic normal pressure hydrocephalus	Chronic osteomyelitis
	Parkinson's disease	Spondylodiscitis
	All primary tumors of the cranium	
	Glioblastoma	
	Meningioma	
	Brain metastases	
	Cerebrovascular disease	

Notes: PET, Positron emission tomography; FDG, Fluorodeoxyglucose.

Interictal temporal lobe epilepsy (TLE) and extra-temporal lobe epilepsy (ETLE) epileptogenic foci are linked to a region of impaired glucose metabolism that often extends outside the seizure start zone[52,53]. The evidence supports that PET interictal hypometabolism is better for lateralizing seizure foci and regionalizing the epileptic focus on the lobar level but not for identifying a seizure's starting loci. Therefore, studying the patient's clinical data is essential for accurate image interpretation[54,55]. FDG PET has been demonstrated to be useful in locating hypometabolic areas in non-lesioned epileptogenic lesions and in individuals with modest structural imaging[56,57]. Studies have similarly demonstrated TLE with normal imaging present also to get the seizure focus appropriately lateralized using FDG PET data[58].

Neurooncology: Regarding tumor identification for possible neurosurgical intervention, PET scans are highly predictive of brain tumor presence, often used to identify gliomas[59,60] or brain metastases[61]. For neoplastic pathologies, the diagnostic performance of FDG PET is moderate, with a sensitivity and specificity of 71% and 77%, respectively[62]. For the diagnosis of primary brain tumors, FET PET demonstrates a pooled sensitivity and specificity of over 80%[60]. Somatostatin receptor positron PET imaging may also be useful for meningioma identification, and although less utilized than other imaging modalities in the initial diagnosis of meningiomas, PET is important since MRI alone demonstrates difficulties detecting meningiomas that were close to the falx cerebri or at the base of the skull, had trans-osseous extension, or had ambiguous imaging signals caused by calcifications or aberrations[63-66].

In oncology of the spine, primary and secondary tumor imaging is increasingly being done clinically via PET modalities, particularly with the new technological advancements in this area. These advancements in technology have made it possible for neurosurgeons to evaluate a variety of physiological parameters in vivo, which are crucial for (A) Correctly grading primary and secondary spinal tumors, (B) Tissue characterization, (C) Determining the extent and infiltration of tumors, (D) Surgical planning, and (E) Monitoring therapy. However, due to the decreased sensitivity for identifying hypermetabolic lesions smaller than 2.5x the scanner spatial resolution, evaluation of the spinal cord with PET is partially constrained[67]. However, this technological challenge is becoming less of an issue with newer PET scanners, which have increased clinical interest in spinal PET.

Cerebrovascular disease: Cerebral blood flow in reversible cerebral ischemia has been investigated using ^{15}O-H_2O PET and perfusion-weighted imaging (PWI)[68]. Adoption of PWI methods, including DSC and ASL, is still lacking for regular clinical usage due to the lack of consistency and unpredictability in the values the techniques produce. The best imaging method for studying cerebral vascular perfusion continues to be PET and MRI[69]. However, because it is difficult to provide a radiotracer with a brief half-life in the right amount of time to examine brain hemodynamics during an acute stroke, the practical use of ^{15}O-H_2O PET in stroke remains a challenge.

Spinal infection: While MRI is the imaging technique of choice for spinal infections, 18F-FDG PET can be a complementary tool in properly diagnosing these pathologies. Studies have found PET to be of clinical use when investigating chronic osteomyelitis using 18F-FDG PET and suspected spondylodiscitis[70-72]. 18F-FDG PET has also demonstrated 100% diagnostic precision in axial

bone compared to radiolabeled leukocyte scintigraphy[73].

4.2 Ultrasound

Ultrasound is a highly versatile, real-time imaging technology that relies on sound waves' properties to generate images. It functions via the transduction of sound waves into media, which, in turn, reflect towards the probe with variable shape and intensity. Bone does not allow the transduction of sufficient sound waves; therefore, the cranial-neuropathological application of ultrasound in neurosurgery is often limited to neonates and infants whose cranial sutures have yet to fuse. In these cases, cranial access is most commonly provided by the anterior fontanelle[42]. Physicians often utilize this modality for the observation of both brain maturation and lesion development by way of serial scans[74].

Occasionally, ultrasound use leads to the incidental discovery of abnormalities in cranial structure, such as craniosynostosis and plagiocephaly[75-77]. Ultrasound technology is often used to characterize soft-tissue defects, lesions, and malformation pathologies of the spine, such as incomplete ossification seen in spina bifida[78-80]. To a lesser degree, ultrasound can be used in adults to visualize blood vessels of the neck and monitor blood flow in the brain and help identify potential stroke, brain tumors, hydrocephalus, and vascular issues. Ultrasound can also help neurosurgeons determine tears in ligaments, muscles, tendons, and other soft tissue masses in the back, often more clearly than an X-ray alone, to assist in the differential diagnosis of chronic back pain. Common uses of ultrasound in neurosurgical practice can be found in Table 4.

4.3 Additional Applications

Diagnosis of fetal brain tumors: The first report of a brain teratoma was discovered by ultrasonography (US) in a fetus at 28 weeks of gestation, published in 1980 by Hoff and Mackay[81]. Since then, further pregnancies with congenital brain tumors have been documented; most commonly gliomas and teratomas[82]. Early detection of malignant cancers during the prenatal period is made possible by modern ultrasonography devices and routine ultrasonography screening during pregnancy, further assisting neurosurgeons in diagnosing and acting earlier on the progression of tumor growth[83]. Of note, teratomas make up around 62% of all brain tumors discovered during pregnancy, primarily during the second or third trimester[84].

Choroid plexus papilloma (CPP): The third, fourth, and lateral ventricles are all potential sites for CPP development, with the third trimester being its typical discovery[85]. To aid neurosurgeons in the differential diagnosis of intraventricular hemorrhage, color doppler imaging may help demonstrate vascularization in the lesion[85].

Craniopharyngioma: Craniopharyngiomas make up roughly 2% to 5% of all congenital CNS tumors and are benign. They are most frequently seen in the suprasellar area and arise from squamous cell remnants from Rathke's pouch[86]. Ultrasonography can diagnose this type of large echogenic mass without requiring further imaging.

Hydrocephalus: When the anterior fontanelle is patent throughout the first few months of life, ultrasound is incredibly helpful in assessing the brain and ventricles. Ultrasound is employed for the primary bedside screening of intraventricular hemorrhage and hydrocephalus in newborns[87]. Although the test is sufficient for a general evaluation of the ventricles, it might be difficult to observe specifics regarding the surrounding parenchyma and the third and fourth ventricles. When treating pediatric hydrocephalus, often early in life when the anterior fontanelle is patent, ultrasound works best as a screening or surveillance test for follow-up.

Spinal dysraphism: The range of skin-covered and non-skin-covered abnormalities in neural tube development and closure that make up spinal dysraphism is wide. The dysraphic bone structures may be recognized using ultrasound, and the posterior masses' contents can be visualized[88-90]. Imaging of non-skin-covered abnormalities prior to surgery is typically of little clinical use, as the diagnosis is generally straightforward, with quick skin closure being the key to preventing infection and additional neurological harm. Although US has been proven to be a helpful modality in this scenario, MRI is often used to assess postoperative problems such as retethering[91].

Caudal regression syndrome: Before the fourth week of gestation, caudal cell mass and cloaca injuries can cause various malformations in the caudal spine and pelvic viscera. Although MRI will be necessary for a full examination, US can be utilized to assess the spinal cord and assess the breadth of involvement. Due to short sacral nerve roots and the loss of anterior horn cells, a truncated or blunted cord is frequently observed[92,93].

VATER syndrome: The notochord has an impact on the development of the thoracic and abdominal viscera as well as the vertebral bodies. The VATER syndrome range of visceral and vertebral abnormalities reflects this. Usually, while the newborn is still in the neonatal critical care unit, US is the imaging technique utilized to check for the many visceral defects that might arise. Thus, during the patient's initial examination, abnormalities of the spine and spinal cord may be checked for, and

Table 4. Common Neuropathologies Diagnosed within Neurosurgery by US

US Modality	Cranial	Spine
General	Carotid artery occlusion	Spinal dysraphism
	Carotid artery stenosis	Caudal regression syndrome
	Intracranial teratoma	VATER syndrome
	Choroid plexus papilloma	Tethered cords
	Craniopharyngioma	Spina bifida
	Hydrocephalus	Incomplete ossification
	Craniosynostosis	Congenital malformations
	Encephalitis	Soft-tissue defects/damage
	Meningitis	Chronic back pain
	Intracranial bleeds (infants)	

Notes: Ultrasound, US.

the requirement for any additional imaging can be established. Similarly, dysraphic spinal abnormalities and tethered cords are more common in individuals with urogenital and anorectal malformations[94], and these conditions may be detected with ultrasound.

5 EMERGING DIAGNOSTIC IMAGING

From the viewpoint of current and upcoming neurosurgeons, finding new imaging techniques that provide greater accuracy in demonstrating the anatomy of the central nervous system at microscopic resolutions, in addition to allowing clear visualization of the function or metabolism of the brain, is of the greatest importance moving forward[95]. Several emerging imaging modalities promise to provide such clarity for neurosurgeons to better diagnose various neuropathologies. These include FIESTA sequencing, glymphatic mapping, black-blood MRI, and fMRI changes, among others, which will be discussed here.

5.1 FIESTA Sequencing

Fast imaging employing steady-state acquisition (FIESTA) sequencing is a high-resolution T2-weighted MRI sequence that provides outstanding image contrast[96]. Compared to other steady-state pulse sequences, FIESTA sequence does not suffer from excessive signal saturation or motion artifacts, offering a great signal-to-noise ratio (SNR)[97]. Acting as an excellent adjunct to conventional T1- and T2-weighted sequences, FIESTA sequence has been demonstrated to be of great diagnostic benefit in evaluating cerebral spinal fluid (CSF) within dural reflections of the posterior fossa cranial nerves[98], providing a superior assessment of the effect of tumors on cranial nerve anatomy[99], preoperative localization of the anterior optic pathways in patients with large suprasellar tumors[100], discerning fat graft enhancement from residual or recurrent tumor on delayed postoperative imaging after vestibular schwannoma resection[101], and detecting oculomotor nerve compression in the presence of parasellar lesions[102]. FIESTA sequencing has also been demonstrated to greatly assist in radiosurgical planning and treatment of trigeminal neuralgia[103].

5.2 Glymphatic Mapping

Glial-lymphatic or glymphatic cerebrospinal fluid flow 3D mapping in the brain is accomplished via dynamic contrast-enhanced MRI. The glymphatic system is a fluid-waste clearance pathway recently identified that subserves the flow of CSF into the brain, brain interstitium, and later venous perivascular and perineuronal spaces, ultimately clearing potentially toxic metabolites from neuropil into meningeal and cervical lymphatic drainage vessels[104]. Dysfunction of the glymphatic pathways may be the source of many neuropathologies diagnosed and cared for by neurosurgeons. Although primarily limited to rodent studies, it is understood that these pathways play an important role in CNS health, with glymphatic dysfunction evident in traumatic brain injury[105,106]. Alzheimer's disease and other dementias[107,108], and micro-infarct disease or stroke[109-111]. If glymphatic mapping proves to be significant for human brain homeostasis, as demonstrated in rodents, it would provide neurosurgeons with new prognostic and diagnostic tools, particularly in TBI and neurovascular care[104].

5.3 Black-blood MRI

MRI has been heavily used in neurosurgery since its inception due to its high versatility with various options for tissue contrast. One of new importance for neurosurgeons, termed black-blood contrast, allows the user to suppress the blood signal in the brain to visualize the vessel wall or better characterize tissue adjacent to the blood pool[102]. Black-blood sequencing has been demonstrated to be superior to conventional T1-sequencing in the automated detection of brain

metastases by convolutional neural networks[113,114]. Black-blood imaging has also demonstrated great value in diagnosing and determining the management of patients with intracranial neurovascular pathologies, including intracranial atherosclerosis, aneurysms, vasculitis and vasculopathy, moyamoya disease, dissection, and vertebrobasilar hypoplasia[115].

5.4 Functional MRI (FMRI)

FMRI is a non-invasive option that measures brain activity by detecting changes associated with the blood flow throughout the brain, such as increased movement to the left motor cortex for the movement a patient's right hand. It allows for determining the spatial relationships between tumor tissue and eloquent brain areas, requiring as a minimum a high-power 3 Tesla MRI unit to reliably detect exact blood flow[116]. FMRI has increasingly been used for preoperative counseling and planning among neurosurgeons in neuro-oncology patients, in addition to intraoperative guidance for tumor resection, particularly in the eloquent cortex[117]. FMRI demonstrates particular importance in neuro-oncology, as it is a much less invasive technique neurosurgeons can use compared to traditional functional studies, such as direct electrical stimulation, while also allowing for more areas of the brain to be mapped for pre- and postoperative decision-making[118].

5.5 Additional Upcoming Advanced Diagnostic Options

Several newer imaging options have come into existence and practices around the globe for a neurosurgeon's improved diagnostic abilities and subsequent surgical planning. For improved tumor differentiation and characterization, newer techniques include susceptibility-weighted imaging , providing greater sensitivity to the magnetic susceptibility of different tissues, as well as magnetic resonance spectroscopy, allowing for greater evaluation of tumor biochemical and metabolic profile[121]. Newer options for improved perfusion imaging include dynamic susceptibility contrast (DSC), dynamic contrast enhanced (DCE) imaging, arterial spin labeling (ASL), and amino acid positron emission tomography. DSC, DCE, and ASL focuse on cerebral blood volume, permeability, and blood flow, allowing for improved grading of tumors and the prediction of tumor recurrence risk[121]. For improved preoperative planning, diffusion tensor imaging, in addition to the described FMRI, are newer options to better examine the white matter tracts relative to infiltrative tumor material.

6 FUTURE DIRECTIONS

While much progress has been made in neuroimaging modalities, there is surely more to come. One area within neuroimaging which shows great promise involves the development of artificial intelligent systems, machine deep-learning algorithms, radiomics, and ever-increasingly sophisticated imaging analytic methods. Another area of interest is the use of image fusion, or exactly overlapping scans in three-dimensional space, to further assist the neurosurgeon past the diagnostic stage into the operating room, for a more successful operation. These advances are being explored as augmentative tools to enhance the diagnosing capacities of current providers by distinguishing characteristics of various pathologies heretofore invisible to the naked human eye[119]. It is likely that artificially intelligent systems will be increasingly useful to neurosurgeons in deciphering radiographical data to inform patient care in the coming years[120].

7 CONCLUSION

The progression of neurosurgery as a specialty remains heavily reliant on advances in radiology and available neuroimaging options. The authors have provided a clear review of the commonly used imaging modalities and their uses in diagnosis within neurosurgery, including MRI, CT, PET, and US, with important advantages and inherent limitations for the surgeon and patient discussed for each. In addition, several new advancements in neuroimaging tools have come to fruition in recent years, providing a glimpse into what neurosurgeons can expect within the next decade. The synthesis of techniques provided herein may provide meaningful guidance for neurosurgeons in effectively diagnosing neurological pathologies while also helping guide future efforts in neuroimaging developments.

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Conflicts of Interest

The authors reported no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contribution

Conception and Design: Cole KL, Lucke-Wold B. Drafting the article: Cole KL, Findlay MC, Kundu M, Johansen C, Rawanduzy C, Lucke-Wold B. Critically revising the article: Cole KL, Findlay MC, Lucke-Wold B. Administrative/technical/material support: Lucke-Wold B.

Abbreviation List

ASL, Arterial spin labeling
CPP, Choroid plexus papilloma
CSF, Cerebral spinal fluid
CT, Computed tomography
CTA, CT angiography
DCE, Dynamic contrast enhanced
DSC, Dynamic susceptibility contrast

ETLE, Extra-temporal lobe epilepsy
FLAIR, Fluid-attenuated inversion recovery
FMRI, Functional MRI
MRI, Resonance imaging
PET, Positron emission tomography
PWI, Perfusion-weighted imaging
TLE, Temporal lobe epilepsy
US, Ultrasonography

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