

Review

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Review

21st Century Innovations in Neuroradiology Treatments

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Abstract

Rapid technological progress in the 21st century has transformed neuroradiology from primarily a diagnostic tool into a vital component of modern neuroscience. This abstract summarizes innovations that have marked a paradigm shift in neurological and neurosurgical patient care. From symptom onset through hospitalization and recovery, these advancements have introduced novel techniques and redefined existing models to improve short-term and long-term outcomes. Artificial intelligence (AI) integration has significant implications in stroke triage, brain tumor segmentation, and treatment planning. Wearable AI-enabled devices detect abnormal changes in movement and speech, prompting patients to seek care immediately to ensure they remain within the therapeutic window for reperfusion therapy. AI models can also identify tumors that may be undetectable to the naked eye and provide precise lesion margins, reducing overestimation and underestimation during surgical planning. Image-guided minimally invasive procedures have reduced reliance on open surgery while increasing precision, minimizing perioperative risk, shortening postoperative hospital stays, improving functional outcomes, and lowering recurrence rates. Refinements in stent and catheter technology have further enhanced the safety and efficiency of these procedures in treating neurological disorders. Advanced imaging enables neurosurgeons to target surgically inaccessible lesions while preserving surrounding tissue and to analyze tumor behavior to objectively predict treatment response. Innovations in neuroradiology address disparities in access to care, as minimally invasive approaches offer therapeutic options for patients ineligible for open surgery, and remote interventions aim to expand timely access to specialized treatment in underserved regions. Continued advancements in neuroradiology will further optimize interventions, enhancing patient care.

Keywords: neuroradiology; imaging; minimally invasive

1. Introduction

The 20th century marked a period of exploration in neuroradiology, defined by the development of foundational imaging techniques and interventional tools. These early innovations revealed possibilities that fueled 21st-century advances focused on redefining existing methods, integrating emerging technologies, optimizing techniques, and improving precision and patient safety. Minimally invasive therapy, the expanding use of artificial intelligence (AI), and advances in imaging have since revolutionized the management of neurological diseases. Recent developments in CT and MRI technology now allow clinicians to visualize neurovascular structures with much greater clarity than ever before (1). Minimally invasive treatments such as endovascular embolization have been shown to improve the safety and effectiveness of AVM treatment (2). Concurrently, A.I. has helped

to generate solutions to complex neurological problems, leading to the development of algorithms that can actually be applied in clinical practice (3).

Despite these major advancements, there is limited consolidated literature that evaluates how these innovations translate into improved clinical outcomes, reduced procedural risks, and enhanced quality of life for patients. This may partly explain why deep learning, although very successful in controlled research environments, has appeared in only a small number of clinical trials (4). While the information exists, organizing it in a centralized, accessible format may facilitate clinicians’ engagement, increase awareness of emerging tools, and encourage exploration of new approaches in clinical practice.

A broad overview of these innovations is therefore essential to identify the current strengths and limitations in neuroradiology. Such an assessment can highlight areas of the field that require further investigation and help guide future research priorities. Given the rapid advancements in technology, continuous reassessment is necessary to ensure that clinical practice employs evidence-based tools and treatments. In this review, we discuss 21st-century advances in minimally invasive therapies, artificial intelligence, and imaging in neuroradiology to illustrate progress, identify future priorities, and provide neurologists and neurosurgeons with practical insights to improve patient care. A summary of these innovations is included in *Table 1*.

Table 1. Summary of 21st century innovations in neuroradiology.

Field of Advancements	Description of Innovations
Mechanical Thrombectomy of Acute Ischemic Stroke	- Higher rates of reperfusion - Faster neurological improvement - Superior functional outcomes
AI-Driven Stroke Triage and Imaging-Analysis	- Enable timely and accurate patient evaluation - AI-enabled technology can help reduce prehospital delays - Can rapidly detect large vessel occlusions
Endovascular Aneurysm Treatment (Flow Diverters)	- Alter aneurysmal hemodynamics to promote progressive occlusion and parent vessel remodeling - Minimally Invasive
Minimally Invasive Tumor Ablation- (Laser Interstitial Thermal Therapy –LITT)	- Well suited for small lesions that are difficult to access surgically - Help preserve surrounding healthy tissue
Focused Ultrasound for Essential Tremor & Parkinson’s	- Noninvasive - Can assess effects during treatment to monitor ablation
Endovascular Treatment of Arteriovenous Malformations (AVMs)	- Refined microcatheters and newer embolic agents improve safety and efficacy of endovascular treatment
Spine Cement Augmentation- (Vertebroplasty and Kyphoplasty)	- Percutaneous injection of PMMA under imaging guidance. can relieve pain due to osteoporosis
Neurovascular Robotics and Remote-Intervention	- Can help overcome geographic barriers - Expedite stroke treatment
AI for Brain Tumor Segmentation and Treatment Planning	- Can detect small lesions that could have been overlooked - Reduces the risk of overtreatment
Advanced Perfusion and Functional-Imaging Integration	- Enables precise localization - Preserves eloquent cortex
Minimally Invasive Spine Interventions	- Improves targeting accuracy - Associated with reduced blood loss
Endovascular Stenting for Intracranial-Atherosclerotic Disease	- Prevents plaque protrusion - Reduced rates of major adverse events

Image-Guided Therapies (Emerging)	Gene and Cellular-	Enable precise visualization of drug delivery
	-	Potential treatment for neurodegenerative diseases
Radiomics and Predictive Analytics in-Neuroradiology		Reveal patterns imperceptible to the naked eye
	-	Allow clinicians to anticipate symptom recurrence

2. Materials and Methods

A focused literature search was conducted through September 12, 2025, using PubMed, ScienceDirect, JSTOR, and Google Scholar. Search terms included *artificial intelligence*, *minimally invasive*, *endovascular*, and *neuroimaging*, along with condition and procedure-specific keywords. A total of 66 peer-reviewed articles were included. Additional relevant studies were identified through the reference lists of primary articles. Only peer-reviewed publications from 1990 onward were included; articles published before 1990 and non-peer-reviewed sources were excluded.

The literature was synthesized thematically and organized by major categories and subcategories. Primary categories included minimally invasive treatments, artificial intelligence, and advanced imaging. Subcategories included mechanical thrombectomy for acute ischemic stroke, AI-driven stroke triage and imaging analysis, endovascular aneurysm treatment using flow diverters, minimally invasive tumor ablation with laser interstitial thermal therapy (LITT), focused ultrasound for essential tremor and Parkinson’s disease, and endovascular treatment of arteriovenous malformations (AVMs). This narrative review was guided by established principles for narrative synthesis in medical literature.

3. Discussion

1. Mechanical Thrombectomy for Acute Ischemic Stroke

Mechanical thrombectomy is a minimally invasive procedure that uses catheter-based techniques, including stent retrievers or aspiration catheters, to remove intravascular clots under image guidance. It is primarily indicated for acute ischemic stroke, a leading cause of death and disability worldwide (5). For decades, intravenous thrombolysis was the most commonly used treatment for acute ischemic stroke; however, limitations such as a narrow therapeutic window for tissue plasminogen activator (tPA) administration (3–4.5 hours), low recanalization rates for large vessel occlusions, and numerous contraindications, including recent surgery and active bleeding, restricted its overall effectiveness (6). Advances in mechanical thrombectomy during the 21st century have shifted standards of care, establishing it as first-line therapy for eligible patients.

Clinical studies demonstrate that early thrombectomy using devices such as the Solitaire FR stent retriever results in higher rates of reperfusion, faster neurologic improvement, and superior functional outcomes compared with intravenous alteplase alone (7). Importantly, mechanical thrombectomy has proven effective for large clots and may be performed up to 24 hours after symptom onset in select patients. In a landmark randomized controlled trial, patients who received endovascular therapy achieved significantly greater reperfusion than those treated with alteplase alone, with neurologic improvement observed within three days and improved functional outcomes at 90 days (8).

Beyond clinical recovery, image-guided removal of large vessel occlusions has had broad implications for survival, disability, and healthcare utilization. Campbell et al. demonstrated that patients treated with mechanical thrombectomy spent significantly more days at home within the first 90 days after discharge compared with those receiving alteplase alone (median 73 vs. 15 days; $p = 0.001$), fewer days in acute stroke units (median 5 vs. 8 days; $p = 0.04$), and fewer days in rehabilitation facilities (mean 14 vs. 33 days) (7). Additionally, mechanical thrombectomy reduced mortality risk and yielded a median gain of 9.3 disability-adjusted life years, compared with 4.9 in the control group. Although thrombectomy carries higher upfront costs than thrombolysis, its substantial gains in quality-adjusted life years and reductions in inpatient care make it a cost-effective intervention.

2. AI-Driven Stroke Triage and Imaging Analysis

Artificial intelligence (AI) has transformed modern medicine by introducing novel approaches to disease diagnosis, reducing diagnostic errors, accelerating drug discovery, enhancing communication between clinicians and patients, and enabling rapid analysis of medical imaging. Among its most impactful applications has been its integration into neuroradiology. In the 21st century, AI has significantly improved stroke triage and imaging interpretation. Both traditional machine learning techniques and deep learning models have been applied across multiple domains of stroke management, including stroke detection, identification of large vessel occlusions, assessment of perfusion deficits, estimation of time since symptom onset, and prediction of functional recovery (9). Collectively, these advances enable more timely and accurate patient evaluation, directly influencing clinical decision-making and outcomes.

Timely recognition remains one of the most critical determinants of outcome in acute ischemic stroke. Earlier identification of neurological symptoms allows patients to seek care sooner, undergo diagnostic imaging, and receive appropriate intervention. However, a retrospective study reported that 74.6% of patients arrived more than 4.5 hours after symptom onset, with only 22% arriving within three hours (10). Given that intravenous tPA is limited to a 4.5-hour therapeutic window, most patients present too late to qualify for reperfusion therapy. AI-enabled technologies—including smartphones, wearable sensors, smartwatches, and tablets—have therefore emerged as tools to reduce prehospital delays by monitoring changes in motor function and speech. A prospective study demonstrated that wrist-worn accelerometers integrated with AI algorithms could detect unilateral upper extremity weakness when worn continuously, achieving high diagnostic accuracy with an area under the curve ranging from 0.893 to 0.947 for detection windows as short as 15 minutes after symptom onset (11). Similarly, a smartphone-based application using machine learning algorithms analyzed 18,311 images and detected facial asymmetry with a sensitivity of 99.42%, specificity of 93.67%, and overall accuracy of 97.11% (12). Together, these technologies have the potential to enhance prehospital stroke triage and facilitate the timely routing of patients to appropriate stroke centers.

AI platforms have also been implemented for the rapid detection of large vessel occlusions. Automated software such as RAPID CTA correctly identified 93% of patients with occlusions, achieving a sensitivity of 0.94 and a negative predictive value of 0.98 (13). Similarly, the FDA-cleared Viz.ai convolutional neural network demonstrated high diagnostic performance with rapid processing times of approximately five minutes (14). When combined with CT perfusion imaging, AI-based tools can estimate ischemic core and penumbral tissue volumes, allowing neurologists to expedite interventions such as mechanical thrombectomy (9). Given that large vessel occlusions account for a substantial proportion of stroke-related disability and mortality, reductions in prehospital delays and treatment times may significantly improve outcomes and reduce the global burden of disease.

3. Endovascular Aneurysm Treatment (Flow Diverters)

Flow-diverting stents represent a major advancement in the endovascular management of intracranial aneurysms, redirecting blood flow away from the aneurysm sac to promote gradual thrombosis and healing without the need for open surgery. Early attempts to treat intracranial aneurysms, while often beneficial, were associated with substantial limitations and procedural risks. Surgical ligation of the parent artery effectively occluded aneurysms but disrupted distal blood flow, increasing the risk of ischemic stroke. Subsequent techniques, including surgical clipping and endovascular coil embolization, addressed this limitation by isolating the aneurysm sac while preserving the parent vessel. Despite their widespread use, these approaches remain suboptimal for large, wide-necked, or fusiform aneurysms (15).

The development of flow-diverting stents in the 21st century marked a paradigm shift in aneurysm management. Unlike traditional intracranial stents, which are primarily designed to support coils, flow diverters alter intra-aneurysmal hemodynamics to promote progressive occlusion and parent vessel reconstruction (16). These devices redirect blood flow away from the aneurysm,

inducing thrombosis within the sac while maintaining patency of the parent artery. Key design features include low porosity, increased metal surface area coverage, and high radial force, which together stabilize the construct, reduce aneurysmal inflow, and promote durable vessel remodeling.

A major advantage of flow diversion is its minimally invasive nature, which eliminates the need for craniotomy, reduces perioperative risk, and shortens recovery time. Compared with earlier techniques, flow diversion has demonstrated lower recurrence rates and higher rates of complete occlusion. One study reported complete occlusion in 55.1% of aneurysms treated with stent-assisted coiling, with a recurrence rate of 28%, whereas 86.7% of aneurysms treated with flow diverters achieved complete occlusion with only a 2.2% recurrence rate (17). These outcomes reflect the ability of flow diverters to reconstruct the parent artery and achieve durable aneurysm exclusion.

Flow diversion was specifically developed to address complex aneurysms poorly suited to earlier approaches. In wide-necked aneurysms, coil embolization carries a risk of coil prolapse into the parent artery, potentially leading to thromboembolism, whereas surgical clipping can be challenging due to the risk of clip slippage or incomplete occlusion. In a clinical trial of 108 patients with unruptured large and giant wide-necked aneurysms, complete occlusion was achieved in 73.6% of cases at six months and 86.8% at 12 months (18). Although flow diversion carries limitations, including the risk of in-stent thrombosis and the need for prolonged dual antiplatelet therapy, continued refinement has expanded its safety profile and therapeutic applications. As a result, flow-diverting stents have become an integral and evolving tool in contemporary aneurysm management.

4. Minimally Invasive Tumor Ablation (Laser Interstitial Thermal Therapy – LITT)

Minimally invasive tumor ablation is an image-guided approach that uses thermal energy, cryoablation, or targeted energy delivery to destroy tumor tissue. These techniques are particularly well-suited for small lesions that are difficult to access surgically and for patients who are poor candidates for open procedures. Among available modalities, laser interstitial thermal therapy (LITT) has emerged as a promising option. Although LITT was first introduced in 1983, early adoption was limited by the inability to monitor tissue temperature during laser application, which restricted precise control of ablation extent (19). Advances in intraoperative magnetic resonance imaging (MRI) during the 21st century have renewed interest in LITT by enabling real-time thermometry using T1-weighted two-dimensional images acquired throughout the procedure. This capability allows clinicians to monitor thermal spread and minimize injury to adjacent structures precisely. With improvements in safety and precision, LITT has become an established treatment option for epilepsy, radiation necrosis, and metastatic brain tumors while minimizing collateral damage.

Technological refinements have ensured that thermal injury is largely confined to target tissue while sparing surrounding brain structures (20). This precision has been especially beneficial in managing lesions considered high risk or surgically inaccessible using conventional approaches. Currently, two major commercially available systems exist: NeuroBlate and Visualase. NeuroBlate offers directional laser capabilities advantageous for irregularly shaped lesions, whereas Visualase is better suited for symmetric targets. In a study using the NeuroBlate system, median survival in patients with recurrent glioblastoma increased from 90–150 days to 361 days following LITT (21). Additional evidence supports the efficacy of LITT in metastatic brain disease. In a study of patients with recurrent metastatic lesions previously treated with radiation therapy, LITT was associated with minimal discomfort, early discharge, and radiographic evidence of effective ablation (22). Subsequent studies reported that 60–75% of treated metastatic lesions did not recur within six months.

LITT has also been incorporated into the management of medically refractory epilepsy. In a cohort of 77 patients with drug-resistant mesial temporal lobe epilepsy, 58% achieved Engel class I outcomes at two years, and 57% achieved International League Against Epilepsy (ILAE) class 1 or 2 outcomes following LITT (23). These outcomes are comparable to those of anterior temporal lobectomy while offering a substantially less invasive alternative. As imaging technologies and image-guided therapeutic systems continue to advance, the clinical applications of LITT are expected to expand further.

5. Focused Ultrasound for Essential Tremor & Parkinson's

Magnetic resonance-guided high-intensity focused ultrasound (MR-gHIFU) is a noninvasive technique that ablates targeted intracranial structures without incisions or ionizing radiation. Parkinson's disease and essential tremor are common movement disorders affecting millions of individuals worldwide. Although both conditions present with tremor, Parkinson's disease is typically characterized by resting tremor that diminishes with voluntary movement, whereas essential tremor manifests as an action tremor during purposeful tasks such as writing or eating. In addition to pharmacologic therapy, surgical interventions have long been used to manage refractory tremors. In the 21st century, MR-gHIFU has emerged as a novel treatment modality. This technique uses multiple ultrasound beams to concentrate acoustic energy at a stereotactically defined intracranial target, producing biological effects that depend on the delivered thermal dose; higher temperatures result in tissue ablation (24). Its noninvasive nature and ability to assess clinical effects during treatment have made MR-gHIFU an appealing option for tremor management.

MR-gHIFU has demonstrated efficacy in patients with medication-refractory tremors. A pilot study evaluating unilateral ventral intermediate nucleus ablation for essential tremor reported significant symptom improvement, with tremor severity decreasing from a mean baseline score of 20.4 to 4.3 at three months and 5.2 at twelve months (25). Physical performance scores also improved substantially. Similarly, MR-gHIFU thalamotomy has shown benefit in Parkinson's disease. Schlesinger et al. reported immediate tremor resolution in all treated patients, with Unified Parkinson's Disease Rating Scale scores decreasing from 37.4 to 18.8 one week after treatment (26).

In 2018, the U.S. Food and Drug Administration (FDA) approved unilateral MR-gHIFU for Parkinsonian tremor, and in 2025, approval was expanded to include bilateral treatment for both essential tremor and Parkinson's disease-related tremor. MR-gHIFU is frequently compared with deep-brain stimulation (DBS), which involves surgical implantation of electrodes. Compared with DBS, MR-gHIFU eliminates hardware-related complications and reduces long-term maintenance requirements (27). However, given its relative novelty and potential for irreversible adverse effects, long-term safety and durability continue to be evaluated, and DBS remains the standard surgical option for many patients.

6. Endovascular Treatment of Arteriovenous Malformations (AVMs)

Intracranial arteriovenous malformations (AVMs) are abnormal vascular connections that can result in intracerebral hemorrhage, seizures, and vascular steal phenomena, all of which may be life-threatening. Open surgical resection was the earliest treatment modality developed for AVMs and remains the gold standard for select patients, owing to its high obliteration rates (28). Microsurgical series have reported complete AVM obliteration rates exceeding 98%, with favorable functional outcomes achieved in the majority of patients (29). However, surgical resection is limited in deep-seated or complex AVMs, where operative access is challenging and hemorrhagic risk is substantial.

Endovascular therapy emerged in the 1970s as a minimally invasive alternative involving catheter-based delivery of embolic agents to reduce or eliminate flow within the AVM nidus. Although embolization can serve as definitive therapy in select cases, it has evolved primarily as an adjunct to microsurgery, improving operative safety and efficacy (2). Advances in embolic materials during the 21st century, most notably the introduction of agents such as Onyx and PHIL, have further improved treatment outcomes.

Early embolic agents, including n-butyl cyanoacrylate (n-BCA), played a critical role in facilitating surgical resection by reducing nidus size and delineating arterial feeders. However, n-BCA polymerizes rapidly upon contact with blood, making injection control difficult and increasing the risk of catheter entrapment or vessel occlusion. In contrast, non-adhesive agents such as Onyx and PHIL solidify more slowly, allowing prolonged and controlled injection with deeper nidus penetration. A retrospective study demonstrated significantly higher occlusion rates and reduced need for subsequent surgery with Onyx compared with n-BCA (30).

Advances in microcatheter technology have further enhanced procedural safety. Early catheters were prone to entrapment due to adhesive embolic agents and limited flexibility, increasing the risk of arterial perforation (31). The introduction of detachable-tip microcatheters addressed this

limitation by allowing the distal segment to detach safely when necessary. The Apollo microcatheter, introduced in 2014, was the first commercially available detachable-tip system. In a prospective post-market study, catheter tip detachment occurred intentionally in over half of procedures, with minimal unintended detachment and no associated complications (32). These innovations have improved control, safety, and efficacy in modern endovascular AVM treatment.

7. Spine Cement Augmentation (Vertebroplasty and Kyphoplasty)

Vertebral compression fractures are disruptions of the vertebral body that commonly result in severe back pain involving the thoracic and lumbar spine. Although fractures may arise from trauma, infection, or malignancy, osteoporosis remains the most common underlying cause. Osteoporosis is characterized by reduced bone density and structural deterioration, increasing the risk of fractures. It is estimated that approximately 1.4 million osteoporotic vertebral compression fractures occur annually, and nearly 40% of women experience one during their lifetime (33). Historically, conservative management such as bed rest, bracing, analgesics, physical therapy, and nutritional supplementation served as the primary treatment strategy. However, these approaches do not stabilize fractures or restore vertebral body integrity. In the 21st century, image-guided vertebral augmentation procedures, specifically vertebroplasty and kyphoplasty, have emerged as effective minimally invasive interventions that rapidly improve pain and mobility, particularly in osteoporotic patients (34).

Vertebroplasty restores spinal mechanics by stabilizing a fractured vertebral body through percutaneous injection of polymethylmethacrylate (PMMA) cement under fluoroscopic or CT guidance. Cement hardening reinforces the vertebra, reduces micromotion, and alleviates pain (35). In a retrospective study of 38 patients with 70 symptomatic osteoporotic fractures refractory to medical therapy, 68% experienced complete pain relief within 48 hours, while 32% reported moderate improvement (36). At a mean follow-up of 18 months, 94% of patients reported sustained pain relief, with a low complication rate of 6.4%.

Kyphoplasty similarly employs image-guided cement injection but incorporates a balloon-tamponade device to create a cavity within the vertebral body before cement placement. This technique restores vertebral height and reduces kyphotic deformity. Kyphoplasty has been shown to restore up to 97% of vertebral height compared with approximately 30% achieved with vertebroplasty alone (34). The balloon also reduces cement extravasation by sealing potential leakage pathways. A systematic review demonstrated significantly greater pain reduction at one month and sustained improvement at three months compared with conservative management (37). Although both procedures carry risks, including cement leakage, adjacent-level fractures, and postprocedural pain, their favorable safety profiles and consistent functional improvement support their role as effective treatments for vertebral compression fractures.

8. Neurovascular Robotics and Remote Intervention

Robotic systems have been widely adopted across multiple medical specialties; however, their application in neuroendovascular interventions has only been reported since the early 2000s. In 2007, a feasibility study demonstrated that magnetic navigation systems combined with magnetic microguidewires enabled safe and accurate microcatheter placement in patients with neurovascular disease, with no reported complications or deaths (38). Modern endovascular robotic platforms consist of two primary components: a patient-side robotic unit that manipulates catheters and guidewires, and a remote-control station where operators direct device movement using joysticks, sensors, and computer interfaces (39). These systems enable precise catheter navigation and open the door to remote neurointerventional procedures, potentially reducing disparities in access to specialized stroke care.

Given the time-sensitive nature of acute ischemic stroke, neurovascular robotics holds particular clinical promise. In a study involving four remote clinicians and one on-site clinician connected to a robotic system, operators successfully navigated catheters and guidewires from the femoral artery to the middle cerebral artery within 15 minutes without manual assistance (40). These findings suggest

that hospitals in rural or underserved regions without on-site neurointerventionalists may eventually provide mechanical thrombectomy through remote guidance.

Despite these advances, current systems face technical limitations. The CorPath GRX system, while FDA-approved for coronary and peripheral interventions, lacks support for the triaxial catheter approach required for most neurovascular procedures (39). As robotic platforms continue to evolve and adapt to neurovascular demands, these technologies have the potential to overcome geographic barriers, expedite stroke treatment, and improve patient outcomes.

9. AI for Brain Tumor Segmentation and Treatment Planning

Cancer remains the second leading cause of death in the United States, and brain tumors pose unique diagnostic and therapeutic challenges (41). The integration of artificial intelligence into oncology has begun to address limitations in tumor detection, characterization, and treatment planning that have historically relied on manual interpretation (42). In neuro-oncology, AI has enhanced the precision and efficiency of brain tumor management.

AI-based models can detect small lesions that may be overlooked on conventional imaging. In a study evaluating a three-dimensional U-Net convolutional neural network for detecting brain lesions on ^{18}F -FET PET imaging, the model achieved an accuracy of 0.9868 during training and 0.9856 during validation, with 100% sensitivity and specificity and no false positives (43). Early detection enables earlier intervention, potentially preventing tumor progression and improving prognosis.

Accurate tumor segmentation is essential for diagnosis, longitudinal monitoring, and treatment planning. Manual segmentation is time-consuming and subject to interobserver variability (44). AI-based segmentation improves efficiency and reproducibility. In a study using two-dimensional U-Net models trained on expert-labeled data, mean Sørensen–Dice scores of 0.80, 0.84, and 0.91 were achieved for enhancing tumor, tumor core, and whole tumor segmentation, respectively (45). These improvements reduce the risk of overtreatment and enable precise surgical and radiation planning. By providing objective quantification of tumor boundaries and treatment response, AI facilitates earlier intervention and improved clinical outcomes.

10. Advanced Perfusion and Functional Imaging Integration

Historically, neurosurgical planning relied heavily on anatomical landmarks and intraoperative cortical stimulation, limiting preoperative precision and increasing the risk of neurological deficits. Critical white matter pathways, including the corticospinal tract and arcuate fasciculus, were invisible on conventional MRI, making them vulnerable to inadvertent injury during tumor resection. In the 21st century, advanced imaging technologies have transformed neurosurgical practice by enabling precise localization of pathology and preservation of the eloquent cortex (46).

Advanced perfusion and functional imaging modalities, including CT/MR perfusion, diffusion tensor imaging (DTI), and functional MRI (fMRI), now work synergistically to generate detailed functional and vascular maps. Dynamic susceptibility contrast (DSC) MRI measures cerebral blood flow, cerebral blood volume, and mean transit time through contrast-induced signal changes on T2-weighted images (47). A study by Hakyemez et al. demonstrated that relative cerebral blood volume ratios were significantly higher in high-grade gliomas than in low-grade tumors, enabling reliable tumor grading (48).

DTI further enhances surgical planning by visualizing white-matter tract orientation and integrity, enabling surgeons to assess tumor displacement or infiltration (49). When combined with fMRI, which identifies eloquent cortical regions using blood oxygen level–dependent signals, these modalities provide comprehensive structural and functional mapping. Case studies have demonstrated that combined DTI and fMRI enable identification of functional cortex and displaced tracts, contributing to favorable postoperative neurological outcomes (50). Together, these tools support maximal safe resection while preserving neurological function.

11. Minimally Invasive Spine Interventions

Minimally invasive spine interventions treat spinal disorders such as disc herniation and spinal stenosis through small incisions with minimal disruption of surrounding tissue. Compared with traditional open surgery, these procedures reduce tissue trauma, blood loss, hospital stay, and

recovery time while maintaining safety and efficacy (51). Advances in imaging and instrumentation during the 21st century have transformed procedures such as epidural steroid injections, percutaneous discectomy, and spinal ablation into precise therapeutic options.

Epidural steroid injections deliver corticosteroids into the epidural space to reduce inflammation and relieve radicular pain. Advances in C-arm fluoroscopy and transforaminal techniques have improved targeting accuracy. In patients with cervical radicular pain refractory to conservative therapy, transforaminal epidural steroid injections performed using advanced fluoroscopic systems resulted in significant improvements in PROMIS Pain Interference scores at 3, 6, and 12 months (52).

Percutaneous discectomy removes herniated disc material using image-guided instruments without general anesthesia, reducing procedural risk. Advances in endoscopic visualization have improved precision and outcomes. Compared with open discectomy, percutaneous endoscopic lumbar discectomy has been associated with reduced blood loss, shorter hospitalization, smaller incisions, and lower postoperative inflammatory markers (53). Adjunctive spinal ablation further enhances outcomes. Patients undergoing combined percutaneous discectomy and sinuvertebral nerve ablation experienced significantly lower pain and disability scores compared with discectomy alone (54). These findings support minimally invasive spine interventions as effective treatment options for patients with lumbar disc herniation and chronic low back pain.

12. Endovascular Stenting for Intracranial Atherosclerotic Disease

Early-generation stents were moderately effective but carried substantial risks due to large cell openings, excessive rigidity, limited conformability, poor scaffolding coverage, incompatibility with embolic protection devices, and increased endothelial injury. For example, bare-metal stents are prone to neointimal hyperplasia, which can lead to restenosis and increase the risk of ischemic stroke (55). Drug-eluting stents (DES) were introduced to address this limitation. A systematic review comparing DES with bare-metal stents demonstrated significantly lower rates of in-stent restenosis and stroke recurrence within one year among patients treated with DES (56). In the 21st century, continued refinements in stent design have made endovascular treatment safer and more effective.

Modern stents are engineered to overcome the limitations of earlier devices. Dual-layer micromesh stents feature micron-sized pores that prevent plaque protrusion and function as a protective net, trapping debris that could otherwise embolize during stent deployment, post-dilatation, and the early post-stenting period (57). This design is associated with reduced rates of major adverse events, including stroke and death. A retrospective study found that patients undergoing carotid artery stenting with single-layer stents experienced significantly more periprocedural neurological complications, particularly transient ischemic attacks, than those treated with dual-layer micromesh stents (58). Balloon-expandable stents provide precise deployment and high radial force, enabling immediate, stable expansion and facilitating treatment of rigid, calcified plaques. In patients with intracranial arterial stenosis, Qureshi et al. (59) reported that balloon-expandable stents were associated with significantly lower residual postprocedural stenosis and reduced rates of postprocedural stroke and death compared with self-expanding stents.

In addition to device refinement, improved patient selection criteria have strengthened the role of endovascular therapy. Historically, stents were used too broadly, leading to unfavorable outcomes. Clinical trial data have clarified which patients benefit most from stenting and which are at increased risk. For example, middle cerebral artery stenting in elderly patients has been associated with a high risk of ischemic stroke (60), whereas younger patients generally have more favorable vascular anatomy and fewer complications. Endovascular stenting is not recommended for patients with stroke attributable to 50%–69% intracranial arterial stenosis, as medical therapy alone is associated with a low recurrence rate (61). Appropriate candidates for stenting include patients with high-grade stenosis, severe cardiopulmonary disease, renal failure, or prior neck radiation. Careful patient selection allows stenting to be reserved for those most likely to benefit while reducing unnecessary procedures, complications, and healthcare costs.

13. Image-Guided Gene and Cellular Therapies (Emerging)

Neurodegenerative diseases are difficult to treat because many medications struggle to cross the blood–brain barrier, and when they do, they often affect the entire brain rather than the specific region involved. MRI-guided catheters allow direct delivery of therapeutic agents into the brain, offering several advantages, including enhanced bypass of the blood–brain barrier, reduced systemic side effects, and higher drug concentrations at the target site (62). These systems also enable precise visualization of drug delivery, minimizing the risk of misplacement and injury to surrounding tissue. Improvements in precision delivery have opened the door for gene therapy and stem cell infusion as potential treatments for neurodegenerative disorders, enabling better targeting and improved drug distribution.

Recent advancements have demonstrated the feasibility of MRI-guided catheter delivery for targeted gene therapy in conditions such as Alzheimer’s disease, Parkinson’s disease, and amyotrophic lateral sclerosis. In a study of fifteen patients with advanced Parkinson’s disease and refractory motor fluctuations, participants were divided into three cohorts of five and received VY-AADC01 gene therapy delivered to the putamen under MRI guidance, along with gadoteridol and an adeno-associated virus serotype 2 (AAV2) vector (63). Cohort doses were $\leq 7.5 \times 10^{11}$, $\leq 1.5 \times 10^{12}$, and $\leq 4.7 \times 10^{12}$ vector genomes, with corresponding putaminal coverage of 21%, 34%, and 42%. PET imaging demonstrated dose-dependent increases in L-amino acid decarboxylase expression (13%, 56%, and 79%), along with reduced antiparkinsonian medication use at six months and improved clinical outcomes and quality of life at twelve months. Approximately 95% of patients were discharged within two days. These findings suggest that MRI-guided gene therapy delivery is safe and clinically promising, with potential applicability to other neurodegenerative diseases pending further research.

14. Radiomics and Predictive Analytics in Neuroradiology

Medical imaging has long been essential in medicine, enabling noninvasive visualization of internal anatomy for diagnosis, planning, and treatment. However, traditional imaging interpretation is limited in its ability to extract all clinically relevant information. Radiomics has expanded imaging from a qualitative to a quantitative tool by using algorithms to extract features such as texture and shape from MRI and CT scans. These features can reveal patterns imperceptible to the naked eye and can be incorporated into models that predict tumor behavior, treatment response, and prognosis. Radiomics “addresses the limitations of subjective radiological interpretation, which can be influenced by interobserver variability and the inherent complexity of neurological structures” (64), promoting more objective, data-driven analysis and advancing precision medicine.

Radiomic signatures have been applied extensively to neurological diseases, particularly brain tumors. Extracted features can be analyzed for correlations with tumor genetics and grade, as well as for predicting recurrence and therapeutic response (65). In a study evaluating radiomics combined with machine learning to predict the response of metastatic brain tumors to Gamma Knife radiosurgery, the radiomics-based model achieved accuracies of 78% and 87% and sensitivities of 78% and 87%, respectively, compared with 44% and 54% for visual assessment alone (66).

Radiomics has also shown potential in movement disorders. Innocenzi et al. (67) demonstrated that texture-derived gray-level co-occurrence matrix (GLCM) radiomic features extracted from MRI-guided focused ultrasound lesions 24 hours after treatment could predict tremor recurrence at 12 months. This early predictive capability may guide postprocedural monitoring and allow clinicians to anticipate symptom recurrence. While radiomics shows significant promise in neurology, further validation studies are needed before widespread clinical implementation.

4. Conclusions

Innovations in the 21st century have significantly advanced the field of neuroradiology. From minimally invasive techniques to advanced imaging technologies, these developments have transformed clinicians’ approaches to neurological disease and improved patient outcomes. The integration of artificial intelligence into patient care has demonstrated the potential to optimize triage

processes by reducing the door-to-treatment time, enhancing diagnostic accuracy, and minimizing errors that may lead to complications. Similarly, advances in image-guided interventions have expanded therapeutic options, reduced procedural risks, and improved functional recovery across a wide range of neurological and neurosurgical conditions.

Although current studies have identified limitations in the widespread clinical implementation of these technologies, their demonstrated effectiveness, emphasis on precision, and capacity to improve long-term outcomes underscore their growing clinical relevance. Continued refinement of minimally invasive techniques, artificial intelligence-driven tools, and advanced imaging modalities has the potential to further enhance safety, efficiency, and access to care. As neuroradiology continues to evolve, expanding across diagnosis, intervention, and treatment planning, it will serve as a paradigm for innovation in other areas of medicine.

5. Patents

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
CT	Computed Tomography
MRI	Magnetic Resonance Imaging
LITT	Laser Interstitial Thermal Therapy
AVM	Arteriovenous Malformations
PMMA	Polymethylmethacrylate

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