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Updates on Neuronavigation: Emerging tools for tumor resection

Anjali Patel^{1,*}, Drashti Patel¹, Raja Al-Bahou¹, Rajvi Thakkar¹, Ivelina Kioutchoukova¹, Marco Foreman¹, Devon Foster², Brandon Lucke-Wold³

¹College of Medicine, University of Florida, Gainesville, FL 32610, USA

²College of Medicine, Florida International University, Miami, FL 33199, USA

³Department of Neurosurgery, University of Florida, Gainesville, FL 32610, USA

Abstract

Multiple studies have been conducted to properly elucidate the various tools available to help enhance the resection of tumor tissue, aneurysms, and arteriovenous malformations (AVM). Diffusion tensor imaging (DTI) tractography is useful in providing a map of the tumor borders, allowing the optimal preservation of function and structure of specific regions of the brain. During neurosurgery, especially craniotomies, the possibility of the brain shifting due to swelling or gravity is high. Thus, tools for intraoperative imaging such as high-frequency linear array ultrasound transducers and doppler ultrasonography are utilized for high resolution images and detecting frequency shifts. 4D-digital subtraction angiography (DSA) is another technique used to create spatial resolutions and 3D maps for aneurysms. These similar techniques can also be utilized to assess the integrity of white matter in AVM. By implementing effective evaluation strategies, healthcare professionals can make informed decisions regarding treatment options, preventive measures, and long-term care plans tailored to individual patients.

Keywords

DTI tractography; 4D-digital subtraction angiography (DSA); spatial resolutions; 3D maps; tumor tissue; aneurysms; AVM

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*Corresponding author: Anjali Patel, anjali Patel@ufl.edu.

Author contributions

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Conflict of interest

The authors declare no conflict of interest.

1. Introduction

Primary brain tumors are very aggressive in nature and notoriously difficult to surgically resect. Most of these tumors grow rapidly, are aggressive in nature as well as widely infiltrative. This potentially hinders the marking of healthy versus tumor tissue and, in turn, makes the surgery very challenging. Thus, it is important to explore ways that can make the diagnosis and treatment of brain cancer more efficient. A few of the ways to tackle this point include using diffusion tensor imaging (DTI) tractography or three-dimensional rendering. As mentioned before, DTI tractography is a non-invasive and relatively fast approach to incorporate while delineating brain tumor margins. Furthermore, DTI tractography is one of the only ways to map out the white matter in vivo, thus, aiding as a preoperative modality in planning^[1,2].

In the treatment of multiple different types of brain tumors, DTI has been used and proven to be a beneficial tool before surgery. Firstly, during cerebral glioma surgeries, DTI-based fiber tracking was associated with the safest and the most resection of the tumor^[3,4]. Secondly, in low-grade gliomas, DTI tractography was used to map the extent and areas of resection during the surgery^[5,6]. Thus, DTI tractography has been shown as a tool used to pre-surgically observe a three-dimensional mapping of the white matter and the fibers^[7]. The various DTI tractography patterns seen in different types of brain tumors are shown in Figure 1.

However, using this technique has some drawbacks. Having a brain tumor increases the incidence of edema and compression of the tissue^[8]. This impairs the selection of seed regions of interest (ROI) for the beginning of fiber tracking, based solely on anatomical landmarks. In such cases, research has shown that combining DTI tractography with functional Magnetic Resonance Imaging (fMRI) might be helpful. Two studies—Hendler et al. and Parmar et al.—used both DTI tractography and fMRI to map the white matter^[9,10]. There are studies that also proposed using fMRI to define the seed ROI using DTI tractography for connectivity mapping^[11,12]. Moreover, a study conducted by Schonberg et al. added to this by suggesting that the combined DTI-fMRI approach is successful in cases where the problem of edema is differentiated from the fiber displacement^[9].

In addition to this, DTI tractography can also be combined with stereotactic treatment imaging planning. Stereotactic radiosurgery (SRS) couples radiation with a stereotactic guiding device^[13]. SRS is also used to treat many different types of brain tumors. According to one study, combining DTI tractography with SRS planning has been shown to improve outcomes and reduce complications^[14]. Another study analyzed that incorporating DTI tractography reduced morbidity in patients with arteriovenous malformations, who underwent radiosurgery^[15]. The various benefits of DTI tractography have been described in Figure 2.

Lastly, DTI tractography can be combined with laser interstitial thermal therapy which is also used as an approach in many brain tumors. Laser interstitial thermal therapy is an ablation procedure that uses a laser fiber to heat up the tumor tissue. In surgeries that use

this, tractography is shown to be used both before and during the procedure as a guiding tool^[16,17].

Thus, it can be concluded from this review that DTI tractography can provide relatively important information during the preoperative time of surgery for brain tumors. Studies that have incorporated this technique in their treatment regimen, including combined approaches, have shown positive outcomes. Thus, DTI tractography can be an extremely useful tool during surgical planning and improving the prognosis.

2. Impact of 3D rendering and applied trajectory for tumor patients

Brain tumors are one of the most lethal forms of cancer and are some of the most difficult types to treat^[18]. Of the different forms of brain tumors, glioblastomas are the most common primary brain tumor in adults and have a median approximated survival expectancy of 15 months following diagnosis^[19]. To treat these tumors, surgical resection has been shown to increase survival rate, improve symptom management, increase time to malignant transformation, and improve quality of life following surgery^[20]. The goal of tumor resection surgery is not only to excise the tumor, but to do so in a way that does not compromise the function and integrity of other regions in the brain^[21]. Different operative approaches offer unique strengths when targeting different forms of brain tumors, and considering these strengths have the potential to improve postoperative outcomes^[20].

A craniotomy is the most common surgical approach for brain tumor resections and is performed by temporarily removing a section of the skull to access the tumor. A perforator is a surgical instrument used to drill small holes into the skull. Once the holes are drilled in, a craniotome is used to cut through the bone and connect the drill holes. This allows for the bone flap to be removed in one piece. Once the tumor is surgically removed, the bone flap is put back into place and held together by titanium screws^[22]. Awake craniotomies are craniotomies performed while the patient is awake. This is common during surgical procedures where cortical and subcortical language centers are at risk. By keeping the patient awake, the surgical team can monitor and preserve brain function in order to preserve the patient's motor function and speech^[23].

Neurosurgery utilizes preoperative imaging, like MRI, ultrasound, and CT scans, to visualize pathology and provide useful information when considering the most effective surgical approach^[19,24]. However, during surgeries like craniotomies, the brain may shift due to swelling, gravity, fluid drainage, and displacement due to tumor resection. Intraoperative ultrasound and MRI devices have advanced compared to previous decades and now allow for seamless intraoperative imaging^[25]. High-frequency linear array ultrasound transducers are small handheld devices that provide intraoperative high-resolution images that can be used to better determine tumor margins. In addition to margin identification of tumors, Doppler ultrasonography can be used to intraoperatively assess the vasculature of tumors by observing frequency shifts that indicate the relative velocity of fluid flow^[26]. Intraoperative MRI can be used to visualize residual amounts of tumor and has been shown to increase overall tumor resection in patients and improve postoperative outcomes^[25,27,28]. In recent years, exploration of more minimally invasive forms of brain tumor resections has

implemented the use of intraoperative MRI. MRI-guided laser ablation is a brain tumor resection approach where MRI is used to visualize the tumor and lasers are used to destroy them. This is significantly useful when targeting brain tumors that are located in sensitive regions of the brain or in locations difficult to access with a traditional craniotomy^[29–31].

Another approach for brain tumor resections includes neuroendoscopy. A neuroendoscopy is a minimally invasive surgery where a tumor is removed through small holes, the mouth, or the nose. This procedure is an optimal approach for cases that involve portions of the brain that need to be avoided during surgery^[32,33]. An endoscope is a thin small tube with an attached light source and camera that allows the surgeon to visualize the inside of the body with minimal invasiveness. However, large tumors pose a challenge as the dissection tools needed to safely remove them during an endoscopic approach are lacking. More research is needed in regard to patient outcomes for endoscopic brain tumor removal^[34].

Perforators are used to drain holes into the skull during a craniotomy. ARCA-CUT (Amherst, NY, USA) is currently the only company that produces and develops autonomic-releasing cranial perforators^[35]. ARCA-CUT is involved in the development of cranial perforators for various surgical uses, pediatric patients, and in cases where the skull is thin^[35]. ARCA-CUT has several different types of automatic releasing cranial perforators, such as a disposable cranial perforator, reusable cranial perforator, and the “Smart Drill”^[35]. The “Smart Drill” shares the same features as the disposable cranial perforator, but is also safe for a skull thickness as little as 1.5 mm while also featuring a thicker bone pad^[35]. ARCA-CUT’s perforators are composed of non-skid tips to prevent sliding during insertion along with their patented Cammed-Lug release mechanism that reduces the risk of a problematic penetration^[35]. A bone pad is then made from the inner drill to prevent cutting or nick of the dura^[35].

Tumor treating fields (TTF) are low-intensity alternating electric fields used in a variety of tumor types^[36]. TTF have been found to interrupt mitosis, arrest cells during the cell cycle, and stimulate apoptosis in various tumor types^[37,38]. Optune[®] is an FDA-approved, transportable TTF that delivers 200 kHz to treat glioblastoma multiforme (GBM)^[36]. Optune[®] contains two panels which contain nine insulated electrodes which can be placed on the patient’s shaved head in order to generate the electric current^[36]. The low-intensity electrical fields are distributed through the brain tissues where they have been found to arrest the cell cycle, disrupt mitosis, and prevent the progression of tumor growth^[36]. It’s proposed that Optune disrupts various components of cells such as the tubulin dimers and mitotic spindles to impair cell division^[39]. Additionally, one study found that the use of Optune in combination with temozolomide, a standard chemotherapy, showed a significant benefit in improving survival compared to temozolomide alone^[40]. Another study found that Optune has shown a 15% reduction in tumor volume over the course of 3 months^[41]. Optune has been shown to increase median survival by 0.6 months in recurrent glioblastomas and up to 31% in newly diagnosed glioblastomas^[42,43]. The most common side effect experienced due to Optune was contact dermatitis, but no brain function impairment or systemic toxicity was noted^[36]. However, Optune is not recommended in patients with implanted medical devices, skull defects, or bullet fragments as studies have yet to be conducted in patients with these conditions^[40].

The Pratt School of Engineering at Duke has created a device termed the “Tumor Monorail” that mimics the brain’s white matter and causes the migration of tumor cells towards the exterior brain, where tumor cells can be collected and resected^[44]. The device consists of a long, thin tube of flexible fibers which are inserted through an opening^[45]. Initial success of the concept was demonstrated in rat models in 2014^[46]. The study done in animal models used a polycaprolactone (PCL)-nanofiber film in a PCL/polyurethane conduit to cause the migration of tumor cells^[46]. The study in rat models found a significant proportion of human glioblastoma cells moved towards the nanofiber films^[46]. The study synthesized a cycloamine-conjugated collagen hydrogel to serve as an apoptotic factor^[46]. In the extracortical hydrogel, the tumor cells underwent apoptosis and ultimately resulted in a significant decrease in tumor volume^[46]. The “Tumor Monorail” gained “Breakthrough Device” status by the U.S. Food and Drug Administration as it offers the possibility of extracting a tumor that was previously located in an inoperable location with a more minimalistic approach^[44]. The “Monorail Device” is currently working on seeking FDA approval for human trials, but offers a promising alternative to managing neurologic tumors^[44].

A new device, termed the Oncomagnetic device, works by producing oscillating magnetic fields (OMF) through the rotation of strong magnets^[47,48]. In rat models, the device has shown anticancer effects in xenografted mice without causing any significant side effects^[49,50]. The OMF generators are attached to a helmet which can be placed on a patient’s head without shaving and works by disrupting the electrical transport chain within the mitochondria to increase the number of reactive oxygen species^[49]. The increase of reactive oxygen species results in cancer cell death^[49]. One case report outlined the use of the Oncomagnetic device in a patient presenting with a large tumor spreading from the left frontal lobe into the right frontal lobe^[49]. The patient was diagnosed with end-stage recurrent glioblastoma and had very limited treatment options^[49]. The patient was treated with OMF through the Oncomagnetic device for 36 days and found that the therapy was well tolerated and resulted in a reduction of tumor volume^[49]. Although reducing tumor volume in one patient, further studies evaluating the efficacy of the Oncomagnetic device are needed to demonstrate its safety and efficacy.

3. Impact of 3D rendering and applied trajectory for aneurysm patients

An aneurysm is the abnormal dilatation of an arterial vessel resulting from an acquired lesion that weakens the vessel wall^[51]. These vascular abnormalities can occur throughout the body, but in the context of intracranial aneurysms (IAs), they are predominantly found in the anterior circulation of the circle of Willis, particularly near bifurcation points^[52]. The prevalence of IAs is a cause for concern as they carry a high risk of morbidity and mortality associated with rupture. Once an IA ruptures, the statistics are alarming, with 50% of patients dying within three months and half of these deaths occurring within the first 24 hours^[53]. For this reason, it is imperative to emphasize the importance of appropriate and timely evaluation of unruptured IAs, as it can have significant implications for clinical management, patient quality of life, and ultimately, survival rates. By implementing effective evaluation strategies, healthcare professionals can make informed decisions regarding

treatment options, preventive measures, and long-term care plans tailored to individual patients, thereby mitigating the potential devastating consequences of IA rupture.

In the past, the clinical detection of unruptured IAs was rare, as they were primarily discovered when a patient presented with symptoms indicative of rupture^[54]. However, with a greater understanding of risk factors, such as family history, and the implementation of enhanced screening efforts, the diagnosis of unruptured aneurysms has witnessed a substantial increase^[55]. Notably, the advancements in imaging technologies, particularly the growing utilization of magnetic resonance imaging (MRI) in the clinical setting, have played a pivotal role in identifying unruptured IAs as incidental findings^[56]. This shift in diagnostic practices has led to a paradigmatic change, enabling proactive management strategies for these potentially life-threatening conditions. Moreover, as medical technology continues to evolve, various other modalities have emerged to evaluate IAs comprehensively, leading to a better assessment of their location, risk for rupture, and management options. One such technology that has evolved in recent years is digital subtraction angiography.

3.1. Digital subtraction angiography

Today, digital subtraction angiography (DSA) is the gold standard for evaluating IAs due to its high sensitivity and spatial resolution^[57]. Due to accessibility, cost-effectiveness, and previous research, 2D angiography (2D-DSA) is conventionally used in clinical practice^[58]. 2D-DSA, however, has limitations regarding its difficulty in use in neurological interventions^[59]. For instance, it is difficult to visualize 3D anatomic details on a 2D-DSA; therefore, multiple 2D-DSA acquisitions are necessary to properly evaluate IAs^[60]. The need for multiple acquisitions decreases the efficiency of this technology while increasing healthcare costs. It also increases the amount of exposure and contrast use in patients, which can leave them at a greater risk for kidney dysfunction^[61].

In light of these limitations, 3D-DSA is being increasingly investigated for its ability to characterize IAs and guide their treatment. The formulation of a three-dimensional DSA image requires the use of a flat-panel angiographic system^[59]. The system has a rotating motorized C-arm that can obtain a complete acquisition in two scans, with the first one collecting subtraction marks and the second acquiring images through a contrast medium^[59]. In a clinical setting, 3D-DSA is typically used when the presence of an aneurysm is suggested, and it is indicated for use in follow-up if a coiling procedure is done^[62].

3D-DSA has many advantages when compared to 2D-DSA. For instance, 3D-DSA has the ability to depict significantly smaller aneurysms of up to less than 3 mm^[62]. The increased sensitivity of 3D-DSA to detect smaller aneurysms reduces the number of aneurysms that are overlooked, ultimately reducing the number of aneurysm-negative subarachnoid hemorrhages (SAH)^[63]. 3D-DSA also has extensive utility in detecting aneurysm recurrence after treatment, as it provides a 3D measurement of the refilling area without requiring calibration^[59]. It can detect residual flow if present, localize its origin, and evaluate adjacent vessel branches^[59]. In the event that a stent is placed, 3D-DSA can also accurately localize the stent, which is otherwise difficult to visualize through fluoroscopy due to its design^[64].

The utility of 3D-DSA has been evaluated by many researchers, and these studies are summarized in Table 1.

One disadvantage of using 3D-DSA, however, is that it is more invasive and more expensive than DSA alone^[65]. Despite the cost and invasive nature of 3D-DSA, however, undetected aneurysms have a high morbidity and mortality due to the risk of rupture. One alternative to 3D-DSA is 3D-CT Angiography (CTA), which is much cheaper and can be done without hospitalization^[65]. 3D-CTA could be a better alternative for assessing asymptomatic patients with factors who may have a lower risk of IA rupture. One study by Li et al. assessed the applicability of 3D-CTA in IA evaluation for surgery through a virtual reality model^[66]. He found the accuracy of 3D-CTA to be 90.81% across all aneurysm sizes, with higher accuracies for larger aneurysms^[66]. Given this accuracy and the clinical utility of 3D-CTA, this technique could be the future of 3D rendering in IAs; however, more clinical research on the topic is needed.

Another disadvantage of 3D-DSA is that it lacks the temporal resolution provided by 2D-DSA, which is lost at the expense of increased volume resolution^[67]. One alternative to using 3D-DSA that is suggested by researchers is 4D-DSA. 4D-DSA utilizes C-arm conobeam CT systems to create time-resolved datasets of vascular volumes; furthermore, the flat detector angiographic systems used are commercially available, implying the feasibility of this technique^[60,68]. 4D-DSA allows for 3D-DSA time-resolved volumes and therefore allows for better temporal and spatial resolution. One study by Lang et al. analyzed the utility of 4D-DSA in ten patients with IAs and found that 4D-DSA had nearly complete accordance with 2D-DSA with regard to its temporal resolution^[68]. Another study by Sandoval-Garcia et al. found that the information provided by both 4D-DSA was equivalent to a combination of 2D-DSA and 3D-DSA and concluded that the use of 4D-DSA could decrease the need for 2D-DSA^[69]. In order to assess the true extent of these benefits, however, more clinical research with greater sample sizes is needed.

3.2. Applied tractography in aneurysm imaging

In addition to 3D-DSA, 3T MRI is a form of tractography that can be utilized to improve the evaluation of IAs. One study by Khursheed et al. applied advanced 3T MRI to study aneurysm recovery following a SAH^[70]. One form of treatment for SAH involves the placement of IA clips^[71,72]. After clip placement, MRI is considered to be a routine follow-up, but the magnetic fields produced interact with the clip impacts to produce a notable artifact in the images^[73–76]. Khursheed and colleagues found that advanced 3T MRI can be used to successfully image aneurysms with titanium clips implanted in order to visualize and reconstruct white matter pathways^[77]. Although preliminary, these findings have paved the way for more structural and functional imaging studies regarding aneurysms within the field of applied tractography.

4. Impact of 3D rendering and applied trajectory for AVM resection surgery

Arteriovenous malformation (AVM) is an abnormally developed tangles of blood vessels (nidus) that directly connects arteries and veins together bypassing the capillary bed (<https://www.nature.com/articles/nrdp20158>)^[81]. Normally, oxygen rich blood travels from the heart to the rest of the body through high pressure fast flow systems called the arteries. As the blood passes through the small arteries and arterioles, the pressure substantially drops until it reaches a one cell thick blood vessels called the capillaries where exchange of nutrients and waste takes place between the blood and tissue. The deoxygenated blood then travels back to the heart through low pressure slow flow systems called the veins. However, in AVM, this normal blood flow is disrupted, and high-pressure arterial systems are abnormally connected with the low-pressure venous systems increasing the risk of ischemia, rupture of blood vessels, and hemorrhage^[81,82].

Although the exact pathogenesis of AVM remains unclear, some cases are associated with some genetic mutations like hereditary hemorrhagic telangiectasia (HHT)^[83]. AVM can occur in any part of the body and is commonly associated with the brain and spinal cord^[84]. While brain AVM have a low estimated prevalence, it is considered a significant cause of intracranial hemorrhage (ICH) in children and young adults, which carry high morbidity and mortality^[83].

The most common presentation of symptomatic patients with AVM is ICH due to ruptured vessels. However, symptoms can vary depending on the size and location of the AVM and can include other neurological complications such as headaches, strokes, seizures, and other neurological deficits^[81,83,85]. However, in recent years, the increased use of non-invasive neurological imaging modalities like computed tomography (CT), magnetic resonance imaging (MRI) and angiography have led to an increase in incidental diagnosis of brain AVM^[85].

In asymptomatic patients with non-hemorrhagic AVM, the preferred medical management remains controversial within the medical community. It is important to take into account the accumulated lifetime hemorrhagic risk with the risk of the medical treatment itself when making decisions about interventions^[85]. However, given the invasive nature of the procedural options, conservative treatment is recommended with observation, follow-up, and regular imaging for asymptomatic non-hemorrhagic brain AVM^[81,86,87]. On the other hand, when it comes to treatment of symptomatic patients, the associated high risk of ruptured AVM warrants a procedural approach with the goal of AVM elimination and prevention of future complications, while preserving brain function. The subsequent risk of complications increases five folds following a ruptured AVM or previously ruptured AVM^[81]. Given the recent advances in medical treatments, the medical management of symptomatic AVM often includes a multimodal approach of different treatments like microsurgical removal, endovascular embolization, and stereotactic radiosurgery, which can be alone or in combination^[81,86].

While microsurgical resection, stereotactic radiosurgery, and endovascular embolization have all been indicated in the setting of symptomatic intracranial AVM, each poses a

certain risk that should be taken into account when considering one treatment option over the other. For instance, surgical approach in the management of intracranial AVM is invasive, challenging, complex, and comes with increased risk of intra- and post-operative complications like bleeding and cerebral edema. Thus, age of the patient, the location of the lesion, and the associated risk for post-operative complications related to the adjacent brain tissue are crucial factors in determining surgical indication for intracranial AVM over other procedural approaches^[81,88]. On the other hand, stereotactic radiosurgery is a treatment method that utilizes precision guided delivery of radiation to a specific target, using advanced imaging technology^[20,81]. However, AVM obliteration is highly dependent on the radiation dose and the precise delivery to the lesion site and is coupled to harmful radiation exposure and the risk of damage to adjacent brain tissue^[81]. Endovascular embolization is a non-invasive image-guided procedure that aim to block or reduce blood flow to the feeding artery of intracranial AVM through the introduction of intervascular catheter and embolic materials which decreases the risk of bleeding^[81]. Endovascular embolization is usually used in combination with other therapies like microsurgery^[81]. Therefore, it is essential to find ways to aid clinicians in preoperative assessment and planning for both symptomatic and asymptomatic intracranial AVM in order to balance the risks and benefits of the intervention. One such modality that has been proposed and discussed in patients with intracranial AVM is Diffusion tensor imaging (DTI) tractography or three-dimensional rendering^[89-93].

DTI tractography or three-dimensional rendering, is a non-invasive MRI based technique that provides functional information about the microstructural integrity and directionality of white matter tracts in the brain. The use of this imaging modality has been previously described in primary brain tumors^[94-96]. However, in the context of intracranial AVM, DTI serves as a valuable tool for assessing the impact of these vascular abnormalities on neighboring brain tissue^[96]. DTI works by measuring the diffusion of water molecules along axonal pathways, enabling the study and characterization of the brain's structural connectivity^[95]. For intracranial AVM, DTI helps visualize the specific disruption of axonal white matter tracts caused by the presence of the vascular malformation in the setting of intracranial AVM. Additionally, DTI can detect changes in fractional anisotropy (FA), which reflects the directionality of water diffusion, and apparent diffusion coefficient (ADC), indicating the magnitude of water diffusion.

The incorporation of DTI tractography and three-dimensional rendering into the evaluation of intracranial AVMs offers a noninvasive method to investigate of the extent and impact of the intracranial AVM on the surrounding brain tissue, which in turn helps to guide the pre-operative clinical decision^[88,93]. Also, given that the Microsurgical resection of Intracranial AVM is an “all or nothing” approach, the integration of DTI tractography and three-dimensional rendering with other imaging modalities to study the relationship and structure of the lesion to the tract to guide the surgical approach, prognosis, and outcome has been described^[96,97]. In addition, DTI tractography and three-dimensional rendering has been shown to be a useful in dosage determination as well as decrease morbidity related to stereotactic radiosurgery management in patients with intracranial AVM^[97,98]. A recent systemic review investigating the application of DTI tractography and three-dimensional rendering in the medical management of brain AVM demonstrated Research findings have

shown that the utilization of tractography data enables surgeons to effectively remove brain arteriovenous malformations (bAVMs) located in critical areas, while maintaining acceptable rates of complications. Moreover, the collected data facilitate precise analysis of radiation dosage, ensuring that these lesions can be targeted for stereotactic radiosurgery (SRS) with minimal radiation exposure to nearby essential white matter pathways^[99]. DTI tractography and three-dimensional rendering is not only limited to pre-operative assessment but can also aid in the assessment of post-operative outcomes in patients with AVMs^[88], as shown in Table 2.

All in all, DTI tractography or three-dimensional rendering plays a crucial role in enhancing the understanding and management of intracranial arteriovenous malformations by providing detailed insights into the structural alterations and connectivity changes associated with these vascular anomalies.

5. Conclusion and discussion

As previously mentioned, the severity of outcomes implicated in brain tumor and aneurysm patients cannot be understated. Thus, the topic of update considerations in the context of neuronavigation is of the utmost importance in the field of neurosurgery and warrants further investigation. Traditionally, DTI tractography is a ubiquitous diagnostic and treatment modality employed against aggressive brain neoplasms such as GBM—with the ability to be a stand-alone technology or concomitantly with fMRI, SRS, or laser interstitial thermal therapy^[100–102]. As of late, however, with the dawn of novel 3D rendering technology, models of infiltrative brain tumors have helped assist physicians in identifying accurate margins for the most amount of tumor excision with the least amount of collateral damage to healthy surrounding brain parenchyma. Mainly, with the inability to identify these invasive margins of GBMs persistently hampering attempts to achieve local control, integrating 3D MR spectroscopy into neuronavigation is a promising new development. Specifically, this novel application of 3D MR spectroscopy utilizes glioma metabolism data to perform image-guided resection with more extensive margins^[103]. Although still in early clinical trials, this treatment option offers a more precise alternative to conventional structural imaging, while still preserving clinically efficacious resection methods such as craniotomy, neuroendoscopy, laser ablation, and the various conductive treatment options and devices.

Similarly, 3D rendering technology harbors especially useful clinical applications in the context of aneurysm patients. Prior to the advent of advancements in imaging technologies such as in MRI, aneurysms historically remained undetected until rupture, which significantly increased morbidity and mortality in these patients. Recently, however, improvements in early detection via the use of digital subtraction angiography has served as a vital tool in circumventing the aforementioned consequences. Particularly, by using 4D-DSA technology, practitioners have the ability to combine the advantages of traditional 2D-DSA and 3D-DSA, while omitting their shortcomings such as suboptimal small aneurysm identification and lack of temporal resolution, respectively^[104]. Moreover, the use of 4D-DSA technology allows for superior imaging of cerebral vasculature without the need for overexposure required while using the 2D and 3D modes, which traditionally require

a higher number of acquisitions. This unique characteristic of 4D-DSA also expands its application to the treatment and management of AVMs and dural arteriovenous fistulas^[105].

Over the past couple of years, our vast information concerning the tumor resection tools in neurosurgery has grown immensely. From DTI tractography to 4D-DSA technology, our ability to properly evaluate pre and post operative planning and treatment measures has been enhanced.

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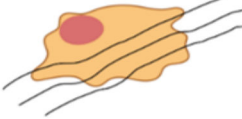
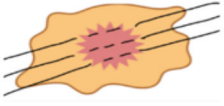
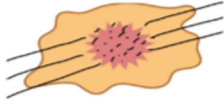
DTI pattern	Illustration	Potential Diagnosis
Deviated		<ul style="list-style-type: none"> - Low grade Gliomas - Anaplastic astrocytoma - Glioblastoma multiforme - Metastasis
Edematous		<ul style="list-style-type: none"> - Metastasis
Infiltrated		<ul style="list-style-type: none"> - Anaplastic astrocytoma - Glioblastoma multiforme
Disrupted		<ul style="list-style-type: none"> - Anaplastic astrocytoma - Glioblastoma multiforme

Figure 1.
DTI tractography pattern seen in different types of brain tumors.

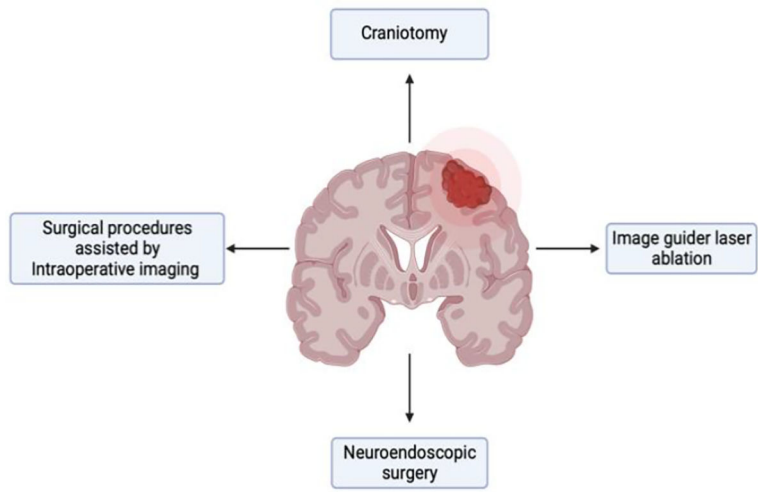


Figure 2. Overview of brain tumor surgical resection approaches.

Table 1.

Evaluating the utility of 3D-DSA in assessing IAs in comparison with other technologies.

Study	Patients enrolled	Outcome
Ishihara H et al. ^[63]	247 patients; 3D-DSA (n = 142), DSA (n = 105)	The use of 3D-DSA decreased the amount of angiogram-negative SAHs when compared to DSA, at 4.2% and 8.6% respectively.
van Rooij WJ et al. ^[62]	350 patients; 3D-DSA (n = 350), DSA (n = 350)	3D-DSA allows for improved detection of small aneurysms <3 mm than DSA alone.
Ishida F et al. ^[65]	15 patients; 3D-DSA (n = 15), 3D-CTA (n = 15)	3D-DSA is a more useful technique for endovascular treatment; whereas, 3D-CTA is the optimal technique for aneurysm detection in patients indicated for surgery or postoperative evaluation.
Halter M et al. ^[78]	43 patients; 3D-DSA (n = 43), 2D-DSA (n = 43)	3D-DSA showed a higher level of interrater reliability and agreement for aneurysm evaluation than 2D-DSA when the results were scored by six independent raters.
Wong SC et al. ^[79]	31 patients; 3D-DSA (n = 31), 2D-DSA (n = 31)	3D-DSA required less contrast, radiation, and procedure time while improving the detection of IAs when compared to 2D-DSA.
Lang S et al. ^[80]	10 patients; 3D-DSA (n = 10), 4D-DSA (n = 10)	4D-DSA shows accordance with 3D-DSA in measuring fluid dynamics with the added aspect of temporal resolution.

Table 2.

Summary of the various applications 3D Rendering and Applied Trajectory.

Application	Description
Preoperative planning	- Assessment of AVM location and its relationship to eloquent brain areas and critical white matter tracts.
-	- Visualization of disrupted white matter tracts caused by the presence of the AVM.
-	- Identification of the optimal surgical approach to minimize damage to essential brain regions.
-	- Determination of the feasibility of complete resection and prediction of postoperative functional outcomes.
Radiation treatment	- Precise targeting of AVM during stereotactic radiosurgery (SRS) based on DTI-derived white matter tractography.
-	- Minimization of radiation doses to in-proximity critical white matter tracts to preserve brain function.
-	- Accurate dosimetric analysis to ensure effective treatment while avoiding damage to surrounding healthy tissues.
Postoperative	- Assessment of white matter tract integrity and connectivity after AVM resection.
-	- Evaluation of the impact of surgical intervention on the structural connectivity of the brain.
-	- Monitoring of long-term changes in white matter tracts and identification of potential complications.

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