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MAGNETIC RESONANCE IMAGING OF BRAIN TUMOR

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INTRODUCTION

Magnetic resonance imaging (MRI) provides detailed information about brain tumor anatomy, cellular structure and vascular supply, making it an important tool for the effective diagnosis, treatment and monitoring of the disease. This article provides an overview of brain tumor, with a focus on gliomas, followed by a description of the principles of MRI signal and image generation. It then reviews the most established MRI techniques for brain tumor imaging, and their clinical utilities for differential diagnosis, tumor grading, and response to treatment assessment. The neurosurgical applications of MRI used to maximize tumor resection while avoiding damage to healthy brain tissue are also described.

OBJECTIVES

After reading this article, the reader will be able to:

1. Define brain tumors and the role of MRI in their detection and treatment
2. Explain the principles of MRI signal and image generation
3. Discuss advantages and limitations of MRI techniques used for brain tumor
4. Understand the value of intraoperative MRI in improving tumor resection and patient survival

BRAIN TUMORS

Brain tumors are abnormal and uncontrolled proliferations of cells. Some originate in the brain itself, in which case they are termed *primary*. Others spread to this location from somewhere else in the body through metastasis, and are termed *secondary*. Primary brain tumors do not spread to other body sites, and can be malignant or benign. Secondary brain tumors are always malignant. Both types are potentially disabling and life threatening. Because the space inside the skull is limited, their growth increases intracranial pressure, and may cause edema, reduced blood flow, and displacement, with consequent degeneration, of healthy tissue that controls vital functions.[1,2]

Brain tumors are, in fact, the second leading cause of cancer-related deaths in children and young adults. According to the Central Brain Tumor Registry of the United States (CBTRUS), there will be 64,530 new cases of primary brain and central nervous system tumors diagnosed by the end of 2011. Overall, more than 600,000 people currently live with the disease.[3]

Although the causes of brain tumors are unknown, a few risk factors have been proposed. These include head injuries, hereditary syndromes, immunosuppression, prolonged exposure to ionizing radiation, electromagnetic fields, cell phones, or chemicals like formaldehyde and vinyl chloride. None of these, however, is proven to actually cause the disease.[4]

Symptoms of brain tumors include persistent headache, nausea and vomiting, eyesight, hearing and/or speech problems, walking and/or balance difficulties, personality changes, memory lapses, problems with cognition and concentration, and seizures.[4]

GLIOMAS

Gliomas are the most common primary malignant brain tumors. They originate from non-neuronal (glial) brain cells called astrocytes. The World Health Organization (WHO) classifies them, from the least to the most aggressive, into four grades[5]:

- Grade I–pilocytic astrocytoma
- Grade II–diffused astrocytomas
- Grade III–anaplastic astrocytomas
- Grade IV–glioblastomas

Gliomas are typically associated with low survival. This is due to a combination of factors, including high relapse rates, which hinder successful treatment.[6,7] Also,

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gliomas are highly invasive. They can infiltrate to surrounding and remote brain areas as single cells. So, there is often no clear boundary between tumor and healthy tissue, which makes surgical resection difficult.[8]

Infiltration may involve eloquent areas; that is, those with specific functions, such as language, vision, and motor control. In this case, gliomas are referred to as infiltrating. IV-grade gliomas include *glioblastoma multiforme*, the most aggressive type of brain tumor. Its median survival rate is just 12 months.[8]

MRI USE IN BRAIN TUMOR

Medical history, biopsy–whereby a small amount of brain tissue is excised and analyzed under the microscope–and imaging studies are all important to reach a diagnosis of brain tumor. Standard x-rays and computed tomography (CT) can initially be used in the diagnostic process. However, MRI is generally more useful because it provides more detailed information about tumor type, position and size. For this reason, MRI is the imaging study of choice for the diagnostic work up and, thereafter, for surgery and monitoring treatment outcomes.[9]

MRI SIGNAL AND IMAGE GENERATION

Conventional MRI exploits three physical properties of tissue protons (Table 1) to generate signals that are imaged as areas of different contrast, which reflect the anatomy and physiology of the organ under investigation.[10]

Protons are positively-charged particles inside the nucleus of elements' atoms. Because we are mainly made up of water, the most abundant element in our body is hydrogen, each atom of which has one proton. To understand how the MRI signal is generated, we can imagine this proton as a minute magnet bar that moves like a spinning top. This tiny magnet bar can be described as a two-dimensional (2D) vector–also called a *spin vector*–with respect to a Cartesian coordinate system.[11]

Table 1. Protons' Properties Contributing to MRI Signal Generation*

Proton density	Number of hydrogen protons per unit volume of tissue
T1 relaxation time	Time needed to recover 63% of the longitudinal magnetization (see explanation in text)
T2 relaxation time	Time needed for 63% of the transverse magnetization to be lost (see explanation in text)

*Data from Westbrook C. *MRI at a Glance*. Wiley-Blackwell; 2010.

In the absence of a magnetic field, the spin vector is randomly orientated. However, when placed in a strong static magnetic field (B_0), such as that generated by MRI scanners, the spin vector tends to align parallel with B_0. As a result, its component along the y-axis (*longitudinal magnetization*) is different from zero but the one along the x-axis (*transverse magnetization*) is zero, and no signal can be produced.[11,12]

If a radio frequency (RF) pulse is applied, the spin vector absorbs energy from the latter and moves out of alignment away from B_0. (This phenomenon is called *resonance* and occurs only if the frequency of the applied RF pulse matches the proton's own natural oscillation frequency.) Both transverse and longitudinal magnetizations are now different from zero, and a signal can be generated (Figure 1).[12]

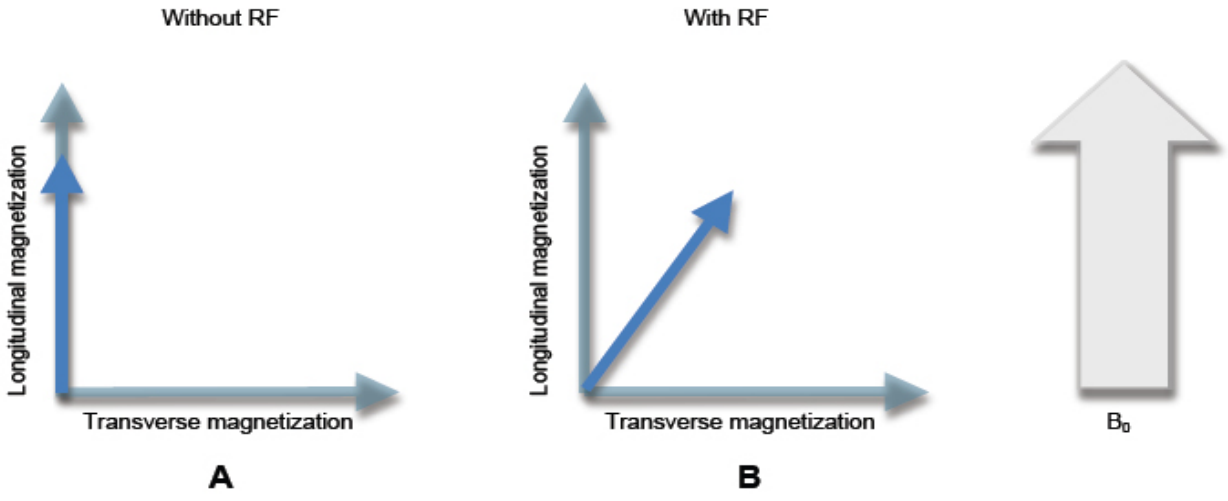

FIGURE 1. (A) Spin vector (blue arrow) aligned parallel with the main magnetic field (B_0). Transverse magnetization is zero, and no signal is generated. (B) Spin vector out of alignment, following the application of an RF pulse. Transverse magnetization is different from zero, and a signal can be generated.

Switching off the RF pulse causes the spin vector to release the energy absorbed from the RF pulse–a process called *relaxation*–and to realign with the main magnetic field (B_0). When this occurs, the transverse magnetization decays, whereas the longitudinal magnetization recovers. The time needed to recover 63% of the longitudinal magnetization is called *T1-relaxation time*. The time taken for 63% of the transverse magnetization to be lost is called *T2-relaxation time*. T1- and T2-relaxation times are specific to different types of tissue, and increase as the magnet's field strength increases.[12]

Both T1 and T2 are components of the MRI signal. A third component is proton density; that is, the number of hydrogen protons per unit volume of the tissue being imaged. All three contribute to contrast generation. But, because they do it simultaneously, the image would be confusing and difficult to interpret. The problem is avoided by weighting the contrast toward one of the three signal's components. As a result, the following images can be obtained: T1-weighted, T2-weighted, and proton density-weighted.[10,12]

In all three types of images, bright areas correspond to tissue with high signal intensity (i.e., large transverse magnetization) and are referred to as hyperintense, whereas dark areas correspond to low signal intensity (i.e., small transverse magnetization) and are referred to as hypointense.[13]

However, contrast is obtained in different ways:

- From differences in the T1 *recovery* times of tissues, in T1-weighted images.[13]
- From differences in the T2 *decay* times of tissues, in T2-weighted images.[13]
- From differences in the proton density of tissues, in proton-weighted images.[13]

In terms of reading and interpreting an MRI scan, this means that high-fat-content tissues appear as bright areas in T1-weighted images, whereas high-water-content tissues appear as dark areas. The opposite is true for T2-weighted images. Since most diseases are characterized by increased water content in tissues, T2-weighted images are particularly useful for pathological investigations. In contrast, T1-weighted images are best for anatomical studies, although they can be used for pathology, if combined with contrast enhancement. Currently, the standard contrast agent is gadolinium (Gd), due to its ability to cross the blood-brain barrier (BBB).[13]

In proton-weighted images, bright areas indicate high-proton-density tissues, such as the cerebrospinal fluid, and dark areas indicate low-proton-density tissues, such as cortical bone. Proton-density images are generally used to show anatomy and some pathology.[13] (See Table 2, which provides an overview of the key features of T1-, T2-, and proton-weighted images at a glance.)

*Table 2. Types, Characteristics and Use of Weighted Images**

Image Type	Contrast	Tissue Appearance	Best For
T1-weighted	Mainly due to differences in T1 recovery times	• High-**fat**-content tissues appear as **bright** areas of high signal intensity (hyperintense) • High-**water**-content tissues appear as **dark** areas of low signal intensity (hypointense)	Anatomy and, if used with contrast enhancement, also pathology
T2-weighted	Mainly due to differences in T2 decay times	• High-**fat**-content tissues appear as dark areas of low signal intensity (hypointense) • High-**water**-content tissues appear as bright areas of high signal intensity (hyperintense)	Pathology
Proton-density weighted	Mainly due to differences in proton density	• Low-proton-density tissues appear as dark areas of low signal intensity (hypointense) • High-proton-density tissues appear as bright areas of high signal intensity (hyperintense)	Anatomy, and some pathology

*Data from Westbrook C. *MRI at a Glance.* Wiley-Blackwell; 2010.

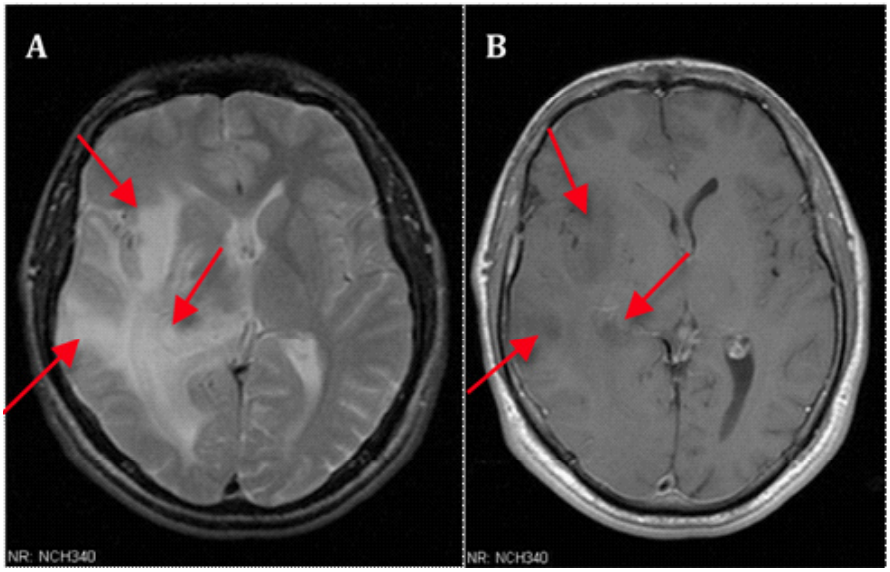

FIGURE 2. (A) Axial T2-weighted image of low-grade glioma in the right hemisphere, showing the lesion as a bright area of high-signal intensity. (B) The same glioma on a T1-weighted image with contrast enhancement, showing the lesion as a dark area of low-signal intensity. (Photo courtesy of Professor Wolfgang Wick and Professor Martin Bendszus, of the Neurooncology Department of Heidelberg University, Germany.)

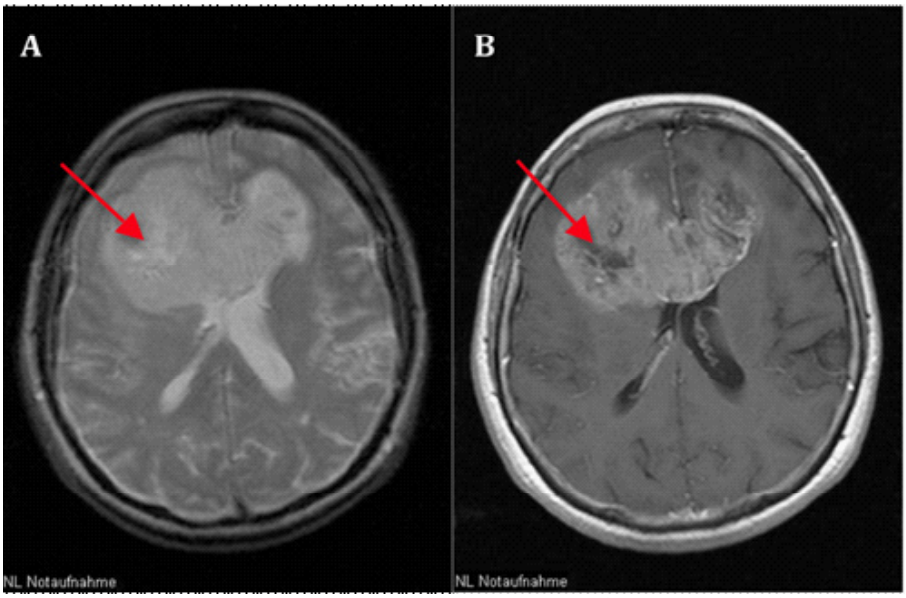

FIGURE 3. (A) Axial T2-weighted image of IV-grade glioma (glioblastoma) in the right hemisphere, showing the lesion as a bright area of high-signal intensity. (B) The same glioblastoma on a T1-weighted image with contrast enhancement, showing the lesion as a dark area of low-signal intensity. (Photo courtesy of Professor Wolfgang Wick and Professor Martin Bendszus, of the Neurooncology Department of Heidelberg University, Germany.)

BRAIN TUMOR MR IMAGING

Primary malignant brain tumors, such as gliomas, appear as hypointense, dark areas on gadolinium-enhanced T1-weighted MRI images, and as hyperintense, bright areas on T2-weighted images (Figures 2, 3).

While interpretation of gadolinium-enhanced T1-weighted images and T2-weighted images remains the mainstay of brain tumor diagnosis, this approach has limitations. For example, it is sometimes difficult to differentiate new from old tumors, or tumors from nontumoral lesions, like ischemia. Grading, monitoring of tumor progression, treatment response assessment, and detection of residual tumor after surgery may also be problematic. Techniques other than T1- and T2-weighted MRI can help overcome these limitations. The following sections describe the most established and widely available.[14]

*Table 3. Diffusion, Signal Intensity and Appearance in DW Images and ADC Maps**

DW Images	Increased diffusion → greater signal attenuation → lower signal intensity → dark area
	Reduced diffusion → smaller signal attenuation → higher signal intensity → bright area
ADC Maps	Increased diffusion → smaller signal attenuation → higher signal intensity → bright area
	Reduced diffusion → greater signal attenuation → lower signal intensity → dark area

*Data from Le Bihan D, Breton E, Lallemand D, Grenier P, Cabanis E, Laval-Jeantet M. MR imaging of intravoxel incoherent motions: application to diffusion and perfusion in neurologic disorders. *Radiology*. 1986;161:401-7.

DIFFUSION-WEIGHTED MRI

In diffusion-weighted imaging (DWI), contrast reflects changes in the random, temperature-dependent movement of water molecules. This movement is termed *diffusion*.[11,15,16]

In biological tissues, structural barriers like cell membranes prevent water molecules from moving completely at random. Therefore, the rate of water diffusion (i.e., the magnitude of water molecule movement) is expressed as *apparent diffusion coefficient* (ADC) value.[11,15,16]

Diffusion-weighted images are acquired by superimposing, for a short time, strong field gradients, called *gradient pulses*, on the main magnetic field (B_0). This results in image sensitization to water in the direction of the gradients, and signal attenuation along the axis to which these are applied.[11,17,18]

Sensitization to water motion is defined by a parameter called *gradient factor* or *b value* (sec/mm^2). The higher the diffusion in the tissue under study the greater the signal attenuation and the darker the correspondent area on the image. Diffusion data can also be presented as mathematical maps of the apparent diffusion coefficient of water obtained from DW images. In this case, the higher the diffusion the smaller the signal attenuation and the brighter the correspondent area on the map (Table 3).[11,17,18]

Primary malignant brain tumors like gliomas usually show lower cellularity and, consequently, greater diffusion than normal tissue. Thus, they are dark on DW images and bright on ADC maps.[9]

Diffusion-weighted imaging is a valuable tool in the follow-up of high-grade gliomas, particularly for differentiating treatment effects from tumor recurrence or progression. This is because radiation and chemotherapy–the standard treatments for brain tumor together with surgery–cause decreased tissue cellularity and, consequently, increased ADC, which is detectable as areas of higher signal intensity (i.e., brighter areas) within the tumor.[19]

In terms of diagnosis, DWI has advantages over other MRI modalities, for it allows distinguishing malignant from benign tumors, and tumoral from nontumoral lesions. However, it has shortcomings. For example, as noted earlier, gliomas in ADC maps normally show as bright areas (high ADC). Yet, a small number of glioblastomas have shown as dark areas (low ADC) in studies. This makes it difficult to distinguish them from other types of brain tumors, like meningiomas, which also have low ADC. It is therefore recommended, to assist with the diagnosis, to combine DWI with other MRI modalities.[14]

PERFUSION-WEIGHTED MRI

Perfusion-weighted MRI measures perfusion (e.g., blood flow) in tissues. It involves the use of an intravascular exogenous contrast agent, typically a bolus injection of gadolinium administered during ultrafast T2 acquisitions. The contrast agent causes reductions in T2 decay. Thus a signal decay curve, called time intensity curve (TIC) can be generated after data acquisition.[11-13]

TICs for several images acquired during and after gadolinium injection are combined to produce a colored map of cerebral blood volume (CBV). On CBV maps, areas of high perfusion, like in malignant brain tumors, are bright. Areas of low perfusion, such as in strokes, are dark.[11-13]

The microvessels of certain brain tumors, such as meningiomas and lymphomas, do not form a BBB. As a result, gadolinium can leak into the interstitial space. This does not occur in other types of brain tumors, like peripheral glioblastomas, whose microvessels form a BBB that prevents leakage of the contrast medium. As a result, differences in time intensity curves can be observed, which help discriminate between tumor types and, therefore, assist with differential diagnosis. Perfusion imaging is also useful for glioma grading, especially for ensuring surgical resection of the highest-grade area of heterogeneous brain tumors. In general, CBV maps that demonstrate elevated blood volume indicate the presence of a glioma, and grade-IV lesions should be suspected when values are similar to, or greater than, that of the cortex.[20-23]

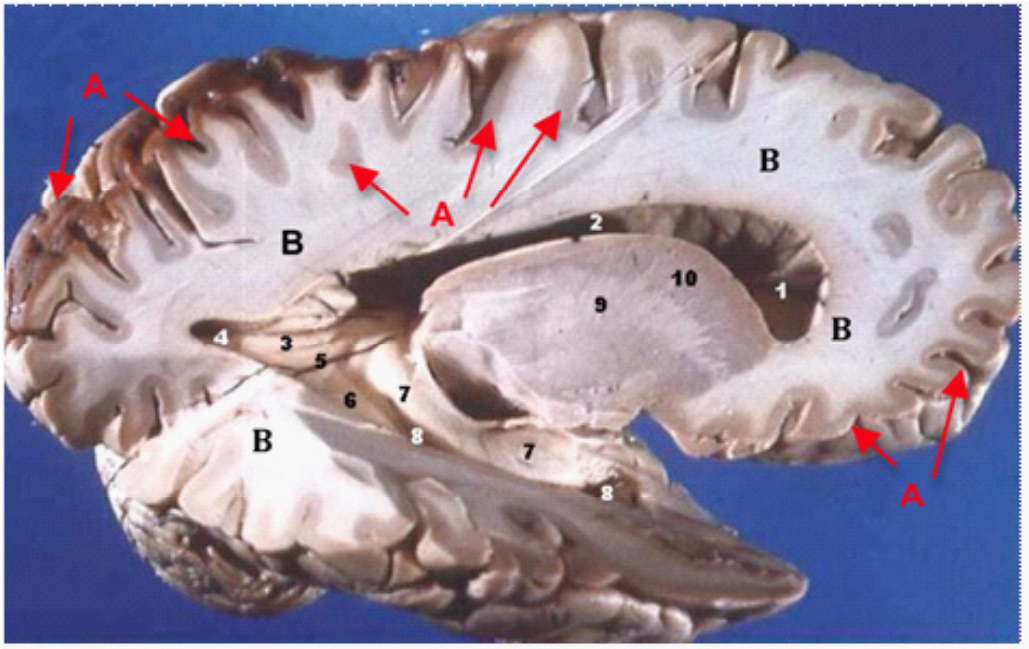

FIGURE 4. Human brain right dissected lateral view. A: Cerebral cortex (gray matter). B: White matter. 1: Lateral ventricle, frontal horn. 2: Lateral ventricle, central part. 3: Calcar avis. 4: Lateral ventricle, occipital horn. 5: Collateral trigone. 6: Collateral eminence. 7: Hippocampus. 8: Lateral ventricle, temporal horn. 9: Internal capsule. 10: Caudate Nucleus. (Photo courtesy of Dr. John A. Beal of the Department of Cellular Biology & Anatomy of Louisiana State University Health Sciences Center, Shreveport, Louisiana.)

DIFFUSION-TENSOR MRI

As with DWI, diffusion-tensor MRI (DTI) detects changes in diffusion of water molecules in tissues, visible on diffusion-weighted images or ADC maps, but involves the use of strong multidirectional gradients to acquire additional data about the preferential direction and magnitude of the diffusion.[24]

In other words, DTI shows the degree to which water diffusion is facilitated in one direction, also called *diffusion anisotropy*. Mathematically, this is expressed by a quantity called *fractional anisotropy* (FA). FA measurements allow mapping, and establishing the integrity of, myelinated fiber tracts (white matter) that connect the processing centers of the cerebral cortex (gray matter) (Figure 4). Consequently, diffusion-tensor imaging can be used to ascertain whether, and to which extent, the tumor has displaced, or otherwise damaged, eloquent areas. This, in turn, allows one to determine preoperatively (i.e., before surgery) the tumor's position respective to such areas, and to predict the type and degree of impairment that may result from injuries caused intraoperatively (i.e., during surgery).[24-26]

Diffusion-tensor imaging has other important uses. For example, one study of patients with meningioma or infiltrating enhancing high-grade glioma has demonstrated that it is possible, with the appropriate choice of *b* values, angular resolution, and signal-to-noise ratio, to distinguish one tumor type from the other by looking, on ADC maps, at differences in FA measurements between areas of vasogenic edema and normal-appearing white matter surrounding the lesions.[27] (Vasogenic edema is the accumulation of extracellular cerebrospinal fluid due to disruption of the blood-brain barrier that typically forms around brain tumors.)

In the study, diffusion-tensor imaging was performed with a 1.5 Tesla MR scanner (Signa; General Electric Medical Systems) using a standard head coil. Imaging data were acquired with a single-shot spin-echo echo planar sequence using the following protocol[27]:

- Repetition time: 12,000 msec
- Inversion time: 2,200 msec
- Matrix size: 128 x 64
- *b* values: 0 and 1,000 sec/mm^2 (six gradient directions, one signal acquired)

DTI showed a difference in FA values in vasogenic edema and normal-appearing white matter between meningiomas and high-grade gliomas, which contributed to differential diagnosis.

Furthermore, a comparison among data acquired with T1-, T2- and diffusion-tensor-weighted imaging in location-matched brain areas led researchers to suggest that DTI can help identify tumor infiltration that is not detected with conventional MRI.[27]

MAGNETIC RESONANCE SPECTROSCOPY

Magnetic resonance spectroscopy (MRS) is mainly used for tissue metabolism studies and for differentiating between tumor types. Data acquired with MRS are presented as a spectrum, consisting of a graph showing the relation between signal intensity and proton resonance frequency. MRS spectra vary with the chemical and molecular structure of the tissue under study. They are used to evaluate frequency differences, or chemical shift, between tissues. The chemical shift is displayed on the x-axis in parts per million (ppm). On the y-axis, are arbitrary units of signal intensity.[12,13]

Typically, MRS spectra show series of peaks corresponding to metabolites found in a tissue. MRS data can be used to generate metabolic maps that show where, in the brain, the peaks are located.[12,13] Major peaks observed in 1.5 Tesla MRS of brain tumor include myoinositol (3.6 ppm), creatine (two resonant peaks at 3.0 and 3.9 ppm), choline (3.2 ppm) n-acetyl aspartate (NAA; 2.0 ppm), lactate (1.3 ppm) and lipid (one broad peak from 0.9 to 1.5 ppm).[14]

The typical MRS spectrum of a glioma has low or absent peaks of NAA (a marker of neuronal density and viability) and high peaks of choline (a marker of cell membrane turnover). High-grade gliomas such as glioblastomas also show lactate and lipid peaks.[14]

Since different types of brain tumors have similar spectra, MRS is not useful for differential diagnosis. However, it has proved to be a valuable tool for glioma grading. For example, high choline/NAA peak height ratios (above 1.5 ppm) have been associated in studies with high-grade lesions.[28]

MRS is also used to:

- More accurately target biopsies, by aiming at areas with high choline/NAA ratios[29,30]
- Recognize tumor recurrence, as this shows as a progressive increase of the choline/NAA ratio[31]
- Detect radiation necrosis, which shows as a complete absence, or progressive reduction over time, of NAA and choline peaks, whereas lactate and lipid peaks are present[29]

To obtain useful data and avoid artifacts it is important to choose an appropriate area of interest and size of voxel (i.e., the volume of patient tissue; defined as pixel area multiplied slice thickness). Also, reliable MRS is generally based on the comparison of several spectra, to see how these change over time. Data acquisition requires the supervision of a trained spectroscopist.[14]

INTRAOPERATIVE MRI

As explained earlier, because gliomas spread by infiltration, it is difficult for the neurosurgeon to distinguish them from normal brain tissue based on visual and textural inspection alone. Therefore, resecting them completely is a major challenge. Yet, the extent of surgical resection (also referred to as *craniotomy*) is crucial to survival, regardless of the level of malignancy.[32]

Image-guided systems are available to assist the neurosurgeon during craniotomy, and allow for a more complete and accurate resection of the tumor. Known as neuronavigation systems, these include ultrasonography, computed tomography (CT), and MRI (computer-guided stereotaxis). However, conventional neuronavigation involves the use of image data acquired preoperatively. Therefore, it does not account for changes in brain position and morphology that occur during the surgery. Such changes are collectively referred to as *intraoperative brain shift*, and hinder the accurate localization and resection of the tumor.[33]

Brain shift occurs at the start of the operation, when the neurosurgeon opens the dura (i.e., the outermost layer surrounding the brain and spinal cord). This alters the pressure inside the skull causing the brain to move. Brain shift continues during the operation, because of gravity, loss of cerebrospinal fluid, swelling due to medications and/or anesthetics, and of course collapse of the resection cavity, as the neurosurgeon removes the tumor.[33]

Intraoperative magnetic resonance imaging (iMRI), whereby MRI scanning takes place immediately before, during, and after surgery, can effectively compensate for these changes, providing consistently accurate guidance as to where the tumor is during the various stages of the operation. This increases the chances of complete resection, in turn improving survival. For this reason, iMRI is considered one of the most important developments in neurosurgery.[34]

The positive correlation between amount of tumor removed and survival has been widely demonstrated. In one study, patients who had their glioma only partially removed were 4.9 times more likely to die, within three years from the operation, than patients who had the tumor completely removed. Partial resection was also associated with a 1.4-fold increased risk of relapse, during the same follow-up period.[35]

In the study, complete resection was achieved using a 0.5 Tesla intraoperative MRI system developed in collaboration with General Electric Medical Systems. The extent of tumor resection was monitored during surgery by performing MRI

- at the initial positioning of the patient,
- after the opening of the dura, and
- at the end of the surgery.

Imaging data sets were acquired using fast spoiled-gradient (FSPGR), T1, T2, and gradient sequences. Slice thickness was 1.5 to 2.5 mm.[35]

Each patient's tumor area was measured on three-dimensional (3D) FSPGR images, as these more precisely define the boundary between tumor and non-tumoral tissue. If the SPGR images were not usable,

for example, because of technical or motion artifacts, T2-weighted sequences of 5-mm-thick slices were used instead. In either case, the tumor's volume was then calculated by adding all the voxels within the tumor area on each slice. Volumetric calculations from SPGR or T2 images obtained at the start of the surgery were compared with those taken at surgery completion. If the latter showed no residual tumor volume, resection was considered complete.[35]

In another study, total resection of low- and high-grade gliomas with no infiltration in eloquent areas was possible, with iMRI, in 100 percent of patients. Without iMRI, total resection was achieved only in 60 percent of patients. Total resection of gliomas with infiltration in eloquent areas was also achieved more often with iMRI than without it (89.23 versus 71.4 percent of patients).[36]

AWAKE CRANIOTOMY

Usually, patients whose preoperative MRI shows that the tumor has not spread to eloquent areas undergo surgery with general anesthesia. Those whose preoperative MRI indicates that the tumor has infiltrated eloquent areas, undergo surgery with local anesthesia. The latter surgical procedure is called *awake craniotomy*.[37]

As noted earlier, resection of infiltrating gliomas poses special challenges. Recognizing and resecting only tumoral tissue is extremely difficult. Therefore, there is a high risk of damaging eloquent areas, causing postoperative neurologic deficits, such as loss of the ability to talk, move, see, etc. To minimize this risk, the neurosurgeon needs to be able to delineate the tumor's margins. This is achieved by performing what is known as *cortical mapping*.

In cortical mapping, patients are only locally anesthetized, so they are awake and able to function during the operation. The procedure involves asking the patient to perform simple tasks, like naming objects, while the neurosurgeon concurrently stimulates their brain with an Ojemann cortical stimulator (Ojemann Cortical Stimulator, Integra Radionics, Inc. Burlington, Mass). This is a battery-powered, hand-held device that allows small currents to be applied to localized areas of the brain's surface, temporarily deactivating them. If, during stimulation of a certain area, the patient performs a given task normally, the area being stimulated is safe to resect. If the patient struggles to complete the task, the area being stimulated must not be removed, even if tumor is present. Resection in that area would cause neurological damage. Cortical mapping is performed continuously during the operation, allowing the neurosurgeon to define the limits of safe tumor resection in real time.[38,39]

AWAKE CRANIOTOMY WITH MRI

The usefulness of awake craniotomy for patients with glioma that is near to, or infiltrating, eloquent areas is enhanced when cortical mapping is performed with the aid of MRI. Initially, this was achieved with the earlier mentioned computer-guided sterotaxis. In one study, combining this technique with cortical mapping achieved near-complete tumor resection–as demonstrated by a greater than 90 percent reduction in T2 signal postoperatively–in 52 percent of patients. There were no deaths during the surgery, and although 74 percent of patients developed neuronal deficits intraoperatively, approximately 71 of these patients recovered within three months.[40] Imaging data were acquired just before surgery and 48 hours after. The protocol included two axial sequences: a T2-weighted, spin echo sequence with long relaxation time, and a three-dimensional volumetric T1-weighted spin echo with short relaxation time and gadolinium enhancement. Both sequences had the following parameters[40]:

- Field of view: 24 cm
- Matrix size: 256 x 256 pixels
- Section thickness: 3 mm

However, because stereotaxis uses preoperative images to guide the neurosurgeon, it cannot compensate for brain shift. Better outcomes can be obtained by performing awake craniotomy with intraoperative MRI. In one study, this approach successfully achieved total resection in eloquent areas with no disruption of neurological function.[41]

Intraoperative MRI was performed with a 1.5 Tesla unit, using the same sequences as in conventional MRI scanning. A flexible surface coil was kept under the patient's head for the entire duration of the surgery. A second surface coil was placed on top of the Mayfield clamp (used to keep the patient's head fixed to the surgical table) only for scanning.[41]

A T2-weighted scan was performed soon after positioning the patient, to identify potential artifacts. During the surgery, scanning was performed on demand. Routine T1-weighted images were used, before and after contrast administration, for tumors showing contrast enhancement. Fluid-attenuated inversion recovery (FLAIR) and axial T2-weighted imaging were used for nonenhancing tumors.[41]

To avoid the possibility that iMRI altered the results of cortical stimulation, surgery was performed in an area of the operating room outside the five-gauss line, that is, outside the static magnetic field generated by the scanner. Patients were transferred from the surgical site to the scanner, and back, with a pivotal table. MRI images were loaded into the navigation system. The imaging interval was kept as short as possible.[41]

Patient transfer to and from the scanner required about three to five minutes every time. Although this prolonged the surgery by up to 60 minutes, the overall procedure was well tolerated by patients, the majority of whom (32 out of 34) said they would undergo a second awake craniotomy with iMRI. Importantly, the use of intraoperative MRI was not associated with adverse effects, such as seizures.[41]

Besides eliminating the risk of MRI potentially affecting cortical stimulation results, performing the surgery outside the five-gauss line allows the use of ferromagnetic tools and equipment. Early iMRI units were designed in a way that required both the patient and the surgeon to be inside the magnet. Consequently, the surgery had to be performed with nonferromagnetic surgical equipment (e.g., operative microscope, cortical stimulator, ultrasonic aspirator), which is more expensive than the standard equipment. In addition, costs increase with stronger magnetic fields. More recently developed iMRI scanners allow the neurosurgeon to operate outside the magnetic field.[42]

MRI scanning is not always performed in the operating room. Some hospitals and other surgical centers have the MRI unit in an adjacent room, which allows the scanner to be used for outpatient imaging when not needed for surgery.[42]

Performing surgery outside the magnetic field is possible with both low-field (0.5 Tesla) and high-field (1.5 Tesla) systems. However, because of increased magnet strength and magnetic gradients, high-field iMRI yields significantly improved image quality and signal-to-noise ratio. Furthermore, it is faster, allows for superior anatomical resolution, and enables the acquisition of sequences that are essential for glioma surgery (e.g., T2-weighted images), all of which contribute to more complete tumor resection.[42] In one study of 46 patients who underwent craniotomy, additional tumor removal after high-field iMRI increased the extent of resection from 76 to 96 percent, and allowed neurosurgeons to achieve gross total resection in 71 percent of cases.[43]

Positive results have also been obtained with ultrahigh-field (3 Tesla) iMRI. In a recent study–the first one to use an ultrahigh-field system for glioma surgery–the number of total gross resections increased by 32.3 percent with iMRI. Additionally, the intraoperative application of MRI made it possible to accurately discriminate between T2-weighted changes in normal tissue and residual tumor.[44]

CONCLUSION

MRI is the preferred imaging study for brain tumor diagnosis, providing detailed information on lesion type, size and location. Although gadolinium-enhanced T1-weighted images and T2-weighted images are the MRI modalities of choice for the initial assessment, their usefulness in identifying tumor types, distinguishing tumors from nontumoral lesions, and assessing treatment effects is limited. For this reason, they are used in combination with other MRI techniques. The most researched and employed of these techniques include diffusion-weighted imaging (DWI), perfusion MRI, diffusion-tensor imaging (DTI) and magnetic resonance spectroscopy (MRS).

Perhaps the most important application of magnetic resonance is intraoperative MRI (iMRI), which assists in localizing the tumor during surgery. Used with or without cortical stimulation, iMRI can maximize tumor resection while minimizing damage to healthy tissue, thereby reducing the risk of neuronal deficit, and improving patient survival.

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MAGNETIC RESONANCE IMAGING OF BRAIN TUMOR POST TEST

Expires: July 15, 2013 Approved for 1 ARRT Category A Credit.

1. **What are brain tumors?**
   a. Areas of reduced blood flow
   b. Abnormal proliferations of cells
   c. Swollen tissues
   d. Buildup of cerebrospinal fluid
2. **Unlike secondary brain tumors, primary brain tumors**
   a. can spread to other body parts and are always malignant.
   b. can spread to other body parts and can be malignant or benign.
   c. remain confined to the brain and are always malignant.
   d. remain confined to the brain and can be malignant or benign.
3. **Which of the following is NOT true of gliomas?**
   a. Patient survival is very low.
   b. Relapse rates are high.
   c. Gliomas can easily be distinguished from healthy tissue.
   d. Gliomas are the most common primary malignant brain tumors.
4. **MRI is the imaging study of choice for brain tumor because it**
   a. provides detailed information about lesion type, size and location.
   b. is more widely available than other imaging modalities.
   c. is inexpensive and time saving.
   d. is less painful than other imaging modalities.
5. **Which of the following DOES NOT contribute to MRI signal generation?**
   a. T2-relaxation time
   b. Voxel
   c. Proton-density
   d. T1-relaxation time
6. **An MRI signal is produced when transverse magnetization is**
   a. zero.
   b. switched off.
   c. different from zero.
   d. applied along the y-axis.
7. **Gliomas appear in gadolinium-enhanced T1-weighted MR images as _____, _____ areas.**
   a. hyperintense; dark
   b. hypointense; dark
   c. hyperintense; bright
   d. hypointense; bright
8. **Gliomas appear in T2-weighted MR images as _____, _____ areas.**
   a. hyperintense; dark
   b. hypointense; dark
   c. hyperintense; bright
   d. hypointense; bright
9. **Vasogenic edema is**
   a. a chronic subdural fluid collection.
   b. the accumulation of extracellular cerebrospinal fluid due to disruption of the blood-brain barrier.
   c. the benign extracerebral fluid collections that are common in infants.
   d. when the BBB remains intact; it is due to derangement in cellular metabolism.
10. **MRS is primarily used**
    a. to compensate for brain shift during intraoperative studies.
    b. to determine the differential diagnosis of glioma.
    c. for tissue metabolism studies and for differentiating between tumor types.
    d. for the imaging of white matter.
11. **In intraoperative MRI (iMRI), images are taken**
    a. immediately before surgery.
    b. immediately after surgery.
    c. immediately before, during, and after surgery.
    d. immediately before and after surgery.
12. **Compared to other imaging modalities, iMRI is more effective at maximizing surgical resection while reducing the risk of damage to healthy tissue because it**
    a. does not require preoperative imaging studies.
    b. can compensate for brain shift.
    c. can be used alone.
    d. allows for the use of ferromagnetic tools.
13. **By maximizing resection, iMRI improves survival. In one study, patients with partial glioma resection were _____ more likely to die within three years than patients with total glioma resection.**
    a. 4.9 times
    b. 2.6 times
    c. 1.8 times
    d. 0.5 times
14. **In another study, use of iMRI increased total resection of non-infiltrating gliomas from ____ to____ percent.**
    a. 60; 100
    b. 60; 85
    c. 60; 80
    d. 60; 75
15. **Besides improving total surgical resection rates, when combined with cortical stimulation, both MRI and iMRI can reduce the risk of**
    a. side effects from anesthetics.
    b. damage to eloquent areas.
    c. artifacts.
    d. patients losing consciousness.
16. **To prevent iMRI from altering the results of cortical stimulation during awake craniotomy, the operation must be performed**
    a. with low-field MRI systems.
    b. with high-field MRI systems.

c. inside the magnetic field generated by the scanner.
d. outside the magnetic field generated by the scanner.

17. iMRI is possible with
a. low-field (0.5 Tesla) and high-field (1.5 Tesla) systems.
b. high-field (1.5 Tesla) and ultrahigh-field (3 Tesla) systems.
c. low-field (0.5 Tesla), high-field (1.5 Tesla), and ultrahigh-field (3 Tesla) systems.
d. low-field (0.5 Tesla) and ultrahigh-field (3 Tesla) systems.

18. Compared to low-field system iMRI, high-field iMRI is associated with
a. improved image quality.
b. worse signal-to-noise ratio.
c. reduced speed.
d. lower anatomical resolution.

19. One study found that high-field (1.5-T) iMRI increased the extent of glioma resection from _____ to _____ percent
a. 76; 96
b. 76; 90
c. 74; 90
d. 74; 88

20. In another study, ultrahigh-field (3 Tesla) iMRI increased the number of total glioma resections by _____ percent.
a. 10.3
b. 18.6
c. 32.3
d. 44.8

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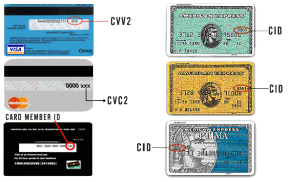

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