Anesthetic Management for Magnetic Resonance Imaging: Problems and Solutions

Stephen K. Patteson, MD, and John T. Chesney, MD

Department of Anesthesia, University of Tennessee Medical Center at Knoxville, Knoxville, Tennessee

Magnetic resonance imaging (MRI) involves use of high-strength magnetic fields to provide digitalized tomographic imaging of the body. Anesthesiologists are sometimes involved in patient care because quality of the image depends in part on the patient remaining immobile. Patient monitoring and anesthetic management are challenging because the high magnetic fields interfere with electronic monitors and ferromagnetic components of common equipment (1). Noise, propelled ferromagnetic objects, access to the patient, and airway management are a few additional problems created by the MRI environment. The following is an overview of the literature and will suggest solutions to the problems encountered with anesthesia for MRI.

Field strengths utilized vary from institution to institution but are generally in the 0.15 Tesla (T) to 2.0 T range (2). The total scanning time typically requires about 1.5 h.

Magnetic resonance imaging is superior to computed tomography for neurologic and soft tissue examination (3). Structures within the cranium, spinal column, and pelvis are delineated with high contrast (4). As a diagnostic tool, MRI may be used for follow up of intracranial lesions and for stereotaxic guidance during intracranial surgery (5,6). Magnetic resonance imaging is well suited for mediastinal and pericardial examinations as it can easily distinguish between fat, vessels, and tumor (4). Airway anatomy can be assessed in cases of suspected or proven difficult intubations or an abnormal epiglottis (7,8). Magnetic resonance imaging may be a primary diagnostic tool for aortic disease (1). Oncologic hyperthermia is possible using the magnetic fields of MRI to increase *local* tissue temperature (9,10).

Basic Principles of Magnetic Resonance Imaging

The Tesla is a measure of the strength of a magnetic field (1 Tesla = 10,000 gauss [G]). The earth's magnetic field is 5×10^{-5} T (11). The MRI magnet is a liquid nitrogen cooled superconductor, cooled to 4°K, producing up to a 2.0-T magnetic field. Because 72–96 h may be required to reestablish the magnetic field, it is deactivated only in an emergency.

Atoms with net electrical charges (those having an odd number of protons and/or neutrons in their nuclei) have intrinsic magnetic properties that enable an extrinsic static magnetic field to align them and induce precessional rotation parallel to this field (2,4). The atoms are then subjected to a radio frequency (RF) pulse that deflects the orientation of the atoms. As the RF pulse is removed, the nuclei rotate back into alignment with the static magnetic field. As these

Accepted for publication August 26, 1991.

Address correspondence to Dr. Patteson, Department of Anesthesia, University of Tennessee Medical Center at Knoxville, 1924 Alcoa Highway, Knoxville, TN 37920.

0003-2999/92/$3.50

nuclei "relax," the energy released is used to create the MRI image. Hydrogen is the atom most often used for imaging; it is present in tissue as mobile water and immobile long chain triglycerides. Because of different chemical environments, the relaxation rates vary for specific body tissues, especially water and fat, allowing for differentiation of body structures.

Magnetic Field Problems

Implanted Objects

Problems with a variety of implanted ferromagnetic objects have been included in numerous reports (11–16). Patients with artificial pacemakers should be excluded from MRI studies because of pacer inactivation or conversion to an inappropriate mode by closure of the reed switch. A field of 17 G can convert some pacers to the asynchronous mode (16). Torque on the pacer itself or voltage induction across the pacing leads may lead to disconnection, discomfort, or microshock. In a 1.5-T field all multiple types of pacers failed (17).

As little fibrosis occurs in the central nervous system, aneurysmal clips may be detached intracranially with disastrous consequences (14). Heating of implanted nonferromagnetic prostheses has not proven to be a problem, and these patients may be able to undergo MRI without incident (11,18). An unusual complication of MRI is eye damage secondary to retinal hemorrhage from an unknown imbedded metallic object (14). Other implants of importance include cochlear and stapedial implants, although these are usually stainless steel. Heart valves implanted in recent years are not ferromagnetic, and flow changes or heating are not significant problems (14). Cosmetic tattoos with metallic dyes have been associated with local irritation. Certain metallic eye make-ups have led to eye and periorbital irritation (14,19).

To avoid or detect these problems with implanted objects, the anesthetist should move the patient slowly into and out of the field before induction and respond quickly to any reported sensations (14).

Propelled Objects

Vigilance and caution must be used to prevent injury to patients, personnel, and equipment from propelled ferromagnetic objects. Monitors and other necessary equipment must be secured. They may be bolted to floors and walls or kept distant from the magnetic field. Care must be taken to search personal attire for pens, needles, vials, scissors, and other objects that are ferromagnetic. Patients should also be carefully searched for ferromagnetic objects. Restraining straps, pins, and other medical devices may cause patient injury (20). Some reports have suggested placing a line on the floor at the 50-G line to alert personnel to the increased danger of propelled objects (14).

Beryllium tools are useful in MRI. However, hands must be washed after handling because beryllium metallic dust is a pulmonary toxin (14). Safe metals include nickel, stainless steel, alloys, tantalum, and titanium (19). It is a good idea to install a "test" magnet outside the scanner room to detect potential ferromagnetic objects (14).

Noise

The noise from the MRI scanner is due to torque on loops of wire which have gradient currents induced in them during the RF pulses. This causes vibration and therefore audible noise, hampering communication and making assessment of cardiac and respiratory function virtually impossible using standard acoustic precordial or esophageal stethoscopes. Ear plugs for pediatric patients and earphones with music for adults are used to decrease noise exposure. Noise during scans may average 95 decibels in a 1.5-T scanner (14). Permissible exposure to noise of this level should be limited to 2 h/day (14).

Radio Frequency Heating

Although no clinical signs of *core* body heating have been reported with MRI, RF heating from induced currents is a potential problem especially with field strengths greater than 2 T (13,14). A measure of this heating is specific absorption rate. The FDA limit is 0.4 W/kg averaged over the whole body. The main concerns occur with field strengths greater than 2 T (14). Specific absorption rate may be reduced by changing the pulse sequence, decreasing the number of slices, lengthening the repeat time, decreasing the RF scale, and switching to a smaller transmitter coil. Ex vivo temperature measurements of large metal prostheses have not demonstrated heating in fields 6.4 times that experienced in MRI (14,18).

Occupational Exposure

Magnetic resonance imaging does not require ionizing radiation, and there are no reports of harm from tissue contact with the magnetic fields (4). Although no oncologic or genotoxic effects have been found, caution is advised during pregnancy, especially during the first trimester (21–24). The FDA has not established limits on total MRI exposure. Local expo-

sure levels, however, are mandated: the field strength is limited to 2 T, with time varying fields less than 3 T/s. Radio frequency must be limited to 2 W/kg over 1 g of tissue and 0.4 W/kg averaged over the whole body (19). Mice exposed over multiple generations to 1.89 T for 2 yr failed to reveal any specific damage (21). Cells exposed to 2.7 T for 17 h have not shown aberrations (22,23). A study of 792 workers exposed with field strengths of 0.5 mT to 2 T did not show increases in 19 disease categories (24). No alterations of cardiac or neurologic function have been reported in field strengths up to 7 T (13,14). Magnetophosphenes causing visual sensations such as light flashes or flickers have been reported in magnetic field changes of 1.3 T/s (25).

Monitor Interference

Electron beams are affected by the static magnetic field, which distorts and displaces the image on monitors and other cathode ray displays. This requires the anesthetist to find a point of least distortion by orienting the monitor in various positions relative to the magnetic field. Most electrocardiographic artifact cannot be eliminated, and monitors used should have good artifact suppression characteristics (3).

Monitors themselves can disturb the signal/noise ratio of the MRI. Electrical connections to the patient act as antennas and introduce RF signals that can distort the MRI image (3,11). Magnetic fields created by the electronics within the monitors can disturb the MRI image.

Monitors and Equipment

Monitors and equipment are listed as described in the original papers. Monitors acceptable in low-strength magnetic fields may not provide useful information in the new high strength magnetic fields used today (1).

Electrocardiography

Electrocardiography (ECG) introduces problems with both image degradation from wire leads acting as antennas and the inability of the ECG monitor to discern the ECG from the background static magnetic field and RF pulses. A reported trial of telemetric and fiberoptic ECG transmission stated that RF pulsing caused severe artifact (11). Voltage induced in the wire leads may pose burn and electrical shock hazards to the patient (3). Acceptable monitors are reported in Table 1.

Table 1. Electrocardiography Devices Reported Acceptable

Author	Field strength (T)	Device	Reference
Roth	0.15	Hewlett-Packard 78 100A Telemetry Waltham, Mass. Saturn Monitor Space Lab, Inc. Chatsworth, Calif.	11
Barnett	0.6	Model 78100 A Hewlett-Packard Palo Alto, Calif.	36
Groh	1.0	Sirecust 404	39
Dimick	1.5	Hewlett-Packard Waltham, Mass.	26
Karlik	1.5	HP 7830	30
Rao	1.5	Astro-Med DashII	28
Patteson	2.0	ARS V-52 Tokyo, Japan	

Dimick reported obtaining a 12-lead ECG in a 1.5-T machine and studied optimal electrode placement. Leads V_5 and V_6 maximized QRS and minimized artifact (26). Placing ECG electrodes in a single line close together was reported acceptable for monitoring (3). Additional suggestions for improving ECG monitoring include twisting cables, keeping electrodes close together, positioning electrodes near the three-dimensional center of the imager, and maintaining the plane of any loop of cable parallel to the magnetic field lines (27). Nonferromagnetic fasteners and electrodes (NDM 01-5010, NDM Corp., Dayton, Ohio) do not interfere with the MRI (27). Graphite and copper cables with plastic springs (BR611U, Nihon-Kohden America Inc., Irvine, Calif.) and NDM ECG leads (NDM Corp.) do not affect the MRI image (11,27).

A 7–10-Hz filter may reduce artifact in most electrocardiography leads (28). Low-pass filters are incorporated into some commercial monitors (HP 78110A/78101A, Hewlett-Packard, Waltham, Mass.) (27). A "gated" ECG signal may be obtained by subtraction of the MRI field and RF pulses from the ECG signal obtained, leaving the net patient ECG signal (29). Most recent MRI imagers contain ECG monitoring to provide gated cardiac images (30). Scan gating, timed to the R wave of the ECG, will prolong the MRI study depending on heart rate.

T-wave changes have been reported in fields greater than 0.3 T, presumably because of alterations in regional blood flow perpendicular to the magnetic field (12). There does not appear to be any significant physiologic change due to the T-wave alterations (12–14,26).

Table 2. Oximetry Monitoring Devices Reported Acceptable

Author	Field strength (T)	Device	Reference
McArdle	0.6	Nellcor N-100 Haywood, Calif. Ohmeda Biox 3700 Madison, Wis.	33
Groh	1.0	Drager-Nellcor	39
Karlik	1.5	Ohmeda Biox 3700	30
Rao	1.5	Biochem 1040	28
Patteson	2.0	Criticare System 501+ Pewaukee, Wis.	

Table 3. Doppler Monitoring Devices Reported Acceptable

Author	Field strength (T)	Device	Reference
Roth	0.15	Parks Medical 811 Parks Medical Beaverton, Ore.	11
McArdle	0.6	811 Ultrasonic Doppler Parks Medical Beaverton, Ore. Hewlett-Packard 8813A Mountain View, Calif.	33
Rao	1.5	Parks Medical 811	28
Shellock	1.5	Medpacific LD 5000 Seattle, Wash.	32
Patteson	2	Parks Medical 806-CA Beaverton, Ore.	

Table 4. Blood Pressure Monitoring Devices Reported Acceptable

Author	Field strength (T)	Device	Reference
Sellden	0.02	Dinamap 1846 Critikon Ltd., Tampa, Fla.	44
Nixon	0.5	Dinamap	12
Rejger	0.5	Accutorr, Datascope Noevelaken, The Netherlands	3
Barnett	0.6	Spacelab 414 Opt21 Hillsboro, Ore. DTX Transducer Gould Oxnard, Calif.	36
Groh	1	Dinamap	39
Karlik	1.5	Dinamap 1846 SK/P Critikon Inc., Tampa, Fla.	30
Shellock	1.5	Omega 1400 Invivo Research Broken Arrow, Okla.	32
Smith	1.5	Accutorr 2A Datascope Corp. Paramus, N.J.	20
Patteson	2.0	Dinamap 8100 Critikon, Inc. Tampa, Fla.	

Pulse Oximetry and Peripheral Perfusion

Various oxygen saturation monitors have been found useful and provide information regarding pulsatile peripheral blood flow and oxygenation. These monitors are susceptible to interference from the changing magnetic field and will occasionally be briefly deactivated by RF pulses. Most monitors may be placed within 2 m of the magnet, but greater distances provide longer periods of uninterrupted function. The probe is placed on a distal extremity as far from the scan site as possible, but severe burns to a finger caused by gradient or RF magnetic fields induced in a loop of wire from a pulse oximeter probe have been reported (31). Oximeters reported acceptable are listed in Table 2.

Plethysmography can provide a waveform from a distal extremity that correlates with pulsatile perfusion (29,32). Higgins et al. (29) describes using a Cardioloine III Pulsorette in a 0.35-T field. At the author's institution, a Hewlett-Packard HP 78330A (Waltham, Mass.) monitor is used with the probe placed on the large toe. This monitor, along with pulse oximetry, provides evidence of pulsatile perfusion.

Pulsatile blood flow through the dorsalis pedis, radial artery, ear lobe, and lips can be acoustically monitored via Doppler probes (11,32,33). Doppler monitoring devices reported acceptable are listed in Table 3. Dopplers may require use of headphones as audio output is hampered by noise during the RF pulses.

Blood Pressure

Blood pressure monitoring during MRI can be accomplished using the oscillometric method, which is particularly immune to electromagnetic interference (12,32). Monitors that provided accurate measurement of blood pressure during MRI are reported in Table 4. Monitors may be equipped with extended tubing and plastic connectors and are usually placed as far from the magnet as possible.

Fiberoptic systems and invasive pressure measurements obtained with long pressure lines have been used to monitor arterial oxygenation and blood pressure (12,32,34,35). Transducers reported to be MRI-compatible include Steridome model 043279-999 (Cobe Monitoring, Lakewood, Col.) and DTX Gould (Gould Inc., Oxnard, Calif.) (35,36). Fiberoptics, placed through an 18-gauge catheter into a femoral artery in a cat, are reported to give measurements of blood pressure and cardiac activity. The report did not state the strength of the magnetic field (34).

Table 5. Anesthesia Machines/Ventilators Reported Acceptable

Author	Field strength (T)	Device	Reference
Boutros	NA	Mapleson D 5116W Vital Signs Totowa, N.J.	40
Andoh	0.15	Boyce International 2 Model B	6
Nixon	0.5	Monaghan 225	12
Rejger	0.5	Laerdal N-4001 Mapleson D Stavanger, Norway Oxylog Drager	3
Barnett	0.6	Monaghan 225	36
Groh	1.0	Siemens 900 C Servo Iselin, N.J.	39
Karlik	1.5	Boyle MS-222 Ohmeda, Madison, Wis. Airshield Ventimeter II Air-Shield Hatboro, Pa. Monaghan 225 Monaghan Medical Plattsburg, N.Y.	30
Mirvis	1.5	Siemens 900 C Iselin, N.J.	38
Rao	1.5	Narco Airshield VC 20-1	28
	1.5	Ohmeda (R) Excel 210	37
Smith	1.5	225/SIMV Monaghan Med Plattsburg, N.Y.	20
Patteson	2.0	Mapleson D. Dryden Corp Indianapolis, Ind.	

Anesthesia Machines

There are several reports describing use of anesthesia machines near MRI scanners. Considerations include (a) no danger to the patient; (b) proper function in the magnetic field; and (c) no effect on the MRI image (6). Breathing circuits and anesthesia machines utilized in magnetic fields are listed in Table 5. Some machines are bolted to the walls and others are modified by removal of ferromagnetic components (11,28,37). Aluminum cylinders replace ferromagnetic ones on the anesthesia machines. Some specially engineered "MRI compatible" ventilators are available. They are pneumatically driven, fluidic-controlled, and volume-cycled (20,34). These machines include the 225 SIMV (Monaghan Medical Corp., Plattsburg, N.Y.) and the Narco Airshield VC 20-1; they have been found to be functional in a 1.5-T field (20,28). The use of a Siemens-Elema 900C (Siemens-Elema Ab, Iselin, N.J.) ventilator has been reported in a 1.5-T machine (38). The limiting feature on this ventilator is the PEEP valve, which is a solenoid type and must be at least 1.2 m away from the magnet bore (38). Anesthesia in a 1-T field has been maintained using inhalational agents with a Siemens 900 C Servo machine (39). Pressurized oxygen must be supplied to power these machines.

The use of a long Mapleson D circuit provides oxygenation and ventilation for the patient undergoing MRI. This circuit is lightweight, portable, flexible, and provides tactile sensation regarding the patient's airway and ventilation. It is also useful during transportation (40). Mapleson D circuits allow transport of patients into the MRI suite from the scanner lobby after induction with anesthesia machines that contain ferromagnetic components. Oxygen may be supplied from plastic cannisters containing liquid oxygen (Penox Technologies, Pittston, Pa.).

Respiratory Gas Analysis

Respiratory gas analysis and capnography allow the anesthesiologist to monitor patient ventilation, circuit integrity, and anesthetic gas concentrations. Devices may be interfaced to the patient with extended plastic tubing. This does not decrease monitor sensitivity (41). Monitors found functional in MRI fields are listed in Table 6. Oxygen analyzers are essential in monitoring gases delivered by anesthesia machines. Infrared monitors analyzing end-tidal carbon dioxide will give rapid detection of loss of ventilation and circuit disconnection (12,32). Chest wall movement has been detected using a chest bellows and apnea alarm mattress (11,12). Fiberoptic monitoring of respiratory motion is possible with esophageal, intraperitoneal, rectal, and bronchial probes (34).

Intravenous Infusion Pumps

Infusion pumps may be nonfunctional or inaccurate in MRI fields (14,15). Medications infused through drips without pumps are subject to inaccurate dosages. Total intravenous anesthesia is most easily managed with infusion pumps (3). Devices found accurate and functional in a magnetic field are listed in Table 7. It is important to remember that pumps must be supported on nonferromagnetic poles. When rapid infusion of fluids is required, plastic disposable pressure bags (Infusable IN-8000, Biomedical Dynamics, Minneapolis, Minn.) may be used.

Specialized Equipment

Some investigators describe use of plastic precordial (Argyle, Sherwood Medical, St. Louis, Mo.) and esophageal stethoscopes. These may not be acceptable monitors when used by themselves as all audible

Table 6. Gas Analysis/Capnography Devices Reported Acceptable

Author	Field strength (T)	Device	Reference
Nixon	0.5	Engstrom Eliza	12
Rao	0.5	Ohmeda 5120	28
Rejger	0.5	Multicap Datex Medical Electronics Hoevelaken, The Netherlands	3
Karlik	1.5	Puritan-Bennett 222 Wilmington, Mass.	30
Shellock	1.5	Tri-med 511G Biochem International Milwaukee, Wis.	32
		515 Respiration Monitor Biochem International Waukesha, Wis.	41
		8800 Capnometer Biochem International Waukesha, Wis.	

Table 7. Intravenous Infusion Devices Reported Acceptable

Author	Field strength (T)	IV pump	Reference
Engler	0.28	IVAC 530	15
Rejger	0.5	WTI SP 102U Adquipment Rotterdam, The Netherlands	3
Karlik	1.5	Fenwal Baxter Corp. Deerfield, Ind. IVAC 530	30

input from these monitors is obscured by scanner noise. Their use is advocated for backup should other monitors fail and for verification of cardiac and respiratory sounds during quiet periods in the scanning process.

Plastic laryngoscopes (North American Medical; PT#6001, Loudonville, N.Y.) are available; however, the batteries in the handle still cause a pull from the magnetic field (12,42). Laryngoscopes have been modified to operate directly from a 5-V DC source connected to the MRI machine. An 8-ft cable with nonmagnetic BNC connectors is used to connect the laryngoscope to the power source (30). Various specialized alternatives to other monitors are described in their respective sections.

Patient Problems

Patient Accessibility

The patient's distance from the anesthetist creates problems with airway management, intravenous access, patient visualization, and monitor application (43). If unintentional extubation occurs, it may be necessary to discontinue the scan and remove the patient to the foot of the scanner bed. It is possible and sometimes necessary for personnel to position themselves within the scanner coil to evaluate the airway during a scan. A quick release table is used for rapid extrication of the patient. With the patient removed from the MRI tube, laryngoscopy at the foot of the magnet bore is possible in emergency situations with plastic laryngoscopes.

Because of the anesthetist's distance from the patient in the MRI tube, extensions must be placed on intravenous lines. In the pediatric population, this increased line distance may add to the fluid volume infused when administering injections.

Table 8. Temperature Monitoring Devices Reported Acceptable

Author	Field strength (T)	Device	Reference
McArdle	0.6	Yellow Springs Temp Module Yellow Springs, Ohio Mon-A-Therm St. Louis, Mo.	33
Karlik	1.5	Yellow Springs Yellow Springs, Ohio	30

Hypothermia

Care must be taken to avoid hypothermia in all patients, especially in the pediatric population. Air flow directed through the scanner cavity increases heat loss, making hypothermia a distinct problem. Warmed fluid packs such as bags of warm intravenous fluids, heating pads, single-use thermal packs (Portawarm #11475-010, Baxter Pharmaseal, Moberly, Mo.), airway humidification, and covering the patient are methods to minimize heat loss. Rectal temperature probes have been used to monitor temperature in 0.6-T fields (30,33). Table 8 lists acceptable monitors. Nonferromagnetic disposable temperature strips (Stat Temp, Trademark Corp, Fenton, Mo.) may be used.

Miscellaneous Problems

Claustrophobia has been reported in up to 7% of awake patients (12). Obesity may limit physical placement of the patient into the magnet bore, as well as decrease space available for access to the patient, airway, and monitor attachments (13). Bank cards,

credit cards, pagers, and digital watches may suffer erasure or alteration of stored information.

Anesthetic Techniques

Many techniques have been described that include some or all of the principles described. Newer drugs such as oral midazolam, used in the pediatric population, have made the anesthetic management of children somewhat easier. Anesthesia can be safely achieved if drug delivery and patient monitoring are applied with knowledge of the effects of magnetic fields.

Monitored Anesthesia Care

Consideration should always be given to use of monitored anesthesia care. Pediatric, anxious, or confused patients may remain immobile for MRI scanning with appropriate medication. Monitoring that would routinely be available for general anesthesia under the same circumstances should be applied. McArdle et al. (33) described the use of oral chloral hydrate (75 mg/kg) for sedation in a term infant. Oral midazolam (0.5–0.75 mg/kg) has also been advocated for sedation in children. In adults, intravenous access is more easily established and many medications, such as midazolam and fentanyl, are available for sedation.

General Anesthesia

Many patients cannot be safely sedated for MRI and therefore require general anesthesia. Pediatric and adult patients present the same considerations for anesthesia in the MRI suite as they would in the operating room. Inhalation inductions are more likely to be required (or requested) in the pediatric population. Inductions of anesthesia in the lobby of the MRI suite distant from the magnetic field may allow use of a familiar anesthesia machine. Total intravenous anesthesia may be maintained once intravenous access is obtained. The patient is then transported into the MRI field on a nonferromagnetic stretcher.

Pediatric. Many techniques have been described in pediatric patients. Rejger et al. (3) described induction in an adjacent induction room. Manual ventilation was then maintained for children under 3 yr of age. Geiger and Cascorbi (42) described oral premedication with diazepam followed by intramuscular methohexital. Anesthesia was then continued with intravenous agents and spontaneous respiration. Boutros and Pavlicek (40) used inhalation induction and obtained intravenous access followed by intubation. Anesthesia was maintained with ventilation using a Mapleson D circuit, 100% oxygen, and incremental thiopental. Sellden et al. (44) obtained intravenous access, then utilized premedication with midazolam (0.2 mg/kg IV) followed by induction with atropine (0.01 mg/kg), thiopental (5 mg/kg), pancuronium (0.1 mg/kg), fentanyl (2 μg/kg), and nasal intubation. Intramuscular ketamine may be used for sedation or induction before intravenous access.

Adult. Numerous techniques are described for adults. Rafferty et al. (45) used a laryngeal mask airway as an adjunct to airway maintenance and support. Rejger et al. (3) utilized continuous total intravenous anesthesia supported by mechanical ventilation or spontaneous respiration after induction in an adjacent room. Smith et al. described total intravenous anesthesia using thiopental, narcotic, muscle relaxant, and mechanical ventilation. Induction and intubation occur outside the scanner's magnetic field. Nasal intubation may provide a more secure airway than does oral intubation within the scanner confines. Many different safe techniques may be devised around available monitors and equipment.

Conclusion

Problems created by the magnetic field have been presented along with possible solutions. Awareness of specific risks associated with anesthesia for MRI should temper its usage in patients requiring general anesthesia. As medications evolve and as technology enhances our monitoring ability, anesthesia in MRI will likely become more commonplace and more easily and safely managed.

References

1. Messick JM, MacKenzie RA, Nugent M. Anesthesia at remote locations. In: Miller RD, ed. New York: Churchill Livingstone, 1990:2061–88.
2. Baker HL, Berquist TH, Kispert DB, Reese DF, Houser OW. Magnetic resonance imaging in a routine clinical setting. Mayo Clin Proc 1985;60:75–90.
3. Rejger VS, Cohn BF, Vielvoye GJ, Raadt FB. A simple anaesthetic and monitoring system for magnetic resonance imaging. Eur J Anaesthesiol 1989;6:373–8.
4. Cahalan MK, Litt L, Botvinick EH, Schiller NB. Advances in noninvasive cardiovascular imaging: implications for the anesthesiologist. Anesthesiology 1987;66:356–72.
5. Carsin M, Rolland Y, Gandon Y, Gagey N, Brassier G, Simon J. Contribution of RMI to the diagnosis and posttherapeutic monitoring of brain stem tumors. J Neuroradiol 1990;17:50–9.
6. Andoh K, Ohkoshi T, Odagiri K, Kyuma Y, Hayashi A. Technical note: enhanced MR-guided stereotaxic brain surgery with the patient under general anesthesia. AJNR 1991;12: 135–8.
7. Hotchkiss RS, Hall JR, Braun IF, Schisler JQ. An abnormal epiglottis as a cause of difficult intubation—airway assessment

using magnetic resonance imaging. Anesthesiology 1988;68: 140–2.
8. Schneider M, Probst R, Wey W. Magnetic resonance imaging—a useful tool for airway assessment. Acta Anaesthesiol Scand 1989;33:429–31.
9. Delannoy J, LeBihan D, Hoult DI, Levin RL. Hyperthermia system combined with a magnetic resonance imaging unit. Med Phys 1990;17:855–60.
10. Dickinson RJ, Hall AS, Hind AJ, Young IR. Measurement of changes in tissue temperature using MR imaging. J Comput Assist Tomogr 1986;10:468–72.
11. Roth JL, Nugent M, Gray JE, et al. Patient monitoring during magnetic resonance imaging. Anesthesiology 1985;62:80–3.
12. Nixon C, Hirsch NP, Ormerod IEC, Johnson G. Nuclear magnetic resonance. Its implications for the anaesthetist. Anaesthesia 1986;41:131–7.
13. Consensus Conference. Magnetic resonance imaging. JAMA 1988;259:2132–8.
14. Gangarosa RE, Minnis JE, Nobbe J, Praschan D, Genberg RW. Operational safety issues in MRI. Magn Reson Imaging 1987; 287:292.
15. Engler MB, Engler MM. The effects of magnetic resonance imaging on intravenous infusion devices. West J Med 1985;143: 329–32.
16. Pavlicek W, Geisinger M, Castle L, et al. The effects of nuclear magnetic resonance on patients with cardiac pacemakers. Radiology 1983;147:149–53.
17. Erlebacher JA, Cahill PT, Pannizzo F, Knowles JR. Effect of magnetic resonance imaging on DDD pacemakers. Am J Cardiol 1986;57:437–40.
18. Davis PL, Crooks L, Arakawa M, McRee R, Kaufman L, Margulis AR. Potential hazards in NMR imaging: heating effects of changing magnetic fields and RF fields on small metallic implants. AJR 1981;137:857–60.
19. Scherzinger AL, Hendee WR. Basic principles of magnetic resonance imaging—an update. West J Med 1985;143:782–92.
20. Smith DS, Askey P, Young ML, Kressel HY. Anesthetic management of acutely ill patients during magnetic resonance imaging. Anesthesiology 1986;65:710–1.
21. Osbakken M, Griffith J, Taczanowsky P. A gross morphologic, histologic, and blood chemistry study of adult and neonatal mice chronically exposed to high magnetic fields. Magn Reson Med 1986;3:502–17.
22. Wolff S, James TL, Young GB. Magnetic resonance imaging: absence of in-vitro cytogenetic damage. Radiology 1985;155: 163–5.
23. Geard CR, Osmak RS, Hall EJ. Magnetic resonance and ionizing radiation: a comparative evaluation in vitro of oncogenic and genotoxic potential. Radiology 1984;152:199–202.
24. Budinger TF, Bristol KS, Yen CK. Biological effects of static magnetic fields. Abstracts of the Society of Magnetic Resonance in Medicine, New York, 1984:113.
25. Budinger TF, Cullander C, Bordow R. Switched magnetic fields thresholds for the induction of magnetophosphenes. Abstracts of the Society of Magnetic Resonance in Medicine, New York, 1984:118.
26. Dimick RN, Hedlund LW, Herfkens RJ, Fram EK, Utz J. Optimizing electrocardiographic electrode placement for cardiac-gated magnetic resonance imaging. Invest Radiol 1987;22: 17–22.
27. Wendt RE, Rokey R, Vick GW. Electrocardiographic gating and monitoring in NMR imaging. Magn Reson Imaging 1988; 6:89–95.
28. Rao CC, McNiece WL, Emhardt J, Krishna G, Westcott R. Modification of an anesthesia machine for use during magnetic resonance imaging. Anesthesiology 1988;68:640.
29. Higgins CB, Lanzer P, Strak D, et al. Imaging by nuclear magnetic resonance in patients with chronic ischemic heart disease. Circulation 1984;3:523–1.
30. Karlik SJ, Heatherley T, Pavan F, Stein J, Lebron F, Rutt B. Patient anesthesia and monitoring at a 1.5-T MRI installation. Magn Reson Med 1988;7:210–21.
31. Shellock FG, Slimp GL. Severe burn of the finger caused by using a pulse oximeter during MR imaging. AJR 1989;153:1105.
32. Shellock FG. Monitoring during MRI. Med Elec 1986;Sept: 93–7.
33. McArdle CB, Nicholas DA, Richardson CJ, Amparo EG. Monitoring of the neonate undergoing MR imaging: technical considerations. Radiology 1986;159:223–6.
34. Legendre JP, Misner R, Forester GV, Geoffrion Y. A simple fiber optic monitor of cardiac and respiratory activity for biomedical magnetic resonance applications. Magn Reson Med 1986;3:953–7.
35. Roos CF, Carroll FE. Fiber-optic pressure transducer for use near MR magnetic fields. Radiology 1985;156:548.
36. Barnett GH, Ropper AH, Johnson KA. Physiological support and monitoring of critically ill patients during magnetic resonance imaging. J Neurosurg 1988;68:246–50.
37. Rao CC, Brandl R, Mashak JN. Modification of Ohmeda (R) Excel 210 anesthesia machine for use during magnetic resonance imaging. Anesthesiology 1988;68:640–1.
38. Mirvis SE, Borg U, Belzberg H. MR imaging of ventilator–dependent patients: preliminary experience. AJR 1987;149: 845–6.
39. Groh J, Weber W, Baierl P, Seiderer M, Peter K. Anaesthesie zur magnetresonanz-tomographie. Anaesthesist 1988;37: 384–6.
40. Boutros A, Pavlicek W. Anesthesia for magnetic resonance imaging. Anesth Analg 1987;66:367–74.
41. Shellock FG. Monitoring sedated pediatric patients during MR imaging. Radiology 1990;177:586–7.
42. Geiger RS, Cascorbi HF. Anesthesia in an NMR scanner. Anesth Analg 1984;63:622–3.
43. Nixon C. Magnetic resonance imaging. Can Anaesth Soc J 1991:420.
44. Sellden H, DeChateau P, Ekman G, Linder B, Saaf J, Wahlund L. Circulatory monitoring of children during anaesthesia in low-field magnetic resonance imaging. Acta Anaesthesiol Scand 1990;34:41–3.
45. Rafferty C, Burke AM, Cossar DF, Farling PA. Laryngeal mask and magnetic resonance imaging. Anaesthesia 1990;45:590–1.