TOPICAL REVIEW

Hazards, Safety, and Anesthetic Considerations for Magnetic Resonance Imaging

Julie A. Smith, DVM, Diplomate ACVA

The increase in the use of magnetic resonance imaging (MRI) for diagnostic use in companion animals has increased the demand for anesthesia support in a strong magnetic environment. In many instances, this may necessitate anesthesia being provided by individuals that are unfamiliar with MRI and the hazards associated with it. The objective of this article is to describe the conditions and hazards associated with a strong magnetic field, review considerations for safe and effective anesthetic management of patients during an MRI, and promote close collaboration and communication between personnel in an effort to insure staff awareness and safety. This report describes conditions that exist for the superconducting high field strength magnets, 1.0, 1.5, and 3.0 Tesla, that are commonly used for clinical imaging of companion animals. Many of these same safety and anesthesia considerations can be applied to any MRI facility.

Keywords: MRI, veterinary, safety, anesthesia, imaging

Magnetic resonance imaging (MRI) has been used in clinical veterinary diagnostics since the late 1980s.[1] Before the availability of veterinary imaging facilities, MRIs for companion animals were performed at facilities designed for human imaging. Veterinary patients were transported to local human MRI facilities located in outpatient facilities, hospitals, or mobile units. Over the past 10 years, MRI has become a mainstream diagnostic tool for veterinary patients. Due to the growing demand for MRI, there are now numerous dedicated veterinary MRI facilities for imaging animals.

To insure optimal diagnostic images, patients must be motionless for an MRI. This requires deep sedation or general anesthesia in veterinary patients. The strong static and dynamic magnetic fields, as well as radiofrequency (RF) energy emissions, used to obtain the MRI, present a unique set of challenges for individuals involved in anesthesia management. It is important that all personnel associated with the anesthesia of patients for MRI acquire a basic understanding of the technology and a familiarity with patient management considerations to provide a level of anesthesia support equal to any other situation, including comprehensive vital signs monitoring.

How MRI Works

MRI uses a magnetic field, radio waves, and advanced computer systems to evaluate the various tissues of the body. The body is made up of millions of hydrogen and other atoms. The nucleus of the hydrogen atom contains protons that are small biological magnets. When these randomly spinning protons are placed in a steady magnetic field, they become magnetized and align themselves parallel to the magnetic field. Short bursts of radio waves, tuned to a specific frequency, are used to disrupt the orientation of the atoms. When the radio signal ceases, the atoms realign, or precess, with the magnetic field and emit energy called *resonance*. This energy is picked up by powerful antennae or coils and sent to the computer to produce an image of the body part being scanned. Different tissues (ie, bone, muscle, nerves, etc.) display different resonance characteristics. Pathology within a tissue responds differently than the normal tissue, making it conspicuous.[2]

The MRI Suite—Forces/Dangers Associated With MRI

There is no ionizing radiation exposure associated with MRI, but the MRI suite is still a potentially dangerous location because of the presence of a strong static magnetic field, high frequency electromagnetic (RF) waves, and time-varied (pulsed) magnetic gradient fields. Other hazards include high-level acoustic noise, systemic and localized heating, and accidental projectiles. Magnets are considered medical devices but are not regulated by the U.S. Food and Drug Administration (FDA). Anesthetists should be aware of the risks associated with working around this powerful imaging tool to prevent adverse events.

The primary feature of the magnetic resonance imaging system is a powerful magnet. A *static magnetic field* is created with superconducting coils and is measured in Tesla (T). High field strength, clinically useful magnets have magnetic

AnimalScan, LLC, Advanced Veterinary Imaging, Vienna, VA.
Address reprint requests to: Julie A. Smith, DVM, AnimalScan, LLC, Advanced Veterinary Imaging, 328 Maple Avenue, East, Vienna, VA 22180. E-mail: drjulie@animalscan.org

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fields measuring 1.0, 1.5, and 3.0 T. The earth's gravitational pull, or the natural magnetic field, is 0.05 mT or 0.5 Gauss (G). There are 10,000 G in 1 T. Therefore, a 1.5-T magnet is 30,000 times stronger than gravity and a 3.0-T magnet is an amazing 60,000 times the pull of gravity.[3]

A large invisible magnetic field, called a fringe field, extends in all directions, well beyond the confines of the magnet and the magnet room. The strength of this fringe field depends on the strength and shielding the magnet. The magnetic field is weakest at its outside edge and its strength increases rapidly in the immediate vicinity of the magnet. It is important to know the location of the *5 Gauss line*. This designates a safety point, inside which access should be limited. The increase in magnetic force beyond this point can cause accidents and medical device malfunction (Fig. 1). Actively shielded magnets have a more compact fringe field. This means that the rate of field strength increase is greater the closer you get to the magnet. A map of the fringe fields associated with individual magnets can be obtained from the magnet vendor, system engineer, or the MR technologist.[3]

There have been no reported harmful biological effects associated with short-term exposure to strong magnetic fields for patients or MR technologists.[4] However, humans and veterinary patients who are anesthetized often require that anesthesia providers remain in the room during the scan. It is often the same person(s) who provides the anesthesia and monitoring for patients during MRI and, consequently, these individuals have prolonged and repeated exposure to strong magnetic fields. No studies evaluating the effects of prolonged exposure to the MRI environment are available. With the advent of interventional MRI, where surgery and other procedures are performed in an MRI suite, more attention is being paid to personnel who spend extended periods of time in the MRI environment. Until more is known about the long-term effects of consistent exposure to a strong magnetic field, precautions should be taken to limit the overall exposure of personnel providing anesthesia support for MRI.

The most significant known danger working around a strong magnet is the risk associated with the attraction of ferromagnetic objects to the magnet causing them to become projectiles. This "missile" or "projectile" effect can be hazardous to the patient inside the magnet or to anyone who is in the path of the projectile. The pull on the object depends on the size and proximity to the magnet. It is often not possible to stop the movement of the object once it has started toward the magnet. Instances of ferromagnetic projectiles causing injury, high cost equipment damage, and loss of imaging time have been reported.[5] To protect against missile events, access to the magnet is restricted, mandatory training programs have been created, and, where indicated, metal detectors installed.

An additional effect of the magnetic field within the magnet bore, where the field is the strongest, is a "rotational" force. Nonspherical metallic objects either inside or outside the body will experience torque as they attempt to align with the magnetic field.[4] The induced rotation of an object inside the body can cause the object to be dislodged and tear

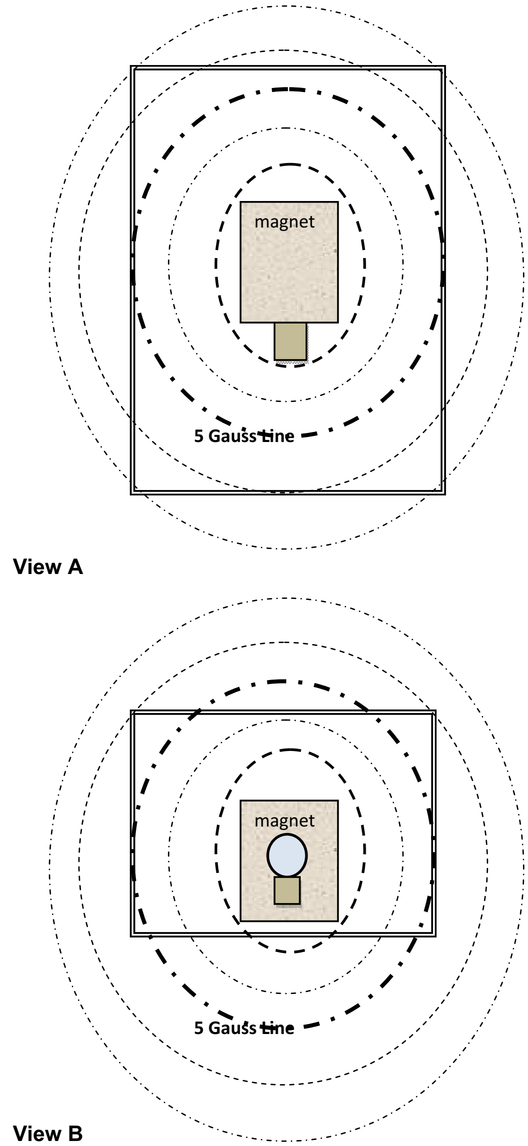

Figure 1. Diagram of the constant magnetic fringe field that exists around all high field strength magnets. The field extends beyond the magnet and the room in all directions. The strongest field is at the center of the bore of the magnet and gets weaker as it moves away from magnet. The 5-G line is shown here for illustration purposes, but its distance from the magnet will vary depending on the strength and shielding of each magnet. (*View A*) Looking down on the top of a magnet and magnet room. (*View B*) Front view of magnet and magnet room. (Color version of figure is available online.)

surrounding tissue. Vascular clamps, intravascular coils, stents, and microchips are stable once adequate scarring has occurred. Implanted devices such as pacemakers may fail due to components being displaced inside the device.[4] Iron containing aneurysm clips have been reported to rotate and cause hemorrhage and death.[6] Although these devices are not common in pets, pet owners and staff with brain aneurysm

MR Safe
An item that poses no known hazards in all MRI environments. Includes all non-conducting, non-metallic, non-magnetic items.

MR Conditional
An item that has been demonstrated to pose no known hazards in a *specified* MRI environment with *specified* conditions of use. MR Conditional items are labeled as to limitations that might exist in the MRI environment.

MR Unsafe
An item that is known to pose hazards in all MRI environments. MR Unsafe items include magnetic items such as a pair of ferromagnetic scissors.

Figure 2. Icons and classification used for implants and medical devices relative to the MRI environment as developed by the American Society for Testing and Materials (ASTM) International, 2005.

clips, pacemakers, defibrillators, or other implanted medical devices should not enter the MRI suite.

Patients should be carefully screened for any history of metal implants or ingestion of metal items. Implants that were considered safe in a 1.5-T magnet may not be safe in the stronger 3.0-T magnet. A comprehensive and consistently updated list of medical implants and their MRI compatibility can be found at www.mrisafety.com.

Devices and equipment are classified according to the American Society for Testing and Materials International. Newly implemented classifications and their corresponding icons are described in Figure 2.[4]

Common items that should not be allowed in the MRI area and other items that are damaged by fields greater than 5 G include, but are not limited to, cards with a magnetic strip (ID badges, credit cards, hotel keys), analog and digital watches, hearing aids, cell phones and pagers, cameras, medical instruments (hemostats, scissors, thermometers, stethoscopes, etc.), keys, pocket knives, hair clips and bobby pins, clip boards, pens, paper clips, and unshielded or noncompatible electronic medical devices (patient monitors, infusion pumps, ventilators, etc.).

Cryogens

Superconducting magnets generate a great deal of energy and heat and therefore are jacketed in cryogens, most commonly supercooled (4.22 K) liquid helium. If the temperature of this liquid rises for any reason, the resultant gases will boil off in an explosive event called a "quench." This is a very rapid process that occurs over 5 to 15 seconds. In the event of a quench, magnet rooms are equipped with large vent pipes for the evacuation of the helium vapor. If the vapor cannot escape through the vent pipe, it will enter the MRI room. The immediate risk to the occupants of the room is asphyxiation, due to the displacement of oxygen, and frostbite.[3] In the event of a quench the magnet room should be evacuated immediately. Stay low, below the helium cloud if possible. Increased pressure in the room may make the door difficult to open and it may need to be broken. If you cannot exit via the door, the window can be broken for escape. A quench rarely occurs spontaneously but can occur due to a malfunction of cryogen system or can be manually triggered if there is a life-threatening emergency (ie, if someone is accidently pinned to the magnet by a ferromagnetic object) that requires the magnetic field be terminated. The loss of magnetic field is not immediate and emergency and rescue personnel should be informed and prevented from rushing into the magnet room. Personnel working in an MR environment should be familiar with the facility's procedure during a quench.

Gradient Magnetic Field

Time varying or gradient magnetic fields (gradients) are generated by three weaker magnets located within the primary magnet. These variations allow precise alterations in the magnetic field, which enable image slices of a specific part of the body to be created. Gradients are switched on and off multiple times per second and vibration of the coils causes the "clanging" noise heard during MRI scanning. Significant levels of acoustic noise are produced depending on the MR sequence and the strength of the magnet. The International Electrotechnical Commission and the FDA limit permissible sound levels to 99 dBA.[4] The Occupational Safety and Health Administration recommends a maximum daily (8-hour time-weighted average) noise exposure of 85 dB.[7] The level of noise can reach 90 to 130 dB or higher depending on the scan sequence. The newer shorter bore magnets are louder than the older long bore systems. A 3.0-T magnet is twice as noisy as a 1.5-T magnet.[8] Exposure to high noise levels can lead to temporary or permanent hearing loss.[9] Hearing protection should always be worn in the MRI room during scanning. Disposable ear plugs provide 30- to 33-dB noise reduction. Close fitting headphones, depending on the style and type, can provide 20 to 80 dB of noise reduction and can be worn over ear plugs for improved protection. Newer MR technology promises redesigned magnets with added insulation to reduce the noise exposure from the gradient magnets.

Gradient switching while imaging can induce electrical currents that may stimulate peripheral nerves or muscles in patients being imaged. Perceptible nerve stimulation or tingling has been reported by awake human patients during imaging. Current standards for gradient magnetic fields have been determined so that patients are protected from any potential injury.[4]

Radiofrequency Field

A radiofrequency transmitter and receiver are necessary to pulse energy into the tissues and to capture the resonance energy as the protons precess back in alignment with the magnetic field. The transmitter/receiver acts like an antenna and is called an "RF coil." There are two main categories of RF coils, the body coil and local or surface coils. The body coil is built into the magnet and surface coils are placed on or wrapped around the body area being imaged (Fig. 3).

Figure 3. Dog positioned on magnet table and instrumented with RF coils over the head and neck for brain and cervical spine imaging.

The energy signal from the patient is very weak so the magnet room must be shielded from any external RF interference (ie, FM radio or cell phone transmissions) that would interfere with image acquisition. Typically this is done by lining the entire MRI room (walls, floor, and ceiling) with a copper shield that acts as a Farraday cage[3] (Fig. 4).

Pipes, ducts, cables, and electrical wires passing in and out of the magnet room pass through a *penetration panel* that contains *waveguides* or filters that prevent leakage of RF and the antenna effect of electrical wiring to maintain the integrity of the RF shield. Some magnets have small waveguides installed in the control room to allow sample tubing, fiber-optic cables, and nonconducting material to be passed into the magnet room for patient monitoring and gas and drug delivery purposes.[10]

Potential biologic effects can occur from direct tissue heating due to the absorption of RF energy. To prevent systemic thermal overload and local thermal injury the tissue RF, specific absorption rate (SAR) is measured throughout the scan. Based on guidelines established by the FDA, the SAR is strictly limited by the MR scanner software and is calculated per kilogram of tissue based on the patient weight entered at the beginning of the scan.[8] Always provide the MRI technologist with an accurate patient weight. The stronger the magnet, the more RF energy is required, causing potential overheating of patients and requiring more time between sequences to limit SAR. A 3.0-T magnet produces four times the RF produced by a 1.5-T magnet.[8]

Figure 4. Photo showing the copper barrier applied before the installation of sheetrock, flooring, and ceiling tiles of an MRI suite.

When conducting materials are placed within the RF field, the result may be a concentration of electrical currents sufficient to cause excessive heating and tissue damage. Superficial burns are the most common reported patient injury in humans during MRI. Use only cables and electrocardiogram (ECG) leads that are approved for use in a magnet. Check all wires and cables to make sure that there are no loops. A looped ECG cable can create a current strong enough to cause a burn severe enough to require skin grafting. Insulate patients from all cables and avoid contact with the body as much as possible. Inspect all potential conductors for evidence of frayed insulation, exposed wires, and other hazards.[11]

The FDA has issued a warning about transdermal drug delivery patches. Patches containing a metallic backing, such as those containing fentanyl and lidocaine, have caused skin burns in humans wearing them during MRI. Drug labeling for the patches has not yet been changed. The best policy is to remove any transdermal patch before scanning.[12]

Anesthetic Considerations

As with any anesthetic plan, individual patients are evaluated based on signalment, underlying disease process, patient condition, and available drugs and equipment. Additional considerations related to MR imaging include limited patient access and visualization, prevention of movement, duration of scan, possibility of additional procedures or surgery to follow scan, positioning, safe patient transport, and availability of magnet safe and compatible equipment. A major portion of the MRI caseload consists of patients with neurologic and orthopedic problems. Specific protocols and anesthetic considerations for these types of patients are discussed in other sections of this publication.

Limited access and visualization may be the most difficult situation in which to adjust. Patients are positioned on a long table, often using foam positioning devices, covered with receiver coils (Fig. 3) and insulating blankets, and then moved into the middle of the narrow bore of the MRI unit. Small patients, such as cats and little dogs, may be totally inaccessible throughout the scan. Access to the intravenous catheter during the scan may be difficult or impossible. Placing catheters in hind legs, or the limb that will be the most accessible during the scan, leaving the limb exposed, and using multiple extensions and adaptor ports will assist in the administration of fluids, contrast agent, and any other medications. If necessary, the table can be moved out for intravenous (IV) injections, but it is preferable not to move the patient or the table during a scan.

MRI images are generated in series, repeated using different sequences, and then compared. Diagnostic comparisons cannot be made if the patient is not in the exact same position for every sequence. Careful positioning and support prevents patients from leaning to one side or moving out of position during the scan. A light plane of anesthesia is desirable during MRI. However, if the plane is too light, the patient may wake up and move before the scan is completed. This will cause a delay in completion of the scan and extend the overall anesthesia time. Movement of the chest, abdomen, and head during spontaneous breathing can cause motion that interferes with some images. Controlled ventilation using a ventilator or manual support can reduce this motion. For some very sensitive and short scans of the chest or abdomen, it may be necessary to eliminate all motion from breathing. These "breath-hold" exams can be done by hyperventilating before the scan, which will provide the 20 or 30 seconds of apnea necessary to obtain the images. On rare occasions, for some pulmonary studies, the lungs may need to be held inflated during this type of scan.

A routine MRI scan using a high field strength magnet will take 20 to 45 minutes, depending on the body part being imaged and the pathology that is identified. Additional sequences or multiple body regions can extend this time to 60 to 120 minutes, or longer. Preparation for the possibility for extending the duration of anesthesia should be done before beginning. Additional sedatives, anesthetic agents, support fluids, and other medications should be available in, or close to, the MRI suite. This is particularly important if the MRI facility is distant from the central anesthesia area or in a trailer or other remote location.

Surgery may be indicated following an MRI examination. The patient may be transported directly from the MRI suite to the surgical suite or it may be necessary to wake them up and re-anesthetize them in a different location. A comprehensive anesthesia record should be kept during the MRI scan and any adverse events that occurred during the MRI should be taken into consideration when determining if the patient can safely be kept under anesthesia or re-anesthetized the same day.

Fifty percent of the cases seen by this author at AnimalScan in Virginia have some form of spinal disease. Many of these patients are weakly or nonambulatory and many of those weigh over 25 kg. A magnet-safe and compatible gurney can be used to move these patients into and out of the magnet suite. There are no veterinary gurneys commercially available for use in the MRI environment, but the gurneys designed for use in people work well, especially for the large breed dogs. They are long enough to accommodate even the largest dogs and are the same height as most MRI tables so the patients can easily be slid from one to the other. Having a gurney that is the correct length and height helps prevent additional spinal trauma in the patient and prevents lifting injuries in the personnel moving these heavy dogs. Ideally these patients are placed on the gurney directly from a lift table or transferred from a noncompatible gurney to avoid any lifting at all. Some magnets may have a detachable table that can be taken out of the room and used as the gurney to transport patients into the room. A nonmagnetic stretcher can also be used when the area is too small to accommodate a gurney, but requires more personnel to lift and move the heavier dogs.

Sedation versus General Anesthesia

Whether you decide to use sedation or general anesthesia for immobilization during an MRI scan, vital signs monitoring should not be minimized and a provision for providing intubation and respiratory support should always be part of the anesthesia plan. Endotracheal tubes, an Ambu bag, and an oxygen source are basic items that should be available. Oxygen may be delivered through an anesthesia machine or from a magnet-compatible portable aluminum oxygen tank equipped with an MR conditional regulator and flowmeter.

Sedation alone may be selected for stable patients and short scans. However, even heavy sedation may be unpredictable in the noisy environment and a sedated patient may become stimulated unexpectedly. Foam positioners and/or straps can be used to make sure that the patient does not move during the scan. Sedated patients may be more difficult to monitor, especially if they are not intubated. Respiratory rate may be the only parameter you have to evaluate ventilation, as capnography cannot be used reliably in nonintubated patients.[13] Pulse oximetry may be unreliable if placed on the tongue if there is motion and peripheral vasoconstriction. Direct observation and staying in the MRI suite during imaging is recommended for a sedated patient so that the pulse can be palpated and any arousal can be managed immediately. It may be necessary to intubate and support ventilation with an Ambu bag (if an anesthesia machine is not available) if there is respiratory depression. Be prepared to institute general anesthesia if the patient will not lay motionless, and/or due to prolonged scan time or transfer to surgery. If the patient becomes compromised, it is difficult to provide support without moving the patient and interrupting the scan. Recovery times may vary depending on the sedative used or if an antagonist is given.

General anesthesia using either intravenous or inhalation agents provides a safer and more controllable situation. *IV anesthesia* may be necessary when a magnet-compatible anesthesia machine is not available or when it is determined to be the best approach for a particular patient. Intravenous anesthesia can be delivered by repeated administration of IV bolus injections or a continuous rate infusion. Infusions can be delivered using an inline fluid regulator or a magnet-compatible syringe or fluid pump. If compatible equipment is not available, then a pump located outside the suite with long delivery tubing passed through a waveguide to the patient is an alternative. The catheter and any connections should be carefully secured before the patient is moved into the bore of the magnet. Displacement of the catheter or disconnection of the infusion will result in arousal, motion, and potential injury to the patient. There is a report of a fatality in a person due to an uncontrolled infusion of propofol and a resultant overdose.[14] An advantage of using general anesthesia is that the patient may be intubated for the delivery of oxygen and provision of ventilatory monitoring and support. General anesthesia also provides better conditions for vital signs monitoring. Recovery is generally rapid after the infusion is stopped, but may be delayed if long acting sedatives are also used.

General anesthesia using an inhalant, either isoflurane or sevoflurane, requires specialized magnet conditional equipment for delivery to the patient. There are several magnet conditional veterinary anesthesia machines available. Delivery hoses need to be long enough to reach the patient inside the bore of the magnet. Coaxial systems are commercially available in lengths of 60 and 72 inches. These lengths are adequate for most situations. In some instances, the anesthesia machine is left outside the room and long hoses are passed through a waveguide to deliver anesthesia to the patient. This is best done with an extra-long, single coaxial delivery hose of either a nonrebreathing or a rebreathing type of circuit. There are risks associated with having long hoses. In one report, a person died after the expiratory limb of a 40-foot expiratory hose became occluded and the patient developed a tension pneumothorax.[14] Having the anesthesia machine close to the patient is advantageous, as it makes it easier to make adjustments while evaluating the patient.

A ventilator attached to the anesthesia machine makes it easier to assist and control ventilation. This is especially important for patients with suspected elevated intracranial pressure where respiratory depression and the resulting high levels of carbon dioxide can be detrimental.[15] Patients with brain disease constitute 34% of the caseload at the AnimalScan MRI facility in Vienna, VA. Many of these have respiratory depression from their disease or are on antiseizure medications that may potentiate respiratory depression when combined with sedation or general anesthesia. When using an inhalant anesthetic, arrangements need to be made for the removal of waste anesthetic gases. An active scavenging system can be installed when the MR suite is built or a passive system can be used inside the suite.

To avoid potential hazards, it is recommended that there be a dedicated anesthesia machine that never leaves the MR suite. This prevents foreign metallic objects that may be left on the anesthesia machine from inadvertently being brought into the room. This is a good policy for all equipment used in the magnet room (ie, pumps, monitors, heat sources, etc.).

Keep a second anesthesia machine outside the magnet area for use during induction, recovery, transport, and/or rescue procedures. In facilities where transfer from the MRI suite to the surgery suite is possible, the patient can be transferred without interruption of anesthetic maintenance. Recovery is generally rapid after the inhalation agent is discontinued, but may be delayed if long-acting sedatives are also used.

Vital Signs Monitoring

Vital signs monitors that are made for use in a magnet suite are costly compared with standard units. These units seem expensive until put into perspective by the overall cost of an MRI scanner and facility or the loss of a patient. Due to limited patient access and visualization, comprehensive vital signs monitoring is critical for evaluation of a patient during an MRI examination. The monitoring capability and standard should be identical in the MRI suite to the surgical suite or any other area where general anesthesia is used. The dangers of using equipment that is not safe in a magnetic field include missile effect, patient burns, equipment malfunction, and image artifacts. A monitor that is compatible with a 1.5-T scanner may not be compatible with a 3.0-T scanner. Safe placement in the room will differ with each facility based on the fringe fields and manufacturer recommendations. Check with the manufacturer about the compatibility of the monitor before using it in with a different magnet.

Having a monitor inside the room next to the patient allows for adjustments and assessment when you are close to the patient. If there is only one monitor, the anesthetist will be required to stay in the room for the entire scan or observe the monitor through a window or door. Monitor screens are difficult to see through the shielded glass. A wireless connection to a remote or slave monitor located outside the suite in the control room or induction/recovery area will provide a display that can be easily seen outside the room. Using a noncompatible monitor placed outside the room with long cables passed through a waveguide is cumbersome and the parameters cannot be evaluated when you are next to the patient. Long cables that cross the work area may become damaged or disconnected, or be a trip hazard for personnel moving around the room. Cables can act as an antenna, causing artifact on the images. The noise of the gradients makes it difficult to hear the alarms in the room. Monitors designed for use in this environment have colored, flashing alarms so that they are easily seen. Set the alarm volume to its highest setting and place the monitor in an area where it can be easily visualized.

Pulse Oximetry

Pulse oximetry determines oxygen saturation and provides a continuous pulse wave and rate. This is useful if you are outside the room and are unable to count the pulse directly. Before the development of fiber-optic technology, use of the hard-wired pulse oximeters resulted in intermittent readings, image artifacts, and numerous human patient burn injuries.[4] Fiber-optic systems are available with a variety of probe styles designed for use on the adult human finger or a neonatal hand or foot. These probes are readily adaptable for use in dogs and cats. There is also a standalone unit that is designed for veterinary use.

The Electrocardiogram

Radiofrequency and gradient magnetic fields distort or obliterate the ECG, making it unreliable during many sequences. Special filtering is built into the newer monitors to help eliminate the interference. Altered appearance of the T-wave or ST segment of the ECG complex may be present from the superimposed voltages generated by aortic blood flow in the high magnetic field.[3] Using specifically designed insulated cables is important because the voltages and currents generated during a scan can cause thermal injuries to tissues adjacent to electrically conductive material, such as ECG cables. To prevent burns, place the cables so that there is limited contact with the patient and run them out of the magnet parallel to and as close to the center of the bore of the magnet as possible. Prevent overlapping and looping of cables as this may create a focal area of current concentration and a burn. If the cables are not bundled together, place the electrodes close together and braid or twist the cables together to insure that loops do not occur. Newer monitors have wireless ECG connections that eliminate this hazard.

Use electrode patches made with carbon graphite that have limited metal content and are recommended for use during MRI. The patches work best with direct skin contact, which requires shaving of an area over the heart. Pet owners do not object to this and having the ECG in place when a dysrhythmia is detected is better than trying to instrument after the fact. When a dysrhythmia is suspected, ask the MR technologist to stop the scan so that the rhythm can be evaluated.

Capnography

Capnography is an especially vital monitor for patients that are difficult to observe for determining respiratory rate, for assessing ventilation, and for immediate recognition of a circuit disconnection or obstruction. Respiratory depression is a common side effect of sedation and general anesthesia. Patients with neurologic disease are particularly sensitive to the depressant effects of sedatives and anesthetics especially if they are being medicated with antiseizure medication. Elevations in carbon dioxide can lead to elevations of intracranial pressure that could be detrimental to patients with space-occupying lesions of the brain.[15] Sidestream sampling technology is available on any MRI-compatible vital signs monitor and extralong sampling lines are available to facilitate collection of exhaled gases.

Body Temperature

Recent developments in temperature monitoring now allow constant monitoring during MRI. Digital thermometers can also be used in the magnet suite. Check with your technolo-

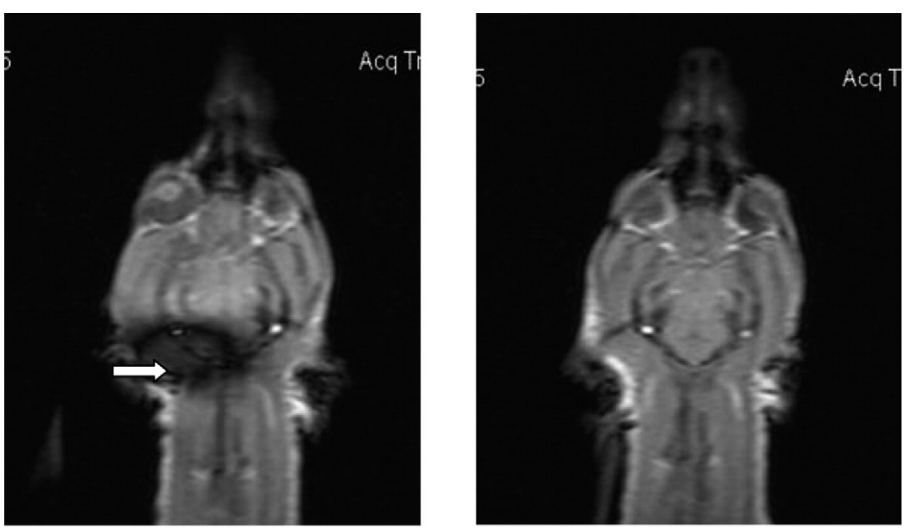

Image A Image B

Figure 5. (*Image A*) Metal artifact (white arrow) on a localizer MR image of a head. This artifact is due to the small amount of metal in the inflation tube portion of the endotracheal tube, which is lying under the head. (*Image B*) Same image repeated after moving the pilot tube away from the head.

Table 1. Operation Guidelines to Minimize Hazards and Prevent Accidents in the MRI Environment

—Attend MRI safety course or create your own for the anesthesia staff working with MRI. Establish and routinely review formal safety procedures and insist on compliance. Provide screening and training for everyone who has access to MR suite.
—Restrict access. Only allow trained individuals to enter magnet room. Acknowledge and emphasize to ALL personnel that the magnet is **ALWAYS ON.**
—Only use equipment tested for use in the field strength MRI were you are working. A device tested for use in a 1.5-T magnet should be assumed to be safe in a 3.0-T magnet.
—DO NOT take any equipment into the room until it has been tested and labeled as safe by the magnet engineer, MR technologist, and/or designated Safety Officer, ie, vital signs monitoring equipment, IV poles, circulating hot water pumps, fluid pumps, sand bags, gurneys, etc.
—Check small items with a strong handheld magnet. If the magnet is attracted to the item, do not take it into the room as it could become a missile hazard in the magnetic field.
—Label all MR safe equipment.
—Be vigilant and recheck any equipment that leaves the MRI area and returns. Best to designate equipment for use in MRI only.
—If you must use equipment containing ferromagnetic components in the MR environment, make sure that it is physically secured a safe distance from the magnet using nonmagnetic bolts, rope, plastic chains, or weighted base assemblies. Properly label the equipment and apply tape lines on the floor around it.
—Bring nonambulatory patients into the MR environment using a nonferromagnetic gurney or stretcher. Always remove blankets and other coverings.
—Remove collars, harnesses, hair clips, etc.
—Diligently screen all personnel to ensure that no oxygen tanks, clippers, stethoscopes, laryngoscopes, pens, scissors, hemostats, neurohammers, or other ferromagnetic objects enter the magnet room.
—Carefully screen patients prior to entrance into the MR suite and imaging. Ask owners about the presence of microchips, implants, bullets, ingested gravel, or other metallic substances that may pose a hazard or interfere with image acquisition.
—In an emergency, remove the patient from the magnet room to perform rescue procedures.
—Inform and train support staff and emergency personnel about the hazards of the magnet room and to NOT run into the magnet room in the case of emergency.

gist or engineer before taking one into the room for the first time. There are no commercially available patient warming systems that are specifically designed for use in the MRI room. Standard circulating water heating blankets and forced air warmers can be used in the magnet room with certain precautions. Do not take any equipment into the MR room without first checking with the technologist or magnet engineer to determine its safety and compatibility. The units can be placed outside the room with long hoses passed through a waveguide to the patient. Circulating water blankets can be seen on some images due to the water content and may have to be removed if they are interfering with image acquisition.

Arterial Blood Pressure

Arterial blood pressure can be monitored directly or indirectly during MRI. Direct blood pressure monitoring is rarely used in companion animals for imaging due to the invasiveness of arterial catheter placement, light planes of anesthesia, and the time and equipment necessary for instrumentation. Noninvasive oscillometric blood pressure monitoring is easy to use and readily available on monitors designed for use in the magnet room. The air-filled hoses do not pose any sort of hazard. Accuracy is dependent on position and size of cuff, size of patient, and hemodynamic condition. When using a system designed for humans, the neonatal cuffs and cables can be used for most small animal patients, but the adult set may be necessary for some of the giant breed dogs.

Contrast Agents

Gadolinium-based contrast agents (GBCAs) are used during MRI to provide an improved image of body organs and tissues. GBCAs are administered slowly intravenously. The contrast agent accumulates in abnormal tissues where there is increased blood flow. Gadolinium is a paramagnetic metal ion that is toxic in its normal state. To reduce toxicity, gadolinium is chelated with a large organic molecule to form a stable complex, preventing direct exposure to the gadolinium and reducing the chance of toxicity. This stable complex is eliminated predominantly unchanged via the kidneys.[16] There are five different formulations available and they all have a low incidence of adverse effects. Two recent retrospective studies evaluating the effects of a gadolinium chelate in anesthetized cats and dogs during cross-sectional imaging found that the most common adverse effects observed were bradycardia, tachycardia, hypotension, and hypertension.[17,18] In humans, GBCAs have been linked to a serious, life-threatening skin disorder called nephrogenic systemic fibrosis or nephrogenic fibrosing dermopathy. Individuals with severe renal insufficiency or dysfunction are most susceptible.[16] This condition has not been reported to occur in animals. Consideration should be given to not using these agents when renal impairment is present.

Emergency Management

Emergency situations are difficult to access and respond to when patients are inside the magnet bore. Call for help and remove the patient from the magnet and the magnet room. Initiate cardiopulmonary cerebral resuscitation while removing the patient from the magnet. Have a prepared and practiced plan for rapid summoning of additional personnel to assist in an emergency. If in a hospital, arrange for transport to a previously designated area where there is a crash cart, oxygen source, monitor, and other emergency support. When in a remote location, a crash kit should always be available outside the MR suite. Make sure that all personnel are aware of magnet dangers and that no one is allowed to rush into the magnet room during an emergency.

Additional Considerations

Patient motion and image artifacts due to improperly shielded equipment or metal in the field will necessitate repeat scans and prolong overall anesthesia time. Image artifacts that can result from actions of anesthesia personnel are patient motion, pilot tube artifact (Fig. 5), RF interference from entering or leaving the room during scanning, RF leak from nonshielded or malfunctioning equipment.

Personnel Considerations

Before working in or around an MRI, personnel working in or around the MRI suite should be screened for all of the following conditions: (1) pacemaker or implanted defibrillator; (2) aneurysm clip; (3) history of ocular injury or welding; (4) transdermal patch; (5) inner ear or cochlear implants. Pregnant individuals can work around the magnet, but should not be in the room during scanning.[4]

Communication and planning is vital when preparing a patient for anesthesia for an MRI. Working closely with the MR technologist and the veterinarian overseeing the facility is key to proper procedure and safe anesthetic management. No accidents have been reported from veterinary facilities, but this does not mean that they do not happen. Accidents are known to be underreported in human facilities.[4] Human error is the most common cause of accidents involving an MRI scanner. Familiarity with the environment of an MR room and following safety guidelines will help prevent serious and life-threatening accidents (Table 1).

All patients sedated or anesthetized for an MRI scan should be provided the same anesthesia and monitoring support that is standard for surgery or any other procedure. Personnel administering anesthesia to patients having an MRI should be properly screened and informed regarding the potential problems and risks associated with this procedure.

References

1. Gavin P: CT, MRI offer enhanced diagnostic options. DVM Newsmagazine, In Focus Supplement pp 1-4, November 2002
2. Berry CR: Physical principles of computed tomography and magnetic resonance imaging, in Thrall DE (ed): Textbook of Veterinary Diagnostic Radiology (ed 4). Philadelphia, PA, Saunders, 2002, pp. 28-35
3. Menon DK, Peden CJ, Hall AS, et al: Magnetic resonance for the anaesthetist. Part I: physical principles, applications, safety aspects. 47:240-255, 1992
4. Shellock FG: Reference Manual for Magnetic Resonance Safety, Implants, and Devices: 2007 Edition. Los Angeles, CA, Biomedical Research Publishing Group, 2007
5. Chaljub G, Kramer LA, Johnson RF, et al: Projectile cylinder accidents resulting from the presence of ferromagnetic nitrous oxide or oxygen tank in the MR suite. AJR Am J Roentgenol 177:27-30, 2001
6. Klucznik RP: Placement of a ferromagnetic intracerebral aneurysm clip in a magnetic field with a fatal outcome. Radiology 187:855-856, 1993
7. Radomskij P, Schmidt MA, Heron CW. Research letters: effect of MRI noise on cochlear function. Lancet 359:1485-1486, 2002
8. Jerrolds J, Keene S: MRI safety at 3T versus 1.5T. Internet J World Health Soc Pol 6(1): 2009
9. Kanal E, Shellock FG, Talagala L: Safety considerations in MR imaging. Radiology 176:593-560, 1990
10. Bell C: Focus on anesthesia in the MRI suite. Clinical Window.net, Issue 10, August 2002
11. Medical Device Safety Reports. Hazard. thermal injuries and patient monitoring during MRI studies. Health Devices 20(9): 362-363, 1991
12. News. Some metal-backed drug patches lack warning about MRI burn risk. JAVMA 235:16, 2009
13. Kelmer E, Scanson LC, Reed A, et al: Agreement between values for arterial and end-tidal partial pressures of carbon dioxide in spontaneously breathing. JAVMA 235:1314-1318, 2009
14. Kempen PM: To the Editor: stand near by in the MRI. Apsf.org resource center newsletter. Summer 2005
15. Harvey RC, Greene SA, Thomas WB: Neurological disease, in Tranquilli WJ, Thurmon JC, Grimm KA (eds): Lumb and Jones' Veterinary Anesthesia and Analgesia (ed 4). Ames, IA, Blackwell Publishing, 2007
16. Marckmann P, Skov L, Rossen K, et al: Nephogenic systemic fibrosis; suspected causative role of gadodiamide used for contrast-enhanced magnetic resonance imaging. J Am Soc Nephrol 17:2359-2362, 2006
17. Pollard RE, Puchalski SM, Pascoe PJ: Hemodynamic and serum biochemical alterations associated with intravenous administration of three types of contrast media in anesthetized dogs. AJVR 69(10):1268-1273, 2008
18. Pollard RE, Puchalski SM, Pascoe PJ: Hemodynamic and serum biochemical alterations associated with intravenous administration of three types of contrast media in anesthetized cats. AJVR 69(10):1274-1278, 2008