19 CT/MRI Safety in Functional Neurosurgery

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Introduction

Unique and ever-changing applications of imaging technologies have played an integral role in transforming the landscape of stereotactic and functional neurosurgery [1]. Both computer tomography (CT) and magnetic resonance imagery (MRI) continue to push forward the boundaries of image-guided neurological surgery. Despite the great benefits offered by CT and MRI, however, each technique poses certain risks to the safety of patients and, in some cases, of healthcare workers [2–4].

This chapter addresses pivotal considerations of the safe use of CT and MRI. The primary risks of CT scanning are associated with ionizing radiation and reactions to iodinated contrast media (ICM) [2,3,5] While MRI is often considered safer than CT because of the absence of ionizing radiation, MRI has raised its own set of safety issues. The use of gadolinium-based MR contrast agents (GBMCAs) has been linked with various types of adverse reactions, especially contrast-induced nephropathy in patients in advanced stages of renal disease [2]. In addition, MRI must be used with caution in patients with implanted devices [1,2].

Computed Tomography

Safety of Ionizing Radiation

Background

Computed tomography uses ionizing radiation: high-energy photons that are known to damage DNA and generate free radicals. This is a safety concern because CT scanners usually deliver radiation doses that are often 100 times greater than those of conventional radiographic examinations, including chest X-rays or mammograms [3]. Scanner-based CT radiation carries a small but serious risk of causing cancer. Ionizing radiation can injure biologic material through several mechanisms, including formation of hydroxyl radicals that damage or break DNA double-strands bases Concern over the risk of ionizing radiation for health problems, including malignancy, has reached a critical level in the current medical climate [5].

CT Scanning and Radiation Parameters

The radiation dose for a specific study is determined by several scan parameters. These include the number of scans, tube current and scanning time in milliampseconds (mAs), size of the patient, axial scan range, scan pitch (the amount of overlap between adjacent CT slices), tube voltage in the kilovolt peaks (kVp), and the design features of the scanner used to deliver the dose [5].

Estimations of CT Radiation-Related Cancer Risk

Estimates of radiation-induced cancer risk are based on epidemiologic follow-up studies of atomic-bomb survivors in Japan and other large

population investigations. One large-scale study examined 400,000 radiation workers in the nuclear industry receiving about 20 milliSieverts (mSv) (a representative organ dose from a single CT scan for an adult). These investigations yielded a significant association between radiation dose and cancer-related mortality in persons exposed to doses between 5 and 150 mSv [3].

The estimated lifetime risk of death from cancer resulting from a single CT scan of the head is determined by adding the estimated organ-specific cancer risks. Again, these risks are derived from estimations of organ-specific data for cancer incidence or mortality in atomic-bomb survivors. A CT study with 2 or 3 series produces a radiation dose in the range of 30–90 mSv. Findings from some investigations suggest that this dose range is associated with a statistically significant increase in the risk of cancer in adults. Approximately 0.4% of all cancers in the United States may be associated with CT scanner-based radiation. Current estimates of excess radiation-related cancer rates range between 1.5 and 2.0%. The evidence for increased risk is most compelling for children. Compared to adults, they are more radiosensitive and have a longer remaining life span during which time a radiation-induced cancer could form. The lifetime cancer mortality risk associated with a single head CT protocol in a 1-year-old child was 0.07% [3].

The methodology for estimating the long-range cancer risk from CT radiation is in dispute over bias. Some investigators claim that the linear no-threshold model in this dose range may overestimate the risk. Excess cancer rates have not been reported in humans for doses below 100 mSv, One possible reason for this is that defense mechanisms that inhibit radiocarcinogenesis may be much more effective at low doses [6,7]. Yet, other evidence reveals that exposure to CT-related radiation exceeds low-level radiation doses, instead falling within the range of medium-level exposure. This is noteworthy because increased cancer risk is related to mid-level radiation doses [5].

Strategies for Reducing Radiation Dose

Strategies for radiation dose reduction include in-plane bismuth shielding, minimizing multiphase scanning, and decreasing or eliminating multiple scans with contrast material. CT settings can be optimized by decreasing tube current (often via automatic tube current modulation (ATCM)), using a larger pitch, and limiting the range of coverage. The automatic exposure-control option on new scanners can be adjusted to decrease the radiation dose. However, there is almost always a tradeoff between lowering the level of radiation dose and producing the highest quality images. The cost of reducing radiation dose by, for example, decreasing gantry rotation time, is an increase in image noise [5,8].

Minimizing patient exposure to radiation remains a priority for healthcare workers in radiology. In some cases, magnetic resonance imaging (MRI) may be a preferred option to CT scans [9]. In the absence of updated CT protocols that reflect current scientific thought, neuroradiologists and neurosurgeons must collaborate to identify optimal techniques for radiation dose reduction during a CT diagnostic or interventional procedure. Since current radiation risk estimates remain ambiguous, CT scans should be performed in accordance with the "ALARA" principle: "As low as reasonably achievable" [5,9]. Nowhere is this more crucial than for the pediatric population. Guidelines established for CT imaging in children recommend adjusting scan parameters for smaller size in order to achieve lower-dose scanning for specific applications. Following CT guidelines protocols for using age-adjusted, relatively lower tube currents may help to reduce the radiation dose for pediatric CT of the brain [3,5].

Iodinated Contrast Media (ICM) Used in Enhanced CT Scans

Background

Indications for the use of iodinated contrast media (ICM) in stereotactic neurosurgery mainly include targeting of mass lesions for stereotactic biopsy and radiosurgery [10]. While in much of the developed world contrast–enhanced MRI has supplanted CT for these uses, CT contrast may still be needed [11]. Patients with pacemakers in general cannot safely undergo MRI, and others who are obese or claustrophobic may not tolerate the small bore and prolonged acquisition times [4]. MRI may not always be available, and in much of the world CT is by far the more common imaging modality. It therefore behooves neurosurgeons to understand potential problems associated with the use of ICM.

Types of Radiographic Iodinated Contrast Media (ICM)

Contrast materials consist of ionic (high osmolar), and organic non-ionic (low osmolar) water soluble agents. The higher osmolarity (600–2,100 mOsm/kg) in solution for ionic contrast agents accounts for some of their adverse effects. By contrast, nonionic agents have approximately half the osmolality of ionic substances, making them less likely to affect the blood-brain barrier. These materials exhibit fewer side effects because they do not ionize in solution. Yet, nonionic agents possess the same degree of radiopacity as ionic contrast materials. Both high and low osmolar iodinated contrast agents are used in current medicine, although nonionic ICM are more common [2].

In clinical practice, ICM are typically classified by osmolality. Low-osmolality ICM may be subcategorized further into (1) nonionic monomers, (2) ionic dimers, and (3) nonionic dimers. Non-ionic ICM are the preferred agents in CT enhanced scans of the head [2].

Safety Studies of Nonionic Versus Ionic Iodinated Contrast Media

Large population studies have demonstrated the relatively lower risk of nonionic ICM compared with ionic ICM. Comparative data from two older large-scale studies suggested that the incidence of mild adverse reactions to contrast media was 2.5% for ionic ICM, but only 0.58% for nonionic ICM. Severe reactions were reported in 0.4% of patients administered ionic ICM and 0% for severe reactions after administration of nonionic ICM [12,13]. Katayama et al. reported that in a series of 337,647 cases, the overall risk of an adverse drug reaction associated with ICM was 12.66% for ionic ICM and 3.13% for nonionic ICM. The risk of a very severe adverse drug reaction was 0.04% for ionic ICM and 0.004% for nonionic ICM [14]. In a meta-analysis of studies published during the 1980s, Caro, et al. documented risks of mortality and severe nonfatal reactions in high-osmolality ICM compared to nonionic ICM. These investigators calculated a rate of severe adverse drug reaction of 0.157% for high-osmolality ICM and 0.031% for nonionic ICM. The rate of a fatal adverse reaction was one death in 100,000 patients for both types of ICM [15].

Adverse Reactions to Iodinated Contrast Media

Background

Despite their poorer safety record, high-osmolality ICM are still used in current medicine, primarily because of their lower cost. These media should be used selectively. High-osmolality ICM have an increased risk for adverse contrast reactions, and a significantly higher risk for contrast-related severe

adverse events [2]. The overall safety of lower-osmolality nonionic ICM has been well established since the 1990s, but adverse events have been reported. Mild and moderate adverse reactions are generally uncommon. Severe and even fatal adverse effects are quite rare, but may occur unpredictably in some patients. Serious reactions may be preceded by a mild or moderate prodromal phase. A "test injection" administered before a contrast-enhanced CT may increase the risk for severe adverse events [2].

ICM may also impair kidney function in certain patients or exacerbate pre-existing renal insufficiency in persons with compromised kidney function. Although contrast-induced nephropathy is not an adverse allergic reaction, it is a serious adverse event that may have debilitating consequences for high-risk persons undergoing iodinated contrast enhanced CT [2].

Safety Issues: Magnetic Resonance Imaging

MRI-Related Management of Metal Implants and Foreign Bodies

Background

Increasing use of technologically advanced MR systems during the past 20 years has introduced growing safety concerns over the MRI environment itself [16]. Compared to older machines, new MRI scanners have stronger static magnetic fields, faster and stronger gradient magnetic fields, and more powerful radiofrequency transmission coils. While there is no evidence that magnetic fields produce irreversible biologic effects, under certain conditions several features of high-field MRI equipment pose serious hazards for the body and for implanted metal devices [17]. Expanding clinical applications of deep brain stimulation (DBS), in particular, require a new set of safety measures for performing MRI examinations in patients with implanted neurostimulation devices [16–18]. Metal implants warrant special consideration because they are typically located near, or contiguous with, brain structures or cerebral vasculature.

As recent descriptions of several MR-related injuries and at least two fatalities illustrate, strict adherence to updated evidence-based safety guidelines on MRI technology is essential. Failure to follow the manufacturer's guidelines when performing MRI on patients with a specific neuromodulation or other metal implant may have devastating consequences. In one reported case, the DBS electrode was heated during an MRI scan of the lumbar spine on a patient with Parkinson's disease. The heating produced a radiofrequency lesion that led to permanent neurological damage [19]. This single case study further underscores the importance of literally complying with safety guidelines for performing MRI in persons with metallic implants. Patients may be subjected to severe injury if healthcare workers attempt to generalize about various conditions, positioning schemes, or other scanning scenarios stipulated for one neurostimulation system during MRI scanning, and then inadvertently apply these generalizations to the operation of other systems [16–18].

The primary hazards associated with MRI equipment in conjunction with implanted devices are categorized as follows [4,16,17,20].

- Risks associated with the static magnetic field (Bo), including complications such as movement of ferromagnetic objects, twisting, heating, artifacts, and device malfunction produced by the static magnetic field.
- Risks associated with radiofrequency field (RF) effects, including complications arising from body coils and specific absorption rate (SAR).

Risks Associated with Static Magnetic Field Strength

Projectile Effect

The projectile effect, or the disturbing movement of ferromagnetic material, is a primary complication of metallic implants that may occur during an MRI. Also known as the missile effect, it is caused by interactions between the static magnetic field and MRI systems [21]. Magnetic translational and rotational forces that are exerted on a ferromagnetic object can move or dislodge the object from its implanted position. A magnet of high field strength can rapidly pull different types of ferromagnetic objects into the MRI scanner. The patient is subsequently at risk for injury by any number of objects, ranging from internal aneurysm clips and pins in joints to oxygen canisters and wheelchairs [22,23].

Heating

The greatest risk for MRI scanning in a patient with a DBS implant is MRI-related heating of metallic objects, especially DBS leads. Heating is poorly tolerated in the central nervous system. When electrically conductive materials are introduced within the magnet and touch the bore of the MRI scanner, these materials may overheat. If a conductive object comes in contact with the patient's tissue, it may burn his skin, possibly resulting in irreversible lesions [16,18,20]. In addition, conductive loops that come in contact with tattoos and eye-liners containing iron-oxides may cause burns [20]. A neurostimulation system used for DBS can generate variable levels of heating. Which levels are most likely to occur, and what factors are most likely to cause overheating depend upon the specific type of implanted device as well as various parameters used for a given MRI procedure [16,18,23].

Intrinsic factors that influence heating include the static magnetic field strength of the MRI system (which determines the transmitted RF used for the device operation); the electrical characteristics and configuration of the individual system (electrode, extension, length, orientation of the IPG); lengths and routing of the extension and leads; the impedance of the wires; and wire breakage [16].

Extrinsic parameters in the heating equation include the type of RF coil used (transmit/receive body vs. transmit/receive head RF coils); the landmarking site; geometry of the RF coil and the quantity of the DBS lead present within this coil; SAR (amount of RF energy delivered); method for calculating the SAR based on a particular MR system; and quantity of RF energy (whole-body averaged SAR) required for imaging [16]. RF burns may occur if currents are induced into electrocardiographic leads, or into monitoring cables and coils that are placed on the patient's skin surface [16]. The safety of MRI in patients with DBS may be increased by placing concentric loops of DBS electrode around the burr hole cap, by using a head-only receive coil, and by adhering to the vendor recommendations re the maximum SAR that can be tolerated [16].

For certain implants that have undergone empirical testing, clinically significant thermal changes may occur at 3.0-T but not at 1.5-T. Yet other data indicate that in some cases a particular implant may exhibit clinically significant levels of heating in seconds at 1.5-T but not at 3.0-T. The greatest risk, therefore, appears to be linked with the rate of temperature increase rather than the thermal change per se. According to one report, most heating occurred within the first minute of the MRI procedure and reached a steady-state within 15 min [16]. As noted previously, in order to mitigate risks of excessive heating, established product safety guidelines for MR scanning in patients with metallic implants must be diligently followed.

Even then, the guidelines should be used only insofar as they apply to the magnetic field strengths that have been evaluated and specified in the guidelines. MR scanning at either stronger and/or weaker magnetic field strengths than those indicated in the manufacturer's guidelines may cause substantial heating. Unless extreme precautionary measures are taken, inadvertent heating may arise and ultimately produce severe injury in the patient [16–18].

Contrast Administration in MRI Scans: Safety Issues

Indications for the use of gadolinium based magnetic contrast agents (GBCMAs) are similar to those noted above for CT scanning.

Allergic Reactions

Allergic reactions have been linked to the use of GBMCAs in persons with impaired kidney function. Gadopentetate dimeglumine and gadoteridol have elicited adverse reactions such as anaphylaxis in patients with impaired renal function. The package insert for gadopentetate dimeglumine warns that a history of asthma or other allergic respiratory condition may increase the possibility of a reaction, including serious, fatal, life-threatening, anaphylactoid, cardiovascular reactions, or other idiosyncratic reactions [4].

Gadolinium-based Contrast-Induced Nephrogenic Systemic Fibrosis (NSF)

More disconcerting than the risk for allergic reactions is the mounting evidence for a linkage between GBMCAs administered to kidney disease patients and an emerging disease called nephrogenic systemic fibrosis (NSF). Nephrogenic systemic fibrosis is a rare, progressive, and potentially fatal fibrosing disorder that affects patients with pre-existing renal dysfunction. It is closely associated with the use of GBMCAs [24].

The disorder was originally called nephrogenic fibrosing dermopathy (NFD) because of its involvement with the skin [18]. NSF is characterized as a systemic disease of connective tissue that targets skeletal muscle, skin, and tendons. The condition is definitively diagnosed by clinical evaluation and a deep skin biopsy of the dermis, subcutaneous fat, and fascia. The pathology involves increased deposits of collagen in connective tissues, resulting in a thickening and hardening of the skin of the extremities [24,25]. In severe illness, joints may become immobile or deformed. In extreme cases of limited motion, some patients may be confined to a wheelchair. NSF also may cause injury to the diaphragm, esophagus, heart, lung, pulmonary vasculature, and skeletal muscles [25]. The disease tends to develop slowly, but advances rapidly in about 5% of patients. At present, there is no consistently efficacious therapy [18].

The American College of Radiology (ACR) recommends that patients at risk for NSF from dialysis or chronic kidney disease be screened before receiving GBMCAs. Glomerular Filtration Rate (GFR) should be measured in patients older than 60 with a history of renal disease, hypertension, diabetes, and/or severe hepatic disease/liver transplant/pending liver transplant. Patients with hepatic dysfunction should undergo a GFR assessment as close as possible to the time at which the GBMCA is to be administered for the MRI examination [26]. GBMCAs should be avoided in patients with GFRs less than 30 mL/min/1.73m^2 unless absolutely necessary. Persons unaware that they have kidney dysfunction may be identified through medical history. If a definitive diagnosis of kidney status is not known, immediate serum creatinine testing may be warranted in addition to a GFR assessment [26].

Conclusions

The evidence presented in this chapter clearly reinforces current expert consensus that safety remains a paramount issue for patients undergoing either CT or MRI scanning. Radiographic safety measures must be properly implemented and followed at the level of the institution, neurosurgical team, and individual healthcare worker. It is incumbent upon clinicians to keep informed of the most recent information generated by the professional organizations that develop practice guidelines and issue advisories, including critical periodic updates.

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