

Practice Advisory on Anesthetic Care for Magnetic Resonance Imaging

An Updated Report by the American Society of Anesthesiologists Task Force on Anesthetic Care for Magnetic Resonance Imaging

PRACTICE advisories are systematically developed reports that are intended to assist decision-making in areas of patient care. Advisories provide a synthesis and analysis of expert opinion, clinical feasibility data, open forum commentary, and consensus surveys. Practice advisories developed by the American Society of Anesthesiologists (ASA) are not intended as standards, guidelines, or absolute requirements and their use cannot guarantee any specific outcome. They may be adopted, modified, or rejected according to clinical needs and constraints and are not intended to replace local institutional policies.

Practice advisories are not supported by scientific literature to the same degree as standards or guidelines because of the lack of sufficient numbers of adequately controlled studies. Practice advisories are subject to periodic revision as warranted by the evolution of medical knowledge, technology, and practice.

This document updates the "Practice Advisory on Anesthetic Care for Magnetic Resonance Imaging," adopted by the ASA in 2008 and published in 2009.*

Methodology

A. Definition of Anesthetic Care for MRI and High-risk Imaging

This Advisory defines anesthetic care for magnetic resonance imaging (MRI) as moderate sedation, deep sedation, monitored anesthesia care, general anesthesia, or ventilatory and critical care support. High-risk imaging refers to imaging in patients with medical or health-related risks, imaging with equipment-related risks, and procedure-related risks such as MRI-guided surgery, minimally invasive procedures (*e.g.*, focused ultrasound and radiofrequency ablation), or cardiac and airway imaging studies.

- What other guideline documents are available on this topic?
 - This Practice Advisory updates the "Practice Advisory on Anesthetic Care for Magnetic Resonance Imaging: A Report by the American Society of Anesthesiologists Task Force on Anesthetic Care for Magnetic Resonance Imaging" adopted by the American Society of Anesthesiologists in 2008 and published in 2009.¹
 - Other guideline documents addressing, in part, anesthetic care for magnetic resonance imaging have been published by the American College of Radiologists² and the Society for Cardiovascular Magnetic Resonance.³
- Why was this Practice Advisory developed?
 - In October 2013, the Committee on Standards and Practice Parameters elected to search for new evidence to determine if recommendations in the existing practice advisory continue to be supported by current evidence. The resultant Practice Advisory, presented in this issue, includes an update of the scientific literature and additional explanatory information.
- How does this statement differ from existing guidelines?
 - This updated American Society of Anesthesiologists Advisory differs from the existing advisory because it provides new evidence obtained from recent scientific literature as well as additional information.
 - New evidence presented includes acknowledgment that the Food and Drug administration has approved a magnetic resonance imaging conditional implantable cardiac pacing generator and lead system, which is commercially available, and will require increased awareness among providers.
 - Consistent with current guidelines published by the American College of Radiologists, categories of various levels of magnetic resonance imaging facilities have been eliminated.
 - The updated American Society of Anesthesiologists Practice Advisory differs from documents published by other organizations by focusing specifically on anesthetic care of patients in the magnetic resonance imaging environment, whereas other organizations' guidelines are focused on broader safety issues in that environment.

This article is featured in "This Month in Anesthesiology," page 1A. Supplemental Digital Content is available for this article. Direct URL citations appear in the printed text and are available in both the HTML and PDF versions of this article. Links to the digital files are provided in the HTML text of this article on the Journal's Web site (www.anesthesiology.org). A complete bibliography used to develop this updated Advisory, arranged alphabetically by author, is available as Supplemental Digital Content 1, <http://links.lww.com/ALN/B98>.

Submitted for publication October 15, 2014. Accepted for publication October 15, 2014. Approved by the ASA House of Delegates on October 15, 2014. Updated by the American Society of Anesthesiologists Committee on Standards and Practice Parameters: Jeffrey L. Apfelbaum, M.D. (Committee Chair), Chicago, Illinois; Mark A. Singleton, M.D. (Task Force Co-Chair), San Jose, California; Jan Ehrenwerth, M.D. (Task Force Co-Chair), Madison, Connecticut; Charlotte Bell, M.D., Milford, Connecticut; Richard T. Connis, Ph.D., Woodinville, Washington; Keira P. Mason, M.D., Wellesley Hills, Massachusetts; Craig D. McClain, M.D., Brookline, Massachusetts; David G. Nickinovich, Ph.D., Bellevue, Washington; and Warren S. Sandberg, M.D., Ph.D., Nashville, Tennessee.

* American Society of Anesthesiologists: Practice advisory on anesthetic care for magnetic resonance imaging: A report by the American Society of Anesthesiologists Task Force on Anesthetic Care for Magnetic Resonance Imaging. ANESTHESIOLOGY 2009; 110:459-79.

Copyright © 2014, the American Society of Anesthesiologists, Inc. Wolters Kluwer Health, Inc. All Rights Reserved. Anesthesiology 2015; 122:495-520

B. Purpose

The MRI suite is a hazardous location because of the presence of a very strong static magnetic field, high-frequency electromagnetic (radiofrequency) waves, and a time-varied (pulsed) magnetic field. Secondary dangers of these energy sources include high-level acoustic noise, systemic and localized heating, and accidental projectiles. There may be significant challenges to anesthetic administration and monitoring capabilities due to static and dynamic magnetic fields as well as radiofrequency energy emissions. Direct patient observation may be compromised by noise, darkened environment, obstructed line of sight, and other characteristics unique to this environment (*e.g.*, distractions). Unlike a conventional operating room, the MRI environment frequently requires the anesthesiologist to assume broader responsibility for immediate patient care decisions.

The purposes of this updated Advisory are to: (1) promote patient and staff safety in the MRI environment, (2) prevent the occurrence of MRI-associated accidents, (3) promote optimal patient management and reduce adverse patient outcomes associated with MRI, (4) identify potential equipment-related hazards in the MRI environment, (5) identify limitations of physiologic monitoring capabilities in the MRI environment, and (6) identify potential health hazards (*e.g.*, high decibel levels) of the MRI environment.

C. Focus

This updated Advisory focuses on MRI settings where anesthetic care is provided. Four zones within the MRI suite have been identified, with ascending designations indicating increased hazard areas.^{4,5} These areas within the MRI suite are categorized as zones I–IV (appendix 1).

D. Application

This updated Advisory is intended for use by anesthesiologists or other individuals working under the supervision of an anesthesiologist and applies to anesthetic care performed, supervised, or medically directed by anesthesiologists or to moderate sedation care supervised by other physicians. Because the safe conduct of MRI procedures requires close collaboration and prompt coordination between anesthesiologists, radiologists, MRI technologists, and nurses, some responsibilities are shared among the disciplines. When shared responsibilities are described in this Advisory, the intent is to give the anesthesiologist a starting point for participating in the allocation and understanding of shared responsibilities. The Advisory may also serve as a resource for other physicians and healthcare professionals (*e.g.*, technologists, nurses, safety officers, hospital administrators, biomedical engineers, and industry representatives).

This updated Advisory does not address specific anesthetic drug choices and does not apply to patients who

[†] International Anesthesia Research Society, 82nd Clinical and Scientific Congress, San Francisco, California, March 30, 2008; Society for Pediatric Anesthesia, Annual Meeting; San Diego, California, April 5, 2008.

receive minimal sedation (anxiolysis) in order to complete the scan or procedure safely and comfortably.

E. Task Force Members and Consultants

In 2013, the ASA Committee on Standards and Practice Parameters requested that scientific evidence for this Advisory be updated. The update consists of an evaluation of literature that includes new studies obtained after publication of the original Advisory.

The original Advisory was developed by an ASA-appointed Task Force of 13 members. These individuals included 10 anesthesiologists in private and academic practice from various geographic areas of the United States, a radiologist, and two consulting methodologists from the ASA Committee on Standards and Practice Parameters.

The Task Force developed the original Advisory by means of a seven-step process. First, they reached consensus on the criteria for evidence. Second, a systematic review and evaluation was performed on original published research studies from peer-reviewed journals relevant to MRI safety. Third, a panel of expert consultants was asked to: (1) participate in opinion surveys on the effectiveness of various MRI safety strategies and (2) review and comment on a draft of the Advisory developed by the Task Force. Fourth, opinions about the Advisory were solicited from a random sample of active members of the ASA. Fifth, the Task Force held an open forum at two major national meetings[†] to solicit input on its draft recommendations. Sixth, the consultants were surveyed to assess their opinions on the feasibility of implementing this Advisory. Seventh, all available information was used to build consensus within the Task Force to create the final document. A summary of recommendations is found in appendix 2.

F. Availability and Strength of Evidence

Preparation of this update used the same methodological process as was used in the original Advisory to obtain new scientific evidence. Opinion-based evidence obtained from the original Advisory is reported in this update. The protocol for reporting each source of evidence is described below.

Scientific Evidence. Scientific evidence used in the development of this updated Advisory is based on cumulative findings from literature published in peer-reviewed journals. Literature citations are obtained from PubMed and other healthcare databases, direct Internet searches, Task Force members, liaisons with other organizations, and manual searches of references located in reviewed articles.

Findings from the aggregated literature are reported in the text of the Advisory by evidence category, level, and direction. Evidence categories refer specifically to the strength and quality of the *research design* of the studies. Category A evidence represents results obtained from randomized controlled trials (RCTs), and Category B evidence represents observational results obtained from

nonrandomized study designs or RCTs without pertinent controls. When available, Category A evidence is given precedence over Category B evidence in the reporting of results. These evidence categories are further divided into evidence levels. Evidence levels refer specifically to the strength and quality of the summarized study *findings* (*i.e.*, statistical findings, type of data, and the number of studies reporting/replicating the findings) within the two evidence categories. For this document, only the highest level of evidence is included in the summary report for each intervention, including a directional designation of benefit, harm, or equivocality for each outcome.

Category A: RCTs report comparative findings between clinical interventions for specified outcomes. Statistically significant ($P < 0.01$) outcomes are designated as either beneficial (B) or harmful (H) for the patient; statistically nonsignificant findings are designated as equivocal (E).

Level 1: The literature contains a sufficient number of RCTs to conduct meta-analysis,‡ and meta-analytic findings from these aggregated studies are reported as evidence. No meta-analyses were conducted for this Advisory.

Level 2: The literature contains multiple RCTs, but the number of RCTs is not sufficient to conduct a viable meta-analysis for the purpose of this updated Advisory. Findings from these RCTs are reported as evidence.

Level 3: The literature contains a single RCT, and findings from this study are reported as evidence.

Category B: Observational studies or RCTs without pertinent comparison groups may permit *inference* of beneficial or harmful relationships among clinical interventions and outcomes. Inferred findings are given a directional designation of beneficial (B), harmful (H), or equivocal (E). For studies that report statistical findings, the threshold for significance is $P < 0.01$.

Level 1: The literature contains observational comparisons (*e.g.*, cohort, case-control research designs) between clinical interventions for a specified outcome.

Level 2: The literature contains observational studies with associative statistics (*e.g.*, relative risk, correlation, and sensitivity/specificity).

Level 3: The literature contains noncomparative observational studies with descriptive statistics (*e.g.*, frequencies and percentages).

Level 4: The literature contains case reports.

‡ All meta-analyses are conducted by the ASA/CSPP methodology group. Meta-analyses from other sources are reviewed but not included as evidence in this document.

§ When an even number of responses are obtained, the median value is determined by calculating the arithmetic mean of the two middle values. Ties are calculated by a predetermined formula.

Insufficient Literature: The lack of sufficient scientific evidence in the literature may occur when the evidence is either unavailable (*i.e.*, no pertinent studies found) or inadequate. Inadequate literature cannot be used to assess relationships among clinical interventions and outcomes because such literature does not permit a clear interpretation of findings due to methodological concerns (*e.g.*, confounding in study design or implementation) or does not meet the criteria for content as defined in the “Focus” of the Advisory.

Opinion-based Evidence. The original Advisory contained formal survey information collected from expert consultants and a random sample of members of the ASA. Additional information was obtained from open-forum presentations and other invited and public sources. All opinion-based evidence relevant to each topic (*e.g.*, original survey data, original open-forum testimony, Internet-based comments, letters, and editorials) is considered in the development of this Advisory. However, only the findings obtained from formal surveys are reported.

Opinion surveys were developed by the Task Force to address each clinical intervention identified in the document. Identical surveys were distributed into two groups of respondents: expert consultants and ASA members.

Expert Opinion: Survey responses from Task Force-appointed expert consultants are reported in summary form in the text. A complete listing of consultant survey responses is reported in table 1 in appendix 3.

Membership Opinion: Survey responses from a random sample of members of the ASA and, when appropriate, responses from members of other organizations with expertise in the selected topics of interest are reported in summary form in the text. A complete listing of ASA member survey responses is reported in table 2 in appendix 3.

Survey responses are recorded using a 5-point scale and summarized based on median values.§

Strongly Agree: Median score of 5 (at least 50% of the responses are 5)

Agree: Median score of 4 (at least 50% of the responses are 4 or 4 and 5)

Equivocal: Median score of 3 (at least 50% of the responses are 3, or no other response category or combination of similar categories contain at least 50% of the responses)

Disagree: Median score of 2 (at least 50% of responses are 2 or 1 and 2)

Strongly Disagree: Median score of 1 (at least 50% of responses are 1)

Informal Opinion: Open-forum testimony, Internet-based comments, letters, and editorials are all informally evaluated and discussed during the development of the Advisory. When

warranted, the Task Force may add educational information or cautionary notes based on this information.

Advisories

I. Education

MRI safety education includes, but is not limited to, the following topics: (1) MRI magnet hazards in zones III and IV, (2) challenges and limitations of monitoring, and (3) long-term health hazards.

Literature Findings. There is insufficient published evidence to evaluate the effect of education regarding magnet hazards, monitoring limitations, or long-term health hazards associated with MRI. One observational study examined the potential long-term health hazards of pregnant MRI workers and pregnant non-MRI workers and found no significant difference in the relative risk of early delivery, low birth weight, or spontaneous abortions (*Category B2-E evidence*).⁶

Survey Findings. The consultants and ASA members strongly agree that all anesthesiologists should have general safety education on the unique physical environment of the MRI scanner. The ASA members agree and the consultants strongly agree that all anesthesiologists should have specific education regarding the features of individual scanners within their institution. The ASA members agree and the consultants strongly agree that anesthesiologists should work in collaboration with radiologists, technologists, and physicists within their institutions to develop safety training programs.

Advisory Statements for Education

- All anesthesiologists should have general safety education on the unique physical environment of the MRI scanner and specific education regarding the specific features of individual scanners within their institution.
- Education should emphasize safety for entering zones III and IV, with special emphasis on hazards in this environment and effects on monitoring capabilities.
- Education should address potential health hazards (*e.g.*, high decibel levels and high intensity magnetic fields) and necessary precautions to deal with the specific field strength and the safety of the MRI scanners within their institutions.
- Education should include information regarding ferromagnetic items (*e.g.*, stethoscopes, pens, wallets, watches, hair clips, name tags, pagers, cell phones, credit cards, and batteries) and implantable devices (*e.g.*, spinal cord stimulators and implanted objects) that should not be brought into zones III and IV of the MRI suite or should be brought in with caution.
- Anesthesiologists should work in collaboration with radiologists, technologists, and physicists within their institutions to ensure that the above topics are included in their safety training programs.

- Education should include how to safely respond to code blue situations in zones III and IV, and this information should be integrated into protocols for the designated code blue team.

II. Screening of Anesthetic Care Providers and Ancillary Support Personnel

The MRI medical director or designated technologist is responsible for access to zones III and IV. Screening of all individuals entering zone III is necessary to prevent accidental incursions of ferromagnetic materials or inadvertent exposure of personnel with foreign bodies or implanted ferromagnetic items.

Literature Findings. The literature is insufficient to evaluate whether the screening of anesthesia care providers and ancillary support personnel improves safety in the MRI suite.

Survey Findings. The ASA members agree and the consultants strongly agree that the anesthesiologist should work in collaboration with the MRI medical director or designee to ensure that all anesthesia team personnel entering zone III or IV have been properly screened.

Advisory Statements for Screening of Anesthetic Care Providers and Ancillary Support Personnel

- The anesthesiologist should work in collaboration with the MRI medical director or designee (*e.g.*, safety officer) to ensure that all anesthesia team personnel entering zone III or IV have been screened for the presence of ferromagnetic materials, foreign bodies, or implanted devices.

III. Patient Screening

Patient screening consists of determining patient and equipment-related risks for adverse outcomes associated with MRI procedures.

Patient-related Risks

Risks related to the patient may include age-related risks, health-related risks, and risks from foreign bodies located in or on the patient or implanted ferromagnetic items. *Age-related risks* apply to neonates or premature infants and elderly patients. *Health-related risks* include, but are not limited to: (1) need for intensive or critical care, (2) impaired respiratory function (*e.g.*, tonsillar hypertrophy and sleep apnea), (3) changes in level of sedation, muscle relaxation, or ventilation, (4) hemodynamic instability and vasoactive infusion requirements, or (5) comorbidities that may contribute to adverse MRI effects (*e.g.*, burns or temperature increases in patients with obesity or peripheral vascular disease). *Foreign bodies* include nonmedical ferromagnetic items imbedded in the patient (*e.g.*, eyeliner tattoos and metallic intraocular fragments) or attached to the patient (*e.g.*, pierced jewelry and magnetic dental keepers). *Implanted ferromagnetic items* may include items such as aneurysm clips, prosthetic heart valves, or coronary arterial stents.

Literature Findings. One comparative study reports that neonates undergoing MRI demonstrate increased fluctuations in heart rate, blood pressure, and oxygen saturation levels compared with neonates not undergoing an MRI (*Category B1-H evidence*).⁷ Two observational studies report that premature neonates can experience heart rate fluctuations, decreases in oxygen saturation, and increases in temperature during MRI (*Category B3-H evidence*).^{8,9} One case report indicates that a child with a history of prior cardiac arrest experienced a cardiac arrest during MRI (*Category B3-H evidence*).¹⁰ Four observational studies^{11–14} and two case reports^{15,16} indicate that patients with impaired renal function are at risk of nephrogenic systemic fibrosis after gadolinium administered for MRI (*Category B3/4-H evidence*).

Case reports indicate that exposure of iron filings to the magnetic field may result in hemorrhage^{10,17} and exposure of eyeliner tattoos may result in image artifacts, burns, swelling, or puffiness^{10,18–20} (*Category B4-H evidence*). Numerous observational studies and case reports indicate interactions with the magnetic field (*e.g.*, movements, displacements, and image artifacts) and increases in temperature during MRI for ferromagnetic items such as aneurysm clips, surgical clips, prosthetic heart valves, intravenous infusion pumps, coronary arterial stents, and implanted dental magnet keepers (*Category B3/4-H evidence*).^{21–46}

Survey Findings. Both the consultants and ASA members strongly agree that, for every case, the anesthesiologist should communicate with the patient and radiologist or referring physician to determine whether the patient has a high-risk medical condition. In addition, they both strongly agree that if the patient presents with a high-risk medical condition, the anesthesiologist should collaborate with all participants, including the referring physician, radiologist, and technologist, to determine how the patient will be managed during the MRI procedure. Both the consultants and ASA members agree that, for patients with acute or severe renal insufficiency, the anesthesiologist should not administer gadolinium because of the elevated risk of nephrogenic systemic fibrosis.

Equipment-related Risks

Patient equipment-related risks include, but are not limited to: (1) physiologic monitors, (2) invasive monitors (*e.g.*, intravascular catheters), (3) intubation equipment, (4) oxygenation and ventilation equipment, and (5) pacemakers, implanted cardiofibrillators, and other implanted devices (*e.g.*, deep brain stimulators, vagal or phrenic nerve stimulators, and middle-ear or cochlear implants).

Literature Findings. One case report notes that cardiac monitor leads interfered with an MRI scan (*Category B4-H evidence*).¹⁰ One observational study and one case report indicate that fire or burns occurred beneath or near cardiac monitor electrodes (*Category B3/4-H evidence*).^{47,48} Five case reports note that burns occurred from the looping of a temperature probe or pulse oximetry cables (*Category B4-H evidence*).^{49–53} One observational study reports ferromagnetic components in ventilators,⁵⁴ and three case reports describe

projectile nitrous oxide or oxygen tanks^{55–57} (*Category B3/4-H evidence*). Additional observational studies and case reports indicate interactions of pacemakers or implanted cardioverter defibrillators with MRI scanning including, but not limited to, pacing artifacts, reed switch closure, generator movement or displacement, alterations of pacing rate, and temperature increases (*Category B3/4-H evidence*).^{10,58–87} Two observational studies report palpitations, rapid heart rate, and discomfort at the pacemaker pocket after MRI.^{78,88} Finally, two cases of cardiac arrest are reported in patients with pacemakers during or after an MRI scan; in one case, the patient died (*Category B4-H evidence*).^{10,60}

Three observational studies report image artifacts when MRI is performed on patients with neurostimulators, infusion pumps, implantable spinal fusion stimulators, or cochlear implants (*Category B3-H evidence*).^{89–91} Six observational studies report increased temperatures in patients with deep brain stimulators, neurostimulators, or spinal cord stimulators,^{92–97} and three report displacement of leads, pulse generators, or other components of deep brain stimulators or middle ear prostheses during MRI scans (*Category B3-H evidence*).^{98–100}

Survey Findings. Both the consultants and ASA members agree that, for every case, the anesthesiologist should communicate with the radiologist or referring physician to determine whether the patient requires equipment that may pose a risk during the scan. In addition, they agree that anesthesiologists should determine the safety and effectiveness of the equipment needed by the patient during the procedure for each MRI location. Further, the consultants and ASA members strongly agree that anesthesiologists should work with their institutions to properly identify and label anesthesia-related equipment according to convention for each MRI scanner. The ASA members agree and the consultants strongly agree that care should be taken to assure that anesthesia equipment does not interfere with image acquisition or quality. Both the consultants and ASA members agree that, in general, MRI should not be performed on patients with implanted electronic devices. Finally, both the consultants and ASA members strongly agree that, when MRI is considered essential by the referring physician and consulting radiologist, a plan for managing patients with implanted electronic devices during the scan should be developed in collaboration with the referring physician, medical director or on-site radiologist, and other appropriate consultants.

Advisory Statements for Patient Screening

- For every case, the anesthesiologist should communicate with the patient, referring physician, and radiologist to determine whether the patient: (1) presents with a high-risk medical condition (*e.g.*, neonatal status or prematurity, intensive or critical care status, impaired respiratory function, hemodynamic instability and vasoactive infusion requirements, or comorbidities such as obesity and peripheral vascular disease), (2) requires

equipment (*e.g.*, physiologic or invasive monitors; intubation, oxygenation, or ventilation equipment), (3) has implanted devices (*e.g.*, pacemakers, cardioverter defibrillators, or nerve stimulators), (4) has been screened for the presence of implanted ferromagnetic items (*e.g.*, surgical clips and prosthetic heart valves), and (5) has been screened for the presence of *imbedded* foreign bodies (*e.g.*, orbital iron filings and eyeliner tattoos).

- The anesthesiologist should communicate with the technologist to ensure that the patient has been screened for the presence of foreign bodies *on the patient* (*e.g.*, pierced jewelry and rings) before entering zone III.
- If a patient presents with a high-risk medical condition, the anesthesiologist should collaborate with all participants, including the referring physician, radiologist, and technologist, to determine how the patient will be managed during the MRI procedure. Anticipated changes in level of sedation, muscle relaxation, or ventilation may also place a patient in a high-risk situation.
- For patients with acute or severe renal insufficiency, the anesthesiologist should not administer gadolinium because of the elevated risk of nephrogenic systemic fibrosis.^{||}
- Anesthesiologists should work with their institutions to properly identify and label anesthesia-related equipment according to convention (safe, unsafe, or conditional) for each MRI scanner.[#]
- For each MRI location, anesthesiologists should determine the safety and effectiveness of the equipment needed by the patient during the procedure. In addition, care should be taken to ensure that equipment does not interfere with image acquisition or quality.
- The Task Force believes that cardiac pacemakers and implantable cardioverter-defibrillators are generally contraindicated for MRI. These devices pose an extreme hazard in this environment and may be life-threatening within the 5 gauss line.^{**} When MRI is considered

^{||} See United States Food and Drug Administration alert: www.fda.gov/drugs/drugsafety/ucm223966.htm.

[#] Equipment is categorized as safe, unsafe, or conditional for use in the MRI environment. MRI “safe” equipment is identified by the American Society for Testing and Materials as having no ferromagnetic parts or radiofrequency interference. MRI “unsafe” equipment is identified as having ferromagnetic parts or being affected by radiofrequency interference. MRI “conditional” equipment may be safe in certain locations of the suite depending on gauss line locations, but cannot be identified as having no ferromagnetic parts (see American Society for Testing and Materials Practice Standards F2503, F2119, and F2052, www.astm.org).

^{**} In 2011, the FDA approved the use of pacemakers and leads as MRI conditional for certain patients, scans of certain parts of the body, and under certain scanning parameters. The subsequent development and clinical application of MRI safe pacemakers and ICDs may be addressed in a future revision of this Advisory.

^{††} American Society of Anesthesiologists: Practice advisory for the perioperative management of patients with cardiac rhythm management devices: Pacemakers and implantable cardioverter-defibrillators: A report by the American Society of Anesthesiologists Task Force on Perioperative Management of Patients with Cardiac Rhythm Management Devices. ANESTHESIOLOGY 2005; 103:186–98.

essential by the referring physician and consulting radiologist, a plan for managing these patients during the scan should be developed in collaboration with the ordering physician, medical director, or on-site radiologist and other appropriate consultants (*e.g.*, the patient’s pacemaker specialist or cardiologist, the diagnostic radiologist, and the device manufacturer).††

- Other implanted electronic devices also pose a hazard in the MRI environment. These devices and associated wiring may transfer energy during the MRI scan, causing tissue damage, malfunction of the device, image artifacts, and device displacement. MRI may be performed on a limited basis for patients with certain implanted electronic devices (*e.g.*, deep brain stimulators, vagal nerve stimulators, phrenic nerve stimulators, wire-containing thermodilution catheters, or cochlear implants). In consultation with the referring physician, the radiologist responsible for the procedure, and the neurosurgeon, the anesthesiologist should ensure that the presence of the device has been noted and determined to be MRI safe/conditional before imaging of these patients.

IV. Preparation

Preparation consists of determining and implementing an individualized anesthetic plan before the MRI procedure begins. In addition to the anesthetic plan, preparation includes a plan for optimal positioning of equipment and personnel in the MRI suite during the procedure.

Literature Findings. The literature is insufficient to determine whether active preparation or pre-MRI planning reduces the frequency of adverse events. One case report indicates that misinformation about the type of aneurysm clip resulted in intracerebral hemorrhage and death, and a second case report indicates that a lack of communication among physicians caring for a pacemaker patient resulted in the death of the patient (*Category B4-H evidence*).^{34,101}

Survey Findings. Both the consultants and ASA members strongly agree that, for every case, the anesthesiologist should prepare, with support personnel, a plan for providing optimal anesthetic care within the special environment of the MRI suite. They both strongly agree that the anesthesiologist should communicate with the radiology personnel to determine the requirements of the scan. The ASA members agree and the consultants strongly agree that the anesthesiologist should collaborate with the magnetic resonance (MR) technologist and/or facility biomedical engineer to determine and demarcate the optimal and safe location of movable equipment in relation to the gauss lines within the MRI suite. They both strongly agree that, because line of sight within the bore will vary depending on the facility, the anesthesiologist should choose a location or position for optimal patient observation and vigilance during delivery of care, whether in zone III or IV. Finally, they both strongly agree that the anesthesiologist should prepare a plan for rapidly summoning additional personnel in the event of an emergency.

Advisory Statements for Preparation

- For every case, the anesthesiologist should prepare, with support personnel, a plan for providing optimal anesthetic care within the special environment of the MRI suite. In addition to addressing the medical needs of the patient, features of the plan should include (1) requirements of the scan and personnel needs, (2) positioning of equipment, (3) special requirements or unique issues of patient or imaging study, (4) positioning of the anesthesiologist and the patient, and (5) planning for emergencies.
- The anesthesiologist should communicate with the radiology personnel to determine the requirements for the scan (*e.g.*, duration of the scan, position of the patient or area of the body in the scanner, positioning of receiver coils, and need for periods of paused respiration). The anesthesiologist should communicate with other anesthesia team members regarding individual roles for anesthetic care.
- The anesthesiologist should collaborate with the MR technologist and/or facility biomedical engineer to determine and demarcate the optimal and safe location of movable equipment in relation to the gauss lines within the MRI suite.
- Because line of sight within the bore will vary depending on the facility, the anesthesiologist should choose a location or position for optimal patient observation and vigilance during delivery of care, whether in zone III or IV. In particular, anesthesiologists should have (1) a clear line of sight of the patient and physiologic monitors, whether by direct observation or by video camera, (2) anesthetic delivery equipment located for optimal control of anesthetic depth and rapid intervention, and (3) access to hospital information systems integral to patient care. In preparing for positioning, the anesthesiologist should take into account potential electromagnetic and auditory hazards.
- Anesthesiologists should prepare a plan for rapidly summoning additional personnel in the event of an emergency. Because the MRI suite is frequently located in an isolated area of the facility, the anesthesiologist should ensure that (1) emergency equipment and drugs are immediately accessible, (2) emergency communication (*e.g.*, phone or code button) is immediately available, and (3) an evacuation plan is in place, including an appropriate location outside the scan room (zone IV) for resuscitation. This location should be complete with physiologic monitors, oxygen, suction, and other appropriate resuscitation equipment. Monitoring requirements, airway management, and emergency preparedness are additional features that should be included in the preparation and planning for an MRI scan and are addressed in section V below.

V. Patient Management during MRI

Features of safe patient management during MRI procedures include (1) monitoring, (2) anesthetic care, (3) airway management, and (4) management of emergencies.

Monitoring

Safe monitoring conditions include (1) the use of MRI safe/conditional monitors, (2) remote monitoring, and (3) compliance with ASA standards.¹⁰²

Literature Findings. Three observational studies indicate that the use of MRI compatible monitoring equipment resulted in no radiofrequency interference, interruptions in scanning, or artifacts (*Category B3-B evidence*).^{103–105} Five observational studies demonstrate that remote monitoring for heart rate, blood pressure, auscultation, respiration, and chest wall movement can be performed safely and effectively (*Category B3-B evidence*).^{104,106–109} One observational study reported that compliance with the ASA “Standards for Basic Anesthesia Monitoring” can be obtained, provided that the monitoring equipment is properly tested before an MRI (*Category B3-E evidence*).¹¹⁰

Survey Findings. The consultants and ASA members both strongly agree that MRI patients should be monitored in a manner consistent with the ASA “Standards for Basic Anesthesia Monitoring.” In addition, they both strongly agree that (1) anesthesiologists should be familiar with the expected limitations of available monitoring equipment, (2) the anesthesiologist should make sure that all monitors used in zone IV are safe/conditional for the scan, and (3) a monitor should be available to view vital signs from zone III when the anesthesia care provider is not in zone IV.

Advisory Statements for Monitoring

- MRI patients should be monitored in a manner consistent with the ASA “Standards for Basic Anesthesia Monitoring.” Anesthesiologists should be familiar with the expected limitations of available monitoring equipment. The Task Force notes that information from electrocardiograms may be limited due to superimposed voltages from blood flow in the high magnetic field (*e.g.*, ST segment interpretation may be unreliable, even with highly filtered monitors).
- The anesthesiologist should make sure that all monitors used in zone IV are safe/conditional for the scan.
- A monitor should be available to view vital signs from zone III when the anesthesia care provider is not in zone IV.
- Additional care should be taken in positioning electrocardiogram and other monitor leads to eliminate burns, even with nonferromagnetic leads.

Anesthetic Care

Literature Findings. Observational studies report a high rate of success in imaging of moderately sedated patients (*Category B3-B evidence*).^{111–118} However, imaging failures or motion artifacts may still occur (*Category B3-H evidence*).^{119–122} Observational studies report a high rate of successful imaging in patients receiving deep sedation or light anesthesia, with low rates of motion artifacts (*Category B3-B evidence*).^{123–127} One RCT reports equivocal findings for scan

repeats when light anesthesia is compared with general anesthesia (*Category A3-E evidence*).¹²⁸ Observational studies and case reports also indicate that respiratory depression, oxygen desaturation, bronchospasm, drowsiness, agitation, and vomiting may occur with moderate sedation or light anesthesia (*Category B3/4-H evidence*).^{103,112,118–120,122,123,125–127,129–145} The Task Force believes that automated apnea monitoring (by detection of exhaled carbon dioxide or other means) may decrease risks during both moderate and deep sedation.

Survey Findings. Both the consultants and ASA members strongly agree that, in general, because MRI is a nonpainful procedure, lighter levels of anesthesia may be appropriate, recognizing that institutional circumstances, patient characteristics, and anesthesiologist preference may warrant more aggressive airway management and deeper anesthetic levels. They both strongly agree that anesthesiologists should ensure that patients who receive moderate or deep sedation are monitored in a manner consistent with their institution's protocol for monitoring similarly sedated patients elsewhere in the facility. In addition, they both strongly agree that equipment and drugs for anesthetic care in the MRI suite should mirror what is available in the operating room. Both the consultants and ASA members are equivocal that, when an MRI safe/conditional anesthesia machine is not available, inhalation anesthetics may be administered from an anesthesia machine inside zone III *via* an elongated circuit through a wave guide. Finally, both the consultants and ASA members agree that, if total intravenous anesthesia is used, it should be administered by using: (1) MRI safe/conditional pumps in zone IV, (2) traditional (*i.e.*, MRI unsafe) pumps in zone III with intravenous tubing passed through a wave guide, or (3) periodic bolus injections in either zone III or IV.

Advisory Statements for Anesthetic Care

- Although lighter levels of anesthesia may be appropriate during an MRI scan, the anesthesiologist should be aware that these lighter levels may result in airway complications (*e.g.*, laryngospasm, coughing, or other airway compromise) that may necessitate interruption of the scan for urgent treatment and alteration of anesthetic depth. Institutional circumstances, patient characteristics, and

[#] See “American Society of Anesthesiologists: Practice guidelines for sedation and analgesia by non-anesthesiologists: An updated report by the American Society of Anesthesiologists Task Force on Sedation and Analgesia by Non-anesthesiologists. ANESTHESIOLOGY 2002; 96:1004–17.” When light general anesthesia is administered, refer to the American Society of Anesthesiologists: Standards for Basic Anesthetic Monitoring (last amended October 20, 2010, effective date July 1, 2011).

[§] When remodeling or building a new facility, input from the anesthesiologist is critical.

^{||} An MRI facility that is newly built or that undergoes a major renovation should have an MRI safe/conditional anesthesia machine.

^{##} A wave guide is a copper-lined conduit with a specific length and diameter that maintains RF isolation of the magnet room installed during construction of the MRI suite. Wires or conducting material act as an antenna and should not be passed through a wave guide.

anesthesiologist preference may warrant more aggressive airway management and deeper anesthetic levels.

- Anesthesiologists should ensure that patients who receive moderate or deep sedation are monitored in a manner consistent with their institution's protocol for monitoring similarly sedated patients elsewhere in the facility.
- Monitoring of exhaled carbon dioxide should be considered for all patients receiving deep sedation and for patients whose ventilation cannot be directly observed during moderate sedation.^{‡‡} The Task Force cautions that, because ventilation and oxygenation are separate though related physiological processes, monitoring oxygenation by pulse oximetry is not a substitute for monitoring ventilatory function.
- Equipment and drugs for anesthetic care in the MRI suite should mirror what is available in other anesthetizing locations including: (1) an integrated anesthesia machine, medical gases, and waste anesthesia gas disposal or gas scavenging, when inhalational anesthesia is administered, (2) suction, (3) adequate electrical outlets and lighting, and (4) storage areas for equipment and drugs. The Task Force recognizes that physical plant variability exists among institutions.^{§§}
- Equipment used in the MRI suite should be appropriate for the age and size of the patient.
- MRI safe/conditional anesthesia machines are always preferred for use in an MRI facility.^{|||} However, when an MRI safe/conditional anesthesia machine is not available, inhalational anesthetics can be administered from an anesthesia machine inside zone III *via* an elongated circuit through a wave guide.^{##} Although this method of anesthetic delivery was commonplace before the commercial manufacture of MRI safe/conditional anesthesia machines, this practice is inherently cumbersome and may be prone to more possibilities for mishaps than the use of an anesthesia machine specifically designed for the MRI environment.
- Alternatively, if total intravenous anesthesia is used, it should be administered by using: (1) MRI safe/conditional pumps in zone IV, (2) traditional (*i.e.*, MRI unsafe) pumps in zone III with intravenous tubing passed through a wave guide, or (3) periodic bolus injections in either zone III or IV. Although an anesthesia machine may not be required for the administration of total intravenous anesthesia, there must be equipment immediately available for the administration of positive pressure ventilation with oxygen.

Airway Management

Unique features of airway management during an MRI scan include (1) the limited accessibility of the patient's airway and (2) the difficulty of conducting visual and auditory assessments of the patient.

Literature Findings. The literature is insufficient to assess the management of airway problems (*e.g.*, obstruction,

secretions, laryngospasm, apnea, and hypoventilation) during an MR scan. In addition, the literature is insufficient to assess whether the use of a tracheal tube or laryngeal mask airway improves outcomes for patients at risk of airway compromise during MRI.

Survey Findings. Both the consultants and ASA members strongly agree that the anesthesiologist should have an advance plan in place to deal with instrumentation of the airway and common airway problems when patients are in an MRI environment. Both the consultants and ASA members strongly agree that, if the patient is at risk for airway compromise, more aggressive airway management should be instituted because the patient's airway may be less accessible when the patient is in the scanner. Both the consultants and ASA members strongly agree that (1) complex airway management (*e.g.*, fiberoptic intubation) should be performed in a controlled environment outside zone IV, (2) alternative airway devices should be immediately available in the MRI suite, and (3) suction equipment should be immediately accessible to the patient's airway at all times.

Advisory Statements for Airway Management

- The anesthesiologist should have an advance plan in place to deal with instrumentation of the airway and common airway problems (*e.g.*, obstruction, secretions, laryngospasm, apnea, and hypoventilation) when patients are in an MRI environment.
- If the patient is at risk for airway compromise, more aggressive airway management (*e.g.*, use of a tracheal tube or laryngeal mask airway) should be instituted because the patient's airway may be less accessible when the patient is in the scanner.
- Complex airway management (*e.g.*, fiberoptic intubation) should be performed in a controlled environment outside zone IV.
- Alternative MRI safe/conditional airway devices should be immediately available in the MRI suite. Suction equipment should be immediately accessible to the patient's airway at all times.

Management of Emergencies

Emergencies in the MR suite include (1) medical emergencies (*e.g.*, cardiopulmonary arrest) and (2) environmental emergencies (*e.g.*, quench, fire, and projectiles). The remote location of the scanner within the facility may delay response of support personnel or availability of equipment during an emergency.

Literature Findings. The literature is insufficient regarding the management of medical emergencies (*e.g.*, cardiopulmonary arrest) or quench in the MR suite. One case report indicates that a fire occurring on the patient was managed by extinguishing the flames, discontinuing the scan, and immediately removing the patient from the bore (*Category B4 evidence*).⁴⁸ Two case reports of projectile nitrous oxide or

oxygen tanks indicate that the emergency was managed by removing patients from zone IV and instituting a controlled quench (*Category B4 evidence*).^{56,57}

Survey Findings. Both the consultants and ASA members strongly agree that when a patient has a medical emergency in the MRI scanner, the following should occur: (1) initiate cardiopulmonary resuscitation (CPR), when needed, while immediately removing the patient from zone IV, (2) call for help, and (3) transport the patient to a previously designated safe location in proximity to the MRI suite. In addition, they both strongly agree that the designated safe location should contain the following resuscitation equipment: (1) a defibrillator, (2) vital signs monitors, and (3) a code cart that includes resuscitation drugs, airway equipment, oxygen, and suction. The consultants and ASA members both strongly agree that when a fire occurs in the MRI suite, team members should perform their preassigned fire management tasks as quickly as possible, in accordance with the ASA Practice Advisory for the Prevention and Management of Operating Room Fires.¹⁴⁶ The ASA members agree and the consultants strongly agree that, when a quench occurs, team members should perform their institution's protocol in reaction to this occurrence. In addition, the ASA members agree and the consultants strongly agree that, when a quench occurs, if possible (1) immediately remove the patient from zone IV and (2) immediately administer oxygen to the patient. Finally, both the consultants and ASA members agree that, since powerful static magnetic fields may persist after a quench or fire, emergency response personnel should be restricted from entering zone IV.

Advisory Statements for Management of Emergencies

- Medical emergencies may be difficult to manage while the patient is in the MRI scanner.
- When a patient has a medical emergency (*e.g.*, cardio-pulmonary arrest) in the MRI scanner, the following should occur: (1) immediately remove the patient from zone IV while initiating CPR, if indicated, (2) call for help, and (3) transport the patient to a previously designated safe area for resuscitation that is not in zone IV. This location should be as close to zone IV as possible so as not to delay resuscitation efforts and should contain the following resuscitation equipment: a defibrillator, vital signs monitors, and a code cart that includes resuscitation drugs, airway equipment, oxygen, and suction.
- When a fire occurs in the MRI suite, team members should perform their preassigned fire management task as quickly as possible, in accordance with the ASA Practice Advisory for the Prevention and Management of Operating Room Fires.¹⁴⁶ If a team member cannot rapidly perform his or her task in the predetermined order, other team members should perform their tasks *without waiting*. When a team member has completed a

- preassigned task, he or she should help other members perform tasks that are not yet complete.
- In the case of projectile emergencies, team members should perform their institution's protocol in reaction to this occurrence. If possible, immediately remove the patient from zone IV and discontinue the scan. If the patient is injured, proceed with medical emergency management as indicated above.
 - A controlled quench may be necessary in order to remove the patient from the bore. A quench occurs when a superconducting magnet turns resistive and catastrophically releases all of the stored energy as heat, boiling off the stored cryogens as gas. The most common cause of quench is an intentional shutdown of the magnet for a life-threatening emergency. Quench may also be the consequence of an unintentional shutdown. If not properly vented, a quench can result in the complete dissipation of oxygen in zone IV, risking hypoxia to the patient and MRI personnel. In addition, entrance to zone IV may not be possible due to high pressure caused by escaping gases, making it impossible to open the door into zone IV. When a quench occurs, team members should perform their institution's protocol in reaction to this occurrence. If possible, immediately remove the patient from zone IV and immediately administer oxygen to the patient.
 - Powerful static magnetic fields may persist after a quench, and therefore, the usual precautions apply when entering zone IV. Emergency response personnel should be restricted from entering zone IV during any environmental emergency because of the persistent magnetic field.

VI. Postprocedure Care

Literature Findings. The literature is insufficient to determine whether postprocedure care consistent with that provided for other areas of the institution reduces the frequency of adverse events.

Survey Findings. The ASA members agree and the consultants strongly agree that the anesthesiologist should collaborate with the radiologist and other staff in the postanesthetic care of the patient. The consultants and ASA members strongly agree that: (1) patients receiving sedation or anesthesia within the MRI suite should have access to postanesthetic care consistent with that provided in other areas of the institution, (2) in all situations, intensive care and recovery areas should include access to vital signs monitors, oxygen, suction, and trained personnel, and (3) patients should be provided written discharge instructions.

Advisory Statements for Postprocedure Care

- The anesthesiologist should collaborate with the radiologist and other staff in the postanesthetic care of the patient.

*** When remodeling or building a new facility, an attempt should be made to locate recovery and resuscitation in proximity to the MRI suite.

- Patients receiving sedation or anesthesia within the MRI suite should have access to postanesthetic care consistent with that provided in other areas of the institution, including transport to other recovery rooms, dedicated intensive care, or recovery areas within the MRI suite.
- In all situations, intensive care and recovery areas should include access to vital sign monitors, oxygen, suction, resuscitation equipment, and trained personnel.***
- Patients should be provided oral and written discharge instructions.

Appendix 1. Zone Definitions

Zone I

This region includes all areas that are freely accessible to the general public. This area is typically outside the MR environment itself and is the area through which patients, healthcare personnel, and other employees of the MR site access the MR environment.

Zone II

This area is the interface between the publicly accessible uncontrolled zone I and the strictly controlled zone III (see below). Typically, the patients are greeted in zone II and are not free to move throughout zone II at will, but rather are under the supervision of MR personnel. It is in zone II that the answers to MR screening questions, patient histories, and medical insurance questions are typically obtained.

Zone III

This area is the region in which free access by unscreened non-MR personnel or ferromagnetic objects or equipment can result in serious injury or death as a result of interactions between the individuals or equipment and the MR scanner's particular environment. These interactions include, but are not limited to, those with the MR scanner's static and time varying magnetic fields. All access to zone III is to be strictly restricted, with access to regions within it (including zone IV; see below) controlled by, and entirely under the supervision of, MR personnel.

Zone IV

This area is synonymous with the MR scanner magnet room itself. Zone IV, by definition, will always be located within zone III as it is the MR magnet and its associated magnetic field, which generates the existence of zone III.

Appendix 2. Summary of Recommendations

I. Education

- All anesthesiologists should have general safety education on the unique physical environment of the MRI scanner and specific education regarding the specific features of individual scanners within their institution.
 - Education should emphasize safety for entering zones III and IV, with special emphasis on hazards in this environment and effects on monitoring capabilities.

- o Education should address potential health hazards (*e.g.*, high decibel levels and high intensity magnetic fields).
- o Education should address necessary precautions to deal with the specific field strength and the safety of the MRI scanners within their institutions.
- o Education should include information regarding ferromagnetic items (*e.g.*, stethoscopes, pens, wallets, watches, hair clips, name tags, pagers, cell phones, credit cards, and batteries) and implantable devices (*e.g.*, spinal cord stimulators and implanted objects) that should *not* be brought into zones III and IV of the MRI suite or should be brought in with caution.
- Anesthesiologists should work in collaboration with radiologists, technologists, and physicists within their institutions to ensure that the above topics are included in their safety training programs.
- Education should include how to safely respond to code blue situations in zones III and IV, and this information should be integrated into protocols for the designated code blue team.

II. Screening of Anesthesia Care Providers and Ancillary Support Personnel

- The anesthesiologist should work in collaboration with the MRI medical director or designee (*e.g.*, safety officer) to ensure that all anesthesia team personnel entering zone III or IV have been screened for the presence of ferromagnetic materials, foreign bodies, or implanted devices.

III. Patient Screening

- For every case, the anesthesiologist should communicate with the patient, referring physician, and radiologist to determine whether the patient:
 - o Presents with a high-risk medical condition (*e.g.*, neonatal status or prematurity; intensive or critical care status; impaired respiratory function; hemodynamic instability and vasoactive infusion requirements; or comorbidities such as obesity and peripheral vascular disease).
 - o Requires equipment (*e.g.*, physiologic or invasive monitors; intubation, oxygenation, or ventilation equipment).
 - o Has been screened for implanted devices (*e.g.*, pacemakers, cardioverter defibrillators, or nerve stimulators).
 - o Has been screened for implanted ferromagnetic items (*e.g.*, surgical clips and prosthetic heart valves).
 - o Has been screened for the presence of *imbedded* foreign bodies (*e.g.*, orbital iron filings and eyeliner tattoos).
- The anesthesiologist should communicate with the technologist to ensure that the patient has been screened for the presence of foreign bodies on the patient (*e.g.*, pierced jewelry, rings) before entering zone III.
- If a patient presents with high-risk medical condition, the anesthesiologist should collaborate with all participants, including the referring physician, radiologist, and

technologist, to determine how the patient will be managed during the MRI procedure.

- o Anticipated changes in level of sedation, muscle relaxation, or ventilation may also place a patient in a high-risk situation.

- For patients with acute or severe renal insufficiency, the anesthesiologist should not administer gadolinium because of the elevated risk of nephrogenic systemic fibrosis.
- Anesthesiologists should work with their institutions to properly identify and label anesthesia-related equipment according to convention (safe, unsafe, or conditional) for each MRI scanner.
- For each MRI location, anesthesiologists should determine the safety and effectiveness of the equipment needed by the patient during the procedure.
- o Care should be taken to assure that the patient's equipment does not interfere with image acquisition or quality.
- Cardiac pacemakers and implantable cardioverter-defibrillators are generally contraindicated for MRI.
- o When MRI is considered essential by the referring physician and consulting radiologist, a plan for managing these patients during the scan should be developed in collaboration with the ordering physician, medical director, or on-site radiologist and other appropriate consultants (*e.g.*, the patient's pacemaker specialist or cardiologist, the diagnostic radiologist, and the device manufacturer).

- MRI may be performed on a limited basis for patients with certain implanted electronic devices (*e.g.*, deep brain stimulators, vagal nerve stimulators, phrenic nerve stimulators, wire-containing thermodilution catheters, or cochlear implants).
- o In consultation with the referring physician, the radiologist responsible for the procedure, and the neurosurgeon, the anesthesiologist should ensure that the presence of the device has been noted and determined to be MRI safe/conditional before imaging of these patients.

IV. Preparation

- For every case, the anesthesiologist should prepare, with support personnel, a plan for providing optimal anesthetic care within the special environment of the MRI suite.
- o In addition to addressing the medical needs of the patient, features of the plan should include (1) requirements of the scan and personnel needs, (2) positioning of equipment, (3) special requirements or unique issues of patient or imaging study, (4) positioning of the anesthesiologist and the patient, and (5) planning for emergencies.
- The anesthesiologist should communicate with the radiology personnel to determine the requirements for the scan

(e.g., duration of the scan, position of the patient or area of the body in the scanner, positioning of receiver coils, and need for periods of paused respiration).

- The anesthesiologist should communicate with other anesthesia team members regarding individual roles for anesthetic care.
- The anesthesiologist should collaborate with the MR technologist and/or facility biomedical engineer to determine and demarcate the optimal and safe location of movable equipment in relation to the gauss lines within the MRI suite.
- The anesthesiologist should choose a location or position for optimal patient observation and vigilance during delivery of care, whether in zone III or IV.
 - Anesthesiologists should have (1) a clear line of sight of the patient and physiologic monitors, whether by direct observation or by video camera, (2) anesthetic delivery equipment located for optimal control of anesthetic depth and rapid intervention, and (3) access to hospital information systems integral to patient care.
 - In preparing for positioning, the anesthesiologist should take into account potential electromagnetic and auditory hazards.
- Anesthesiologists should prepare a plan for rapidly summoning additional personnel in the event of an emergency.
 - The anesthesiologist should ensure that (1) emergency equipment and drugs are immediately accessible, (2) emergency communication (e.g., phone or code button) is immediately available, and (3) an evacuation plan is in place, including an appropriate location outside the scan room (zone IV) for resuscitation.
- This location should be complete with physiologic monitors, oxygen, suction, and other appropriate resuscitation equipment.

V. Patient Management during MRI

- Monitoring
 - MRI patients should be monitored in a manner consistent with the ASA “Standards for basic anesthesia monitoring.”
 - The anesthesiologist should be familiar with the expected limitations of available monitoring equipment.
 - Information from electrocardiograms may be limited due to superimposed voltages from blood flow in the high magnetic field (e.g., ST segment interpretation may be unreliable, even with highly filtered monitors).
 - The anesthesiologist should make sure that all monitors used in zone IV are safe/conditional for the scan.
 - A monitor should be available to view vital signs from zone III when the anesthesia care provider is not in zone IV.
 - Additional care should be taken in positioning electrocardiogram and other monitor leads to eliminate burns, even with nonferromagnetic leads.
- Airway management
 - The anesthesiologist should have an advance plan in place to deal with instrumentation of the airway and common airway problems (e.g., obstruction, secretions, laryngospasm, apnea, and hypoventilation) when patients are in an MRI environment.

- o If the patient is at risk for airway compromise, more aggressive airway management (*e.g.*, use of a tracheal tube or laryngeal mask airway), should be instituted because the patient's airway may be less accessible when the patient is in the scanner.
- o Complex airway management (*e.g.*, fiberoptic intubation) should be performed in a controlled environment outside zone IV.
- o Alternative airway devices should be immediately available in the MRI suite.
- o Suction equipment should be immediately accessible to the patient's airway at all times.

VI. Management of Emergencies

- When a patient has a medical emergency (*e.g.*, cardiopulmonary arrest) in the MRI scanner, the following should occur: (1) immediately remove the patient from zone IV while initiating CPR, if indicated, (2) call for help, and (3) transport the patient to a previously designated safe area for resuscitation that is not in zone IV.
- o This location should be as close to zone IV as possible so as not to delay resuscitation efforts and should contain the following resuscitation equipment: a defibrillator, vital signs monitors, and a code cart that includes resuscitation drugs, airway equipment, oxygen, and suction.
- When a fire occurs in the MRI suite, team members should perform their preassigned fire management task as quickly as possible, in accordance with the ASA practice advisory for the prevention and management of operating room fires.
- o If a team member cannot rapidly perform his or her task in the predetermined order, other team members should perform their tasks without waiting.
- o When a team member has completed a preassigned task, he or she should help other members perform tasks that are not yet complete.
- In the case of projectile emergencies, team members should perform their institution's protocol in reaction to this occurrence.
- o If possible, immediately remove the patient from zone IV and discontinue the scan.
- o If the patient is injured, proceed with medical emergency management as indicated above.
- o A controlled quench may be necessary in order to remove the patient from the bore.
- When a quench occurs, team members should perform their institution's protocol in reaction to this occurrence. If possible: (1) immediately remove the patient from zone IV and (2) immediately administer oxygen to the patient.

††† Unless otherwise specified, outcomes for the listed interventions refer to the occurrence of safety-based outcomes.

o Powerful static magnetic fields may persist after a quench, and therefore, the usual precautions apply when entering zone IV.

- Emergency response personnel should be restricted from entering zone IV during any environmental emergency because of the persistent magnetic field.

VII. Postprocedure Care

- The anesthesiologist should collaborate with the radiologist and other staff in the postprocedure care of the patient.
- Patients receiving sedation or anesthesia within the MRI suite should have access to postanesthetic care consistent with that provided in other areas of the institution, including transport to other recovery rooms, dedicated intensive care, or recovery areas within the MRI suite.
- In all situations, intensive care and recovery areas should include access to vital sign monitors, oxygen, suction, resuscitation equipment, and trained personnel.
- Patients should be provided oral and written discharge instructions.

Appendix 3. Methods and Analyses

A. State of the Literature

For this updated Advisory, a review of studies used in the development of original Advisory was combined with studies published subsequent to approval of the original Advisory in 2009.* The scientific assessment of this updated Advisory was based on evidence linkages or statements regarding potential relationships between patient care interventions and safety outcomes in the MRI suite. The evidence linkage *interventions* are listed below.†††

Education

- MRI education for magnet hazards
- MRI education for monitoring limitations
- MRI education for long-term health hazards

Screening of Anesthesia Care Providers and Ancillary Support Personnel

- Mandatory screening of all personnel entering zone III or IV

Patient Screening

- Patient-related risks for adverse outcomes related to MRI
- Equipment-related risks for adverse outcomes related to MRI

Preparation

- Planning for the anesthetic care of the patient for the scan
- Planning for rapidly summoning additional personnel in the event of an emergency

Patient Management during MRI

- Monitoring during MRI
- Anesthetic care during MRI
- Airway management during MRI

Management of Emergencies

- Medical emergencies
- Environmental emergencies

Postprocedure Care

- Postprocedure care consistent with that provided for other areas of the institution

For the literature review, potentially relevant studies were identified *via* electronic and manual searches of the literature. The updated searches covered a 7-yr period from 2008 through 2014. Over 200 new citations that addressed topics related to the evidence linkages were identified. These articles were reviewed and those meeting the appropriate criteria as outlined in the “Focus” section above were combined with pre-2009 articles used in the original Advisory, resulting in a total of 183 articles that contained direct linkage-related evidence. A complete bibliography used to develop these Guidelines, organized by section, is available as Supplemental Digital Content 2, <http://links.lww.com/ALN/B99>. No evidence linkage contained enough studies with well-defined experimental designs and statistical information to conduct a quantitative analysis (*i.e.*, meta-analysis).

For the original Advisory, interobserver agreement among Task Force members and two methodologists was established by interrater reliability testing. Agreement levels using a κ statistic for two-rater agreement pairs were as follows: (1) type of study design, $\kappa = 0.49$ to 0.85; (2) type of analysis, $\kappa = 0.54$ to 0.93; (3) evidence linkage assignment, $\kappa = 0.77$ to 1.00; and (4) literature inclusion for database, $\kappa = 0.78$ to 1.00. Three-rater chance-corrected agreement values were (1) study design, $Sav = 0.65$, $Var(Sav) = 0.009$; (2) type of analysis, $Sav = 0.69$, $Var(Sav) = 0.010$; (3) linkage

assignment, $Sav = 0.85$, $Var(Sav) = 0.004$; and (4) literature database inclusion, $Sav = 0.85$, $Var(Sav) = 0.013$. These values represent moderate to high levels of agreement.

B. Consensus-based Evidence

For the original Advisory, consensus was obtained from multiple sources, including (1) survey opinion from consultants who were selected based on their knowledge or expertise in MRI, (2) survey opinions solicited from active members of the ASA, (3) testimony from attendees of a publicly held open forum at two national anesthesia meetings, (4) Internet commentary, and (5) Task Force opinion and interpretation. The survey rate of return was 63% ($n = 50$ of 79) for the consultants, and 989 surveys were received from active ASA members. Results of the surveys are reported in tables 1 and 2 and in the text of the Advisory.

The consultants were asked to indicate which, if any, of the evidence linkages would change their clinical practices if the Advisory was instituted. The rate of return was 29% ($n = 23$ of 79). The percent of responding consultants expecting a change in their practice associated with each linkage topic was as follows: (1) education, 30%; (2) screening of anesthesia care providers and ancillary support personnel, 13%; (3) patient screening, 26%; (4) preparation, 13%; (5) patient management during MRI: monitoring, 4%; (6) patient management during MRI: anesthetic care, 0%; (7) patient management during MRI: airway, 0%; (8) patient management during MRI: emergencies, 13%; and (9) postprocedure care, 9%. Seventy-four percent indicated that their clinical practice will not need new equipment, supplies, or training in order to implement the Practice Advisory. Eighty-five percent indicated that the Advisory would not require ongoing changes in their practice which will affect costs. Ninety-five percent of the respondents indicated that the Advisory would have *no effect* on the amount of time spent on a typical case, and 5% indicated that there would be a 10-min increase in the amount spent on a typical case with the implementation of this Advisory.

Table 1. Consultant Survey Responses

	N	Percent Responding to Each Item				
		Strongly Agree	Agree	Uncertain	Disagree	Strongly Disagree
Education						
1. All anesthesiologists should have general safety education on the unique physical environment of the MRI scanner	50	90.0*	10.1	0.0	0.0	0.0
2. All anesthesiologists should have specific education regarding the features of individual scanners within their institutions	50	58.0*	38.0*	2.0	2.0	0.0
3. All anesthesiologists should work in collaboration with radiologists, technologists, and physicists within their institutions to develop safety training programs	50	80.0*	16.0	2.0	2.0	0.0
Screening of anesthesia care providers and ancillary support personnel						
4. The anesthesiologist should work in collaboration with the MRI medical director or designee to insure that all anesthesia team personnel entering zone III or IV have been properly screened	50	60.0*	34.0	4.0	2.0	0.0
Patient screening						
5a. For every case, the anesthesiologist should communicate with the patient and radiologist or referring physician to determine whether the patient has a high-risk medical condition	50	58.0*	20.0	10.0	10.0	2.0
5b. If the patient presents with high-risk medical condition, the anesthesiologist should collaborate with all participants, including the referring physician, radiologist, and technologist, to determine how the patient will be managed during the MRI procedure	50	58.0*	26.0	4.0	10.0	2.0
5c. For patients with acute or severe renal insufficiency, the anesthesiologist should not administer gadolinium because of the elevated risk of nephrogenic systemic fibrosis	49	34.7	34.7*	26.5	4.1	0.0
6a. For every case, the anesthesiologist should communicate with the radiologist or referring physician to determine whether the patient requires equipment that may pose a risk during the scan	49	28.6	36.7*	18.4	14.3	2.0
6b. Anesthesiologist should determine the safety and effectiveness of the equipment needed by the patient during the procedure for each MRI location	50	46.0	34.0*	10.0	10.0	0.0
6c. Anesthesiologists should work with their institutions to properly identify and label anesthesia-related equipment according to convention (safe, unsafe, or conditional) for each MRI scanner	50	74.0*	26.0	0.0	0.0	0.0
6d. Care should be taken to assure that anesthesia equipment does not interfere with image acquisition or quality	50	68.0*	30.0	2.0	0.0	0.0

Downloaded from http://pubs.asahq.org/anesthesiology/article-pdf/122/3/495/369655/20150300_0-00012.pdf by guest on 22 January 2022

(Continued)

Table 1. Continued

	N	Percent Responding to Each Item				
		Strongly Agree	Agree	Uncertain	Disagree	Strongly Disagree
7a. In general, MRI should not be performed on patients with implanted electronic devices	50	22.0	48.0*	14.0	14.0	2.0
7b. When MRI is considered essential by the referring physician and consulting radiologist, a plan for managing patient with implanted electronic devices during the scan should be developed in collaboration with the referring physician, medical director, or on-site radiologist and other appropriate consultants	50	72.0*	26.0	0.0	2.0	0.0
Preparation						
8. For every case, the anesthesiologist should prepare, with support personnel, a plan for providing optimal anesthetic care within the special environment of the MRI suite	50	72.0*	26.0	0.0	2.0	0.0
9. The anesthesiologist should communicate with the radiology personnel to determine the requirements for the scan (e.g., duration of the scan, position of the patient or area of the body in the scanner, positioning of receiver coils, and need for periods of paused respiration)	50	68.0*	30.0	0.0	2.0	0.0
10. The anesthesiologist should collaborate with the MRI technologist and/or facility biomedical engineer to determine and demarcate the optimal and safe location of movable equipment in relation to the gauss lines within the MRI suite	50	62.0*	34.0	2.0	0.0	2.0
11. Because line of sight within the bore will vary depending on the facility, the anesthesiologist should choose a location or position for optimal patient observation and vigilance during delivery of care, whether in zone III or IV	50	64.0*	28.0	8.0	0.0	0.0
12. The anesthesiologist should prepare a plan for rapidly summoning additional personnel in the event of an emergency	50	82.0*	18.0	0.0	0.0	0.0
Patient management during MRI						
Monitoring						
13. MRI patients should be monitored in a manner consistent with the ASA "Standards for Basic Anesthesia Monitoring"	50	72.0*	26.0	2.0	0.0	0.0
14. Anesthesiologists should be familiar with the expected limitations of available monitoring equipment	50	84.0*	16.0	0.0	0.0	0.0
15. The anesthesiologist should make sure that all monitors used in zone IV are safe/conditional for the scan	50	82.0*	12.0	0.0	4.0	2.0
16. A monitor should be available to view vital signs from zone IV when the anesthesia care provider is not in zone IV	50	78.0*	16.0	6.0	0.0	0.0

Downloaded from http://pubs.asahq.org/anesthesiology/article-pdf/122/3/495/369655/20150300_0-00012.pdf by guest on 22 January 2022

(Continued)

Table 1. Continued

	N	Percent Responding to Each Item				
		Strongly Agree	Agree	Uncertain	Disagree	Strongly Disagree
Anesthetic care						
17. In general, because MRI is a nonpainful procedure, lighter levels of anesthesia may be appropriate, recognizing that institutional circumstances, patient preference, and anesthesiologist preference may warrant more aggressive airway management and deeper anesthetic levels	50	58.0*	34.0	2.0	6.0	0.0
18. Anesthesiologists should ensure that patients who receive moderate or deep sedation are monitored in a manner consistent with their institution's protocol for monitoring similarly sedated patients elsewhere in the facility	50	82.0*	18.0	0.0	0.0	0.0
19. Equipment and drugs for anesthetic care in the MRI suite should mirror what is available in the OR	50	76.0*	18.0	4.0	2.0	0.0
20a. When an MRI safe/conditional anesthesia machine is not available, inhalation anesthetics may be administered from an anesthesia machine inside zone III via an elongated circuit through a wave guide	50	6.0	30.0	24.0*	34.0	6.0
20b. If total intravenous anesthesia is used, it should be administered by using: (1) MRI safe/conditional pumps in zone IV, (2) traditional (<i>i.e.</i> , MRI unsafe) pumps in zone III with the intravenous tubing passed through a wave guide, or (3) periodic bolus injections in either zones III or IV	50	30.0	58.0*	10.0	2.0	0.0
Airway management						
21. The anesthesiologist should have an advance plan in place to deal with instrumentation of the airway and common airway problems when patients are in an MRI environment	50	88.0*	12.0	0.0	0.0	0.0
22. If the patient is at risk for airway compromise, more aggressive airway management (<i>e.g.</i> , use of a tracheal tube or LMA) should be instituted because the patient's airway may be less accessible when the patient is in the scanner	50	58.0*	34.0	6.0	2.0	0.0
23. Complex airway management (<i>e.g.</i> , fiberoptic intubation) should be performed in a controlled environment outside zone IV	50	76.6*	18.0	6.0	0.0	0.0
24. Alternative airway devices should be immediately available in the MRI suite	50	78.0*	16.0	4.0	2.0	0.0
25. Suction equipment should be immediately accessible to the patient's airway at all times	49	91.8*	6.1	0.0	2.1	0.0

Downloaded from http://pubs.asahq.org/anesthesiology/article-pdf/122/3/495/369655/20150300_0-00012.pdf by guest on 22 January 2022

(Continued)

Table 1. Continued

	N	Percent Responding to Each Item				
		Strongly Agree	Agree	Uncertain	Disagree	Strongly Disagree
Management of emergencies						
26a. When a patient has a medical emergency (e.g., cardiopulmonary arrest) in the MRI scanner, the following should occur: (1) initiate CPR, when needed, while immediately removing the patient from zone IV, (2) call for help, and (3) transport the patient to a previously designated safe location in proximity to the MRI suite	49	81.6*	18.4	0.0	0.0	0.0
26b. The designated safe location should contain the following resuscitation equipment: a defibrillator, vital signs monitors, and a code cart that includes resuscitation drugs, airway equipment, oxygen, and suction	49	85.7*	14.3	0.0	0.0	0.0
27. When a fire occurs in the MRI suite, team members should perform their preassigned fire management task as quickly as possible, in accordance with the ASA "Practice Advisory for the Prevention and Management of Operating Room Fires"	49	71.4*	14.3	14.3	0.0	0.0
28a. When a quench occurs, team members should perform their institution's protocol in reaction to this occurrence	49	65.3*	28.6	6.1	0.0	0.0
28b. When a quench occurs, if possible: (1) immediately remove the patient from zone IV and (2) immediately administer oxygen to the patient	49	55.1*	22.5	20.4	2.0	0.0
29. Since powerful static magnetic fields may persist after a quench or fire, emergency response personnel should be restricted from entering zone IV	49	44.9	26.5*	20.4	8.2	0.0
Postprocedure care						
30. The anesthesiologist should collaborate with the radiologist and other staff in the postanesthetic care of the patient	50	62.0*	28.0	0.0	10.0	0.0
31. Patients receiving sedation or anesthesia within the MRI suite should have access to postanesthetic care consistent with that provided in other areas of the institution	50	82.0*	16.0	0.0	2.0	0.0
32. In all situations, intensive care and recovery areas should include access to vital sign monitors, oxygen, suction, and trained personnel	50	84.0*	14.0	2.0	0.0	0.0
33. Patients should be provided written discharge instructions	50	66.6*	32.0	2.0	0.0	0.0

N is the number of consultants who responded to each item.

* Indicates the median.

ASA = American Society of Anesthesiologists; CPR = cardiopulmonary resuscitation; LMA = laryngeal mask airway; MRI = magnetic resonance imaging; OR = operating room.

Table 2. ASA Membership Survey Responses

	N	Percent Responding to Each Item				
		Agree	Agree	Uncertain	Strongly Disagree	Disagree
Education						
1. All anesthesiologists should have general safety education on the unique physical environment of the MRI scanner	989	73.6*	25.0	1.0	0.2	0.2
2. All anesthesiologists should have specific education regarding the features of individual scanners within their institutions	986	33.7	42.4*	18.4	5.1	0.5
3. All anesthesiologists should work in collaboration with radiologists, technologists, and physicists within their institutions to develop safety training programs	989	47.0	41.3*	8.1	3.4	0.2
Screening of anesthesia care providers and ancillary support personnel						
4. The anesthesiologist should work in collaboration with the MRI medical director or designee to insure that all anesthesia team personnel entering zone III or IV have been properly screened	988	43.5	45.5*	8.0	2.8	0.2
Patient screening						
5a. For every case, the anesthesiologist should communicate with the patient and radiologist or referring physician to determine whether the patient has a high-risk medical condition	988	54.7*	30.6	6.7	6.9	1.2
5b. If the patient presents with high-risk medical condition, the anesthesiologist should collaborate with all participants, including the referring physician, radiologist, and technologist, to determine how the patient will be managed during the MRI procedure	983	53.8*	34.2	4.6	6.4	1.0
5c. For patients with acute or severe renal insufficiency, the anesthesiologist should not administer gadolinium because of the elevated risk of nephrogenic systemic fibrosis	981	23.7	29.5*	42.9	3.7	0.3
6a. For every case, the anesthesiologist should communicate with the radiologist or referring physician to determine whether the patient requires equipment that may pose a risk during the scan	976	36.2	38.1*	10.5	12.9	2.4
6b. Anesthesiologist should determine the safety and effectiveness of the equipment needed by the patient during the procedure for each MRI location	977	46.9	38.4*	6.7	6.4	1.7
6c. Anesthesiologists should work with their institutions to properly identify and label anesthesia-related equipment according to convention (safe, unsafe, or conditional) for each MRI scanner	981	56.6*	38.8	3.0	1.5	0.1
6d. Care should be taken to assure that anesthesia equipment does not interfere with image acquisition or quality	980	46.2	49.4	3.1	1.0	0.3
7a. In general, MRI should not be performed on patients with implanted electronic devices	982	27.8	42.9*	22.2	6.7	0.4

Downloaded from http://pubs.asahq.org/anesthesiology/article-pdf/122/3/495/369655/20150300_0-00012.pdf by guest on 22 January 2022

(Continued)

Table 2. Continued

	N	Percent Responding to Each Item				
		Agree	Agree	Uncertain	Strongly Disagree	Disagree
7b. When MRI is considered essential by the referring physician and consulting radiologist, a plan for managing patient with implanted electronic devices during the scan should be developed in collaboration with the referring physician, medical director, or on-site radiologist and other appropriate consultants	979	53.7*	41.6	2.8	1.3	0.6
Preparation						
8. For every case, the anesthesiologist should prepare, with support personnel, a plan for providing optimal anesthetic care within the special environment of the MRI suite	977	63.2*	33.6	1.7	1.1	0.4
9. The anesthesiologist should communicate with the radiology personnel to determine the requirements for the scan (e.g., duration of the scan, position of the patient or area of the body in the scanner, positioning of receiver coils, and need for periods of paused respiration)	980	64.5*	33.1	1.2	1.2	0.0
10. The anesthesiologist should collaborate with the MRI technologist and/or facility biomedical engineer to determine and demarcate the optimal and safe location of movable equipment in relation to the gauss lines within the MRI suite	974	48.8	43.2*	6.7	1.2	0.1
11. Because line of sight within the bore will vary depending on the facility, the anesthesiologist should choose a location or position for optimal patient observation and vigilance during delivery of care, whether in zone III or IV	982	53.8*	39.3	5.1	1.3	0.5
12. The anesthesiologist should prepare a plan for rapidly summoning additional personnel in the event of an emergency	978	70.6*	28.0	1.0	0.4	0.0
Patient management during an MRI						
Monitoring						
13. MRI patients should be monitored in a manner consistent with the ASA "Standards for Basic Anesthesia Monitoring"	977	73.7*	22.5	1.4	1.8	0.5
14. Anesthesiologists should be familiar with the expected limitations of available monitoring equipment	978	71.9*	27.8	0.2	0.0	0.1
15. The anesthesiologist should make sure that all monitors used in zone IV are safe/conditional for the scan	977	68.3*	27.7	2.4	1.3	0.3
16. A monitor should be available to view vital signs from zone IV when the anesthesia care provider is not in zone IV	976	71.6*	24.7	3.5	0.1	0.1
Anesthetic care						
17. In general, because MRI is a nonpainful procedure, lighter levels of anesthesia may be appropriate, recognizing that institutional circumstances, patient preference, and anesthesiologist preference may warrant more aggressive airway management and deeper anesthetic levels	976	53.3*	43.3	1.6	1.2	0.5

Downloaded from http://pubs.asahq.org/anesthesiology/article-pdf/122/3/495/369655/20150300_0-00012.pdf by guest on 22 January 2022

(Continued)

Table 2. Continued

	N	Percent Responding to Each Item				
		Agree	Agree	Uncertain	Strongly Disagree	Disagree
18. Anesthesiologists should ensure that patients who receive moderate or deep sedation are monitored in a manner consistent with their institution's protocol for monitoring similarly sedated patients elsewhere in the facility	976	66.9*	30.2	1.3	1.1	0.4
19. Equipment and drugs for anesthetic care in the MRI suite should mirror what is available in the OR	980	61.4*	33.3	3.3	2.0	0.0
20a. When an MRI safe/conditional anesthesia machine is not available, inhalation anesthetics may be administered from an anesthesia machine inside zone III via an elongated circuit through a wave guide	975	10.3	22.8	31.0*	29.1	6.9
20b. If total intravenous anesthesia is used, it should be administered by using: (1) MRI safe/conditional pumps in zone IV, (2) traditional (<i>i.e.</i> , MRI unsafe) pumps in zone III with the intravenous tubing passed through a wave guide, or (3) periodic bolus injections in either zones III or IV	978	24.0	53.2*	12.0	8.7	2.2
Airway management						
21. The anesthesiologist should have an advance plan in place to deal with instrumentation of the airway and common airway problems when patients are in an MRI environment	979	79.6*	20.1	0.3	0.0	0.0
22. If the patient is at risk for airway compromise, more aggressive airway management (<i>e.g.</i> , use of a tracheal tube or LMA) should be instituted because the patient's airway may be less accessible when the patient is in the scanner	981	72.8*	23.0	2.6	1.6	0.0
23. Complex airway management (<i>e.g.</i> , fiberoptic intubation) should be performed in a controlled environment outside zone IV	981	71.9*	24.5	2.7	1.0	0.0
24. Alternative airway devices should be immediately available in the MRI suite	981	70.2*	26.1	2.5	1.2	0.0
25. Suction equipment should be immediately accessible to the patient's airway at all times	978	86.4*	12.8	0.7	0.1	0.0
Management of emergencies						
26a. When a patient has a medical emergency (<i>e.g.</i> , cardiopulmonary arrest) in the MRI scanner, the following should occur: (1) initiate CPR, when needed, while immediately removing the patient from zone IV, (2) call for help, and (3) transport the patient to a previously designated safe a location in proximity to the MRI suite	976	72.2*	25.7	1.8	0.2	0.0
26b. The designated safe location should contain the following resuscitation equipment: a defibrillator, vital signs monitors, and a code cart that includes resuscitation drugs, airway equipment, oxygen, and suction	978	79.4*	19.9	0.5	0.1	0.1

Downloaded from http://pubs.asahq.org/anesthesiology/article-pdf/122/3/495/369655/20150300_0-00012.pdf by guest on 22 January 2022

(Continued)

Table 2. Continued

	N	Percent Responding to Each Item				
		Agree	Agree	Uncertain	Strongly Disagree	Disagree
27. When a fire occurs in the MRI suite, team members should perform their preassigned fire management task as quickly as possible, in accordance with the ASA "Practice Advisory for the Prevention and Management of Operating Room Fires"	970	65.4*	30.4	4.5	0.0	0.1
28a. When a quench occurs, team members should perform their institution's protocol in reaction to this occurrence	967	49.1	29.7*	21.2	0.0	0.0
28b. When a quench occurs, if possible: (1) immediately remove the patient from zone IV and (2) immediately administer oxygen to the patient	963	49.0	27.6*	22.5	0.7	0.1
29. Since powerful static magnetic fields may persist after a quench or fire, emergency response personnel should be restricted from entering zone IV	973	22.3	28.7*	41.0	7.2	0.8
Postprocedure care						
30. The anesthesiologist should collaborate with the radiologist and other staff in the postanesthetic care of the patient	979	41.5	41.5*	4.9	10.5	1.6
31. Patients receiving sedation or anesthesia within the MRI suite should have access to postanesthetic care consistent with that provided in other areas of the institution	981	72.0*	27.1	0.5	0.4	0.0
32. In all situations, intensive care and recovery areas should include access to vital sign monitors, oxygen, suction, and trained personnel	977	77.7*	22.3	0.0	0.0	0.0
33. Patients should be provided written discharge instructions	981	53.1*	39.4	5.9	1.5	0.1

N is the number of ASA members who responded to each item.

* Indicates the median.

ASA = American Society of Anesthesiologists; CPR = cardiopulmonary resuscitation, LMA = laryngeal mask airway; MRI = magnetic resonance imaging; OR = operating room.

Acknowledgments

Supported by the American Society of Anesthesiologists under the direction of Jeffrey L. Apfelbaum, M.D., Chair, Committee on Standards and Practice Parameters.

Competing Interests

The authors declare no competing interests.

Correspondence

Address correspondence to the American Society of Anesthesiologists: 1061 American Lane, Schaumburg, Illinois 60173. This updated Practice Advisory, and all ASA Practice Parameters, may be obtained at no cost through the Journal Web site, www.anesthesiology.org.

References

1. Practice advisory on anesthetic care for magnetic resonance imaging: A report by the American Society of Anesthesiologists. Anesth Analg 2009; 109:1335–47.
2. Expert Panel on MR Safety: Kanal E, Barkovich AJ, Bell C, Borgstede JP, Bradley WG Jr, Froelich JW, Gimbel JR, Gosbee JW, Kuhni-Kaminski E, Larson PA, Lester JW Jr, Nyenhuis J, Schaefer DJ, Sebek EA, Weinreb J, Wilkoff BL, Woods TO, Lucey L, Hernandez D: ACR guidance document on MR safe practices: 2013. J Magn Reson Imaging 2013; 37:501–30.
3. Hundley WG, Bluemke D, Bogaert JG, Friedrich MG, Higgins CB, Lawson MA, McConnell MV, Raman SV, van Rossum AC, Flamm S, Kramer CM, Nagel E, Neubauer S: Society for Cardiovascular Magnetic Resonance guidelines for reporting cardiovascular magnetic resonance examinations. J Cardiovasc Magn Reson 2009; 11:5.
4. Kanal E, Borgstede JP, Barkovich AJ, Bell C, Bradley WG, Felmlee JP, Froelich JW, Kuhni-Kaminski EM, Keeler EK, Lester JW, Scoumis EA, Zaremba LA, Zinniger MD; American College of Radiology; American College of Radiology White Paper on MR Safety. AJR Am J Roentgenol 2002; 178:1335–47.
5. Kanal E, Barkovich AJ, Bell C, Borgstede JP, Bradley WG Jr, Froelich JW, Gilk T, Gimbel JR, Gosbee J, Kuhni-Kaminski E, Lester JW Jr, Nyenhuis J, Parag Y, Schaefer DJ, Sebek-Scoumis

- EA, Weinreb J, Zaremba LA, Wilcox P, Lucey L, Sass N; ACR Blue Ribbon Panel on MR Safety: ACR guidance document for safe MR practices: 2007. *AJR Am J Roentgenol* 2007; 188:1447–74
6. Kanal E, Gillen J, Evans JA, Savitz DA, Shellock FG: Survey of reproductive health among female MR workers. *Radiology* 1993; 187:395–9
 7. Philbin MK, Taber KH, Hayman LA: Preliminary report: Changes in vital signs of term newborns during MR. *AJNR Am J Neuroradiol* 1996; 17:1033–6
 8. Battin M, Maalouf EF, Counsell S, Herlihy A, Hall A, Azzopardi D, Edwards AD: Physiological stability of preterm infants during magnetic resonance imaging. *Early Hum Dev* 1998; 52:101–10
 9. Taber KH, Hayman LA, Northrup SR, Maturi L: Vital sign changes during infant magnetic resonance examinations. *J Magn Reson Imaging* 1998; 8:1252–6
 10. Gangarosa RE, Minnis JE, Nobbe J, Praschan D, Genberg RW: Operational safety issues in MRI. *Magn Reson Imaging* 1987; 5:287–92
 11. Broome DR, Girguis MS, Baron PW, Cottrell AC, Kjellin I, Kirk GA: Gadodiamide-associated nephrogenic systemic fibrosis: Why radiologists should be concerned. *AJR Am J Roentgenol* 2007; 188:586–92
 12. Grobner T: Gadolinium—A specific trigger for the development of nephrogenic fibrosing dermopathy and nephrogenic systemic fibrosis? *Nephrol Dial Transplant* 2006; 21:1104–8
 13. Khurana A, Runge VM, Narayanan M, Greene JF Jr, Nickel AE: Nephrogenic systemic fibrosis: A review of 6 cases temporally related to gadodiamide injection. *Invest Radiol* 2007; 42:139–45
 14. Marckmann P, Skov L, Rossen K, Dupont A, Damholt MB, Heaf JG, Thomsen HS: Nephrogenic systemic fibrosis: Suspected etiological role of gadodiamide used for contrast-enhanced magnetic resonance imaging. *J Am Soc Nephrol* 2006; 17:2359–62
 15. Dharnidharka VR, Wesson SK, Fennell RS: Gadolinium and nephrogenic fibrosing dermopathy in pediatric patients. *Pediatr Nephrol* 2007; 22:1395
 16. Thakral C, Alhariri J, Abraham JL: Long-term retention of gadolinium in tissues from nephrogenic systemic fibrosis patient after multiple gadolinium-enhanced MRI scans: Case report and implications. *Contrast Media Mol Imaging* 2007; 2:199–205
 17. Kelly WM, Paglen PG, Pearson JA, San Diego AG, Solomon MA: Ferromagnetism of intraocular foreign body causes unilateral blindness after MR study. *AJNR Am J Neuroradiol* 1986; 7:243–5
 18. Jackson JG, Acker JD: Permanent eyeliner and MR imaging. *AJR Am J Roentgenol* 1987; 149:1080
 19. Lund G, Nelson JD, Wirtschafter JD, Williams PA: Tatooing of eyelids: Magnetic resonance imaging artifacts. *Ophthalmol Surg* 1986; 17:550–3
 20. Wagle WA, Smith M: Tattoo-induced skin burn during MR imaging. *AJR Am J Roentgenol* 2000; 174:1795
 21. Applebaum E, Valvassori G: Further studies on the effects of magnetic resonance fields on middle ear implants. *Ann Otol Rhinol Laryngol* 1990; 99:801–4
 22. Barratino D, Henkelman RM: Magnetic resonance imaging and surgical clips. *Can J Surg* 1984; 27:509–10, 512
 23. Becker RL, Norfray JF, Teitelbaum GP, Bradley WG Jr, Jacobs JB, Wacaser L, Rieman RL: MR imaging in patients with intracranial aneurysm clips. *AJNR Am J Neuroradiol* 1988; 9:885–9
 24. Brown MA, Carden JA, Coleman RE, McKinney R Jr, Spicer LD: Magnetic field effects on surgical ligation clips. *Magn Reson Imaging* 1987; 5:443–53
 25. Chou CK, McDougall JA, Chan KW: RF heating of implanted spinal fusion stimulator during magnetic resonance imaging. *IEEE Trans Biomed Eng* 1997; 44:367–73
 26. 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 Am J Roentgenol* 1981; 137:857–60
 27. Dujovny M, Kossovsky N, Kossowsky R, Valdivia R, Suk JS, Diaz FG, Berman SK, Cleary W: Aneurysm clip motion during magnetic resonance imaging: *In vivo* experimental study with metallurgical factor analysis. *Neurosurgery* 1985; 17:543–8
 28. Edwards MB, Taylor KM, Shellock FG: Prosthetic heart valves: Evaluation of magnetic field interactions, heating, and artifacts at 1.5 T. *J Magn Reson Imaging* 2000; 12:363–9
 29. Gegauff AG, Laurell KA, Thavendrarajah A, Rosenstiel SF: A potential MRI hazard: Forces on dental magnet keepers. *J Oral Rehabil* 1990; 17:403–10
 30. Hartnell GG, Spence L, Hughes LA, Cohen MC, Saouaf R, Buff B: Safety of MR imaging in patients who have retained metallic materials after cardiac surgery. *AJR Am J Roentgenol* 1997; 168:1157–9
 31. Hug J, Nagel E, Bornstedt A, Schnackenburg B, Oswald H, Fleck E: Coronary arterial stents: Safety and artifacts during MR imaging. *Radiology* 2000; 216:781–7
 32. Kaste S, Laningham F, Stazzone M, Brown SD, Emery K, Newman B, Racadio J, Estroff J, Brill P, Mendelson KL, Slovis TL, Brush D; Society for Pediatric Radiology Safety Committee: Safety in pediatric MR and cardiac CT: Results of a membership survey of the Society for Pediatric Radiology-2006. *Pediatr Radiol* 2007; 37:409–12
 33. Kean DM, Worthington BS, Firth JL, Hawkes RC: The effects of magnetic resonance imaging on different types of micro-surgical clips. *J Neurol Neurosurg Psychiatry* 1985; 48:286–7
 34. Klucznik RP, Carrier DA, Pyka R, Haid RW: Placement of a ferromagnetic intracerebral aneurysm clip in a magnetic field with a fatal outcome. *Radiology* 1993; 187:855–6
 35. Konings MK, Bartels IW, Smits HF, Bakker CJ: Heating around intravascular guidewires by resonating RF waves. *J Magn Reson Imaging* 2000; 12:79–85
 36. Laakman RW, Kaufman B, Han JS, Nelson AD, Clampitt M, O'Block AM, Haaga JR, Alfidi RJ: MR imaging in patients with metallic implants. *Radiology* 1985; 157:711–4
 37. Moscatel MA, Shellock FG, Morisoli SM: Biopsy needles and devices: Assessment of ferromagnetism and artifacts during exposure to a 1.5-T MR system. *J Magn Reson Imaging* 1995; 5:369–72
 38. Pruefer D, Kalden P, Schreiber W, Dahm M, Buerke M, Thelen M, Oelert H: *In vitro* investigation of prosthetic heart valves in magnetic resonance imaging: Evaluation of potential hazards. *J Heart Valve Dis* 2001; 10:410–4
 39. Romner B, Olsson M, Ljunggren B, Holtas S, Saveland H, Brandt L, Persson B: Magnetic resonance imaging and aneurysm clips. *J Neurosurg* 1989; 70:426–31
 40. Shellock FG: Prosthetic heart valves and annuloplasty rings: Assessment of magnetic field interactions, heating, and artifacts at 1.5 Tesla. *J Cardiovasc Magn Reson* 2001; 3:317–24
 41. Shellock FG: Biomedical implants and devices: Assessment of magnetic field interactions with a 3.0-Tesla MR system. *J Magn Reson Imaging* 2002; 16:721–32
 42. Shellock FG, Crues JV: High-field-strength MR imaging and metallic biomedical implants: An *ex vivo* evaluation of deflection forces. *AJR Am J Roentgenol* 1988; 151:389–92
 43. Soulard RL, Budinger TF, Higgins CB: Magnetic resonance imaging of prosthetic heart valves. *Radiology* 1985; 154:705–7
 44. Teitelbaum GP, Lin MC, Watanabe AT, Norfray JF, Young TI, Bradley WG Jr: Ferromagnetism and MR imaging: Safety of carotid vascular clamps. *AJNR Am J Neuroradiol* 1990; 11:267–72
 45. von Roemeling R, Lanning RM, Eames FA: MR imaging of patients with implanted drug infusion pumps. *J Magn Reson Imaging* 1991; 1:77–81
 46. Wichmann W, Von Ammon K, Fink U, Weik T, Yasargil GM: Aneurysm clips made of titanium: Magnetic characteristics and artifacts in MR. *AJNR Am J Neuroradiol* 1997; 18:939–44

47. Dempsey MF, Condon B: Thermal injuries associated with MRI. *Clin Radiol* 2001; 56:457–65
48. Kugel H, Bremer C, Püschel M, Fischbach R, Lenzen H, Tombach B, Van Aken H, Heindel W: Hazardous situation in the MR bore: Induction in ECG leads causes fire. *Eur Radiol* 2003; 13:690–4
49. Anonymous: ECRI: The safe use of equipment in the magnetic resonance environment. *Health Devices* 2001; 30:421–4
50. Bashein G, Syrory G: Burns associated with pulse oximetry during magnetic resonance imaging. *ANESTHESIOLOGY* 1991; 75:382–3
51. Brown TR, Goldstein B, Little J: Severe burns resulting from magnetic resonance imaging with cardiopulmonary monitoring. Risks and relevant safety precautions. *Am J Phys Med Rehabil* 1993; 72:166–7
52. Hall SC, Stevenson GW, Suresh S: Burn associated with temperature monitoring during magnetic resonance imaging. *ANESTHESIOLOGY* 1992; 76:152
53. Shellock FG, Slimp GL: Severe burn of the finger caused by using a pulse oximeter during MR imaging. *AJR Am J Roentgenol* 1989; 153:1105
54. Williams EJ, Jones NS, Carpenter TA, Bunch CS, Menon DK: Testing of adult and paediatric ventilators for use in a magnetic resonance imaging unit. *Anaesthesia* 1999; 54:969–74
55. Anonymous: ECRI hazard report: Patient death illustrates the importance of adhering to safety precautions in magnetic resonance environments. *Health Devices* 2001; 30:311–4
56. Chaljub G, Kramer LA, Johnson RF III, Johnson RF Jr, Singh H, Crow WN: Projectile cylinder accidents resulting from the presence of ferromagnetic nitrous oxide or oxygen tanks in the MR suite. *AJR Am J Roentgenol* 2001; 177:27–30
57. Colletti PM: Size “H” oxygen cylinder: Accidental MR projectile at 1.5 Tesla. *J Magn Reson Imaging* 2004; 19:141–3
58. Achenbach S, Moshage W, Diem B, Bieberle T, Schibgilla V, Bachmann K: Effects of magnetic resonance imaging on cardiac pacemakers and electrodes. *Am Heart J* 1997; 134:467–73
59. Anfinsen OG, Berntsen RF, Aass H, Kongsgaard E, Amlie JP: Implantable cardioverter defibrillator dysfunction during and after magnetic resonance imaging. *Pacing Clin Electrophysiol* 2002; 25:1400–2
60. Avery JE: Loss prevention case of the month. Not my responsibility! *J Tenn Med Assoc* 1988; 81:523–4
61. Bonnet CA, Elson JJ, Fogoros RN: Accidental deactivation of the automatic implantable cardioverter defibrillator. *Am Heart J* 1990; 120:696–7
62. Coman JA, Martin ET, Sandler DA, Thomas JR: Implantable cardiac defibrillator interactions with magnetic resonance imaging at 1.5 Tesla. *J Am Coll Cardiol* 2004; 43:138A
63. Erlebacher JA, Cahill PT, Pannizzo F, Knowles RJ: Effect of magnetic resonance imaging on DDD pacemakers. *Am J Cardiol* 1986; 57:437–40
64. Fetter J, Aram G, Holmes DR Jr, Gray JE, Hayes DL: The effects of nuclear magnetic resonance imagers on external and implantable pulse generators. *Pacing Clin Electrophysiol* 1984; 7:720–7
65. Fiek M, Remp T, Reithmann C, Steinbeck G: Complete loss of ICD programmability after magnetic resonance imaging. *Pacing Clin Electrophysiol* 2004; 27:1002–4
66. Fontain JM, Mohammed FB, Gottlieb C, Callans DJ, Marchlinski FE: Rapid ventricular pacing in a pacemaker patient undergoing magnetic resonance imaging. *Pacing Clin Electrophysiol* 1998; 21:1336–9
67. García-Bolao I, Albaladejo V, Benito A, Alegría E, Zubieto JL: Magnetic resonance imaging in a patient with a dual-chamber pacemaker. *Acta Cardiol* 1998; 53:33–5
68. Gimbel JR, Bailey SM, Tchou PJ, Ruggieri PM, Wilkoff BL: Strategies for the safe magnetic resonance imaging of pacemaker-dependent patients. *Pacing Clin Electrophysiol* 2005; 28:1041–6
69. Gimbel JR, Johnson D, Levine PA, Wilkoff BL: Safe performance of magnetic resonance imaging on five patients with permanent cardiac pacemakers. *Pacing Clin Electrophysiol* 1996; 19:913–9
70. Gimbel JR, Kanal E, Schwartz KM, Wilkoff BL: Outcome of magnetic resonance imaging (MRI) in selected patients with implantable cardioverter defibrillators (ICDs). *Pacing Clin Electrophysiol* 2005; 28:270–3
71. Gimbel JR, Trohman RL, Lindsay WC, Clair WK, Wilkoff BL: Strategies for the safe performance of magnetic resonance imaging in selected ICD patients. *Pacing Clin Electrophysiol* 2002; 25:618
72. Hayes DL, Holmes DR Jr, Gray JE: Effect of 1.5 tesla nuclear magnetic resonance imaging scanner on implanted permanent pacemakers. *J Am Coll Cardiol* 1987; 10:782–6
73. Heatlie G, Pennell DJ: Cardiovascular magnetic resonance at 0.5T in five patients with permanent pacemakers. *J Cardiovasc Magn Reson* 2007; 9:15–9
74. Holmes DR Jr, Hayes DL, Gray JE, Merideth J: The effects of magnetic resonance imaging on implantable pulse generators. *Pacing Clin Electrophysiol* 1986; 9:360–70
75. Lauck G, von Smekal A, Wolke S, Seelos KC, Jung W, Manz M, Lüderitz B: Effects of nuclear magnetic resonance imaging on cardiac pacemakers. *Pacing Clin Electrophysiol* 1995; 18:1549–55
76. Luechinger R, Duru F, Scheidegger MB, Boesiger P, Candinas R: Force and torque effects of a 1.5-Tesla MRI scanner on cardiac pacemakers and ICDs. *Pacing Clin Electrophysiol* 2001; 24:199–205
77. Luechinger R, Zeijlemaker VA, Pedersen EM, Mortensen P, Falk E, Duru F, Candinas R, Boesiger P: *In vivo* heating of pacemaker leads during magnetic resonance imaging. *Eur Heart J* 2005; 26:376–83; discussion 325–7
78. Martin ET, Coman JA, Shellock FG, Pulling CC, Fair R, Jenkins K: Magnetic resonance imaging and cardiac pacemaker safety at 1.5-Tesla. *J Am Coll Cardiol* 2004; 43:1315–24
79. Pavlicek W, Geisinger M, Castle L, Borkowski GP, Meaney TF, Bream BL, Gallagher JH: The effects of nuclear magnetic resonance on patients with cardiac pacemakers. *Radiology* 1983; 147:149–53
80. Roguin A, Zviman MM, Meininger GR, Rodrigues ER, Dickfeld TM, Bluemke DA, Lardo A, Berger RD, Calkins H, Halperin HR: Modern pacemaker and implantable cardioverter/defibrillator systems can be magnetic resonance imaging safe: *In vitro* and *in vivo* assessment of safety and function at 1.5 T. *Circulation* 2004; 110:475–82
81. Rozner MA, Burton AW, Kumar AJ: Pacemaker complication during MRI. *J Am Coll Cardiol* 2005; 45:161–2
82. Schmiedel A, Hackenbroch M, Yang A, Nahle CP, Skowasch D, Meyer C, Schimpf R, Schild H, Sommer T: Magnetic resonance imaging of the brain in patients with cardiac pacemakers. *In-vitro* and *in-vivo* evaluation at 1.5 Tesla. *Rofo* 2005; 177:731–44
83. Shellock FG, Fieno DS, Thomson LJ, Talavage TM, Berman DS: Cardiac pacemaker: *In vitro* assessment at 1.5 T. *Am Heart J* 2006; 151:436–43
84. Shellock FG, Fischer L, Fieno DS: Cardiac pacemakers and implantable cardioverter defibrillators: *In vitro* magnetic resonance imaging evaluation at 1.5-tesla. *J Cardiovasc Magn Reson* 2007; 9:21–31
85. Shellock FG, O’Neil M, Ivans V, Kelly D, O’Connor M, Toay L, Crues JV: Cardiac pacemakers and implantable cardioverter defibrillators are unaffected by operation of an extremity MR imaging system. *AJR Am J Roentgenol* 1999; 172:165–70
86. Sommer T, Vahlhaus C, Lauck G, von Smekal A, Reinke M, Hofer U, Block W, Träber F, Schneider C, Gieseke J, Jung W, Schild H: MR imaging and cardiac pacemakers: *In-vitro* evaluation and *in-vivo* studies in 51 patients at 0.5 T. *Radiology* 2000; 215:869–79

87. Vahlhaus C, Sommer T, Lewalter T, Schimpf R, Schumacher B, Jung W, Lüderitz B: Interference with cardiac pacemakers by magnetic resonance imaging: Are there irreversible changes at 0.5 Tesla? *Pacing Clin Electrophysiol* 2001; 24(4, Part 1):489–95
88. Gimbel JR, Lorig RJ, Wilkoff BL: Safe magnetic resonance imaging of pacemaker patients. *J Am Coll Cardiol* 1995; 25:11A
89. Crane BT, Gottschalk B, Kraut M, Aygun N, Niparko JK: Magnetic resonance imaging at 1.5 T after cochlear implantation. *Otol Neurotol* 2010; 31:1215–20
90. Schueler BA, Parrish TB, Lin JC, Hammer BE, Pangrle BJ, Ritenour ER, Kucharczyk J, Truwit CL: MRI compatibility and visibility assessment of implantable medical devices. *J Magn Reson Imaging* 1999; 9:596–603
91. Shellock FG, Hatfield M, Simon BJ, Block S, Wamboldt R, Starewica PM, Punchard WFB: Implantable spinal fusion stimulator: Assessment of MRI safety. *J Magn Reson Imaging* 2000; 12:214–23
92. Bhidayasiri R, Bronstein JM, Sinha S, Krah SE, Ahn S, Behnke EJ, Cohen MS, Frysinger R, Shellock FG: Bilateral neurostimulation systems used for deep brain stimulation: *In vitro* study of MRI-related heating at 1.5 T and implications for clinical imaging of the brain. *Magn Reson Imaging* 2005; 23:549–55
93. Carmichael DW, Pinto S, Limousin-Dowsey P, Thobois S, Allen PJ, Lemieux L, Yousry T, Thornton JS: Functional MRI with active, fully implanted, deep brain stimulation systems: Safety and experimental confounds. *Neuroimage* 2007; 37:508–17
94. De Andres J, Valia JC, Cerda-Olmedo G, Quiroz C, Villanueva V, Martinez-Sanjuan V, de Leon-Casasola O: Magnetic resonance imaging in patients with spinal neurostimulation systems. *ANESTHESIOLOGY* 2007; 106:779–86
95. Finelli DA, Rezai AR, Ruggieri PM, Tkach JA, Nyenhuis JA, Hrdlicka G, Sharan A, Gonzalez-Martinez J, Stypulkowski PH, Shellock FG: MR imaging-related heating of deep brain stimulation electrodes: *In vitro* study. *AJNR Am J Neuroradiol* 2002; 23:1795–802
96. Heller JW, Brackmann DE, Tucci DL, Nyenhuis JA, Chou CK: Evaluation of MRI compatibility of the modified nucleus multichannel auditory brainstem and cochlear implants. *Am J Otol* 1996; 17:724–9
97. Rezai AR, Finelli D, Nyenhuis JA, Hrdlicka G, Tkach J, Sharan A, Rugieri P, Stypulkowski PH, Shellock FG: Neurostimulation systems for deep brain stimulation: *In vitro* evaluation of MRI-related heating at 1.5 tesla. *J Magn Reson Imaging* 2002; 15:241–50
98. Baker KB, Nyenhuis JA, Hrdlicka G, Rezai AR, Tkach JA, Shellock FG: Neurostimulation systems: Assessment of magnetic field interactions associated with 1.5- and 3-Tesla MR systems. *J Magn Reson Imaging* 2005; 21:72–7
99. Uitti RJ, Tsuboi Y, Pooley RA, Putzke JD, Turk MF, Wszolek ZK, Witte RJ, Wharen RE Jr: Magnetic resonance imaging and deep brain stimulation. *Neurosurgery* 2002; 51:1423–28; discussion 1428–31
100. Williams MD, Antonelli PJ, Williams LS, Moorhead JE: Middle ear prosthesis displacement in high-strength magnetic fields. *Otol Neurotol* 2001; 22:158–61
101. Ferris NJ, Kavoudias H, Thiel C, Stuckey S: The 2005 Australian MRI safety survey. *AJR Am J Roentgenol* 2007; 188:1388–94
102. American Society of Anesthesiologists: Standards for Basic Anesthetic Monitoring. In Standards, Guidelines and Statements (last amended October 20, 2010). Available at: <http://www.asahq.org/publicationsAndServices/standards/02.pdf>. Accessed July 1, 2011
103. Holshouser BA, Hinshaw DB Jr, Shellock FG: Sedation, anesthesia, and physiologic monitoring during MR imaging: Evaluation of procedures and equipment. *J Magn Reson Imaging* 1993; 3:553–8
104. Odegard KC, Dinardo JA, Tsai-Goddman B, Powell AJ, Geva T, Lausser PC: Anaesthesia considerations for cardiac MRI in infants and children. *Paediatr Anaesth* 2004; 14:471–6
105. Salvo I, Colombo S, Capocasa T, Torri G: Pulse oximetry in MRI units. *J Clin Anesth* 1990; 2:65–6
106. Barnett GH, Ropper AH, Johnson KA: Physiological support and monitoring of critically ill patients during magnetic resonance imaging. *J Neurosurg* 1988; 68:246–50
107. Henneberg S, Hök B, Wiklund L, Sjödin G: Remote auscultatory patient monitoring during magnetic resonance imaging. *J Clin Monit* 1992; 8:37–43
108. Mason KP, Burrows PE, Dorsey MM, Zurakowski D, Krauss B: Accuracy of capnography with a 30 foot nasal cannula for monitoring respiratory rate and end-tidal CO₂ in children. *J Clin Monit Comput* 2000; 16:259–62
109. Roth JL, Nugent M, Gray JE, Julsrud PR, Berquist TH, Sill JC, Kispert DB: Patient monitoring during magnetic resonance imaging. *ANESTHESIOLOGY* 1985; 62:80–3
110. Jorgensen NH, Messick JM Jr, Gray J, Nugent M, Berquist TH: ASA monitoring standards and magnetic resonance imaging. *Anesth Analg* 1994; 79:1141–7
111. Beebe DS, Tran P, Bragg M, Stillman A, Truwitt C, Belani KG: Trained nurses can provide safe and effective sedation for MRI in pediatric patients. *Can J Anaesth* 2000; 47:205–10
112. Hubbard AM, Markowitz RI, Kimmel B, Kroger M, Bartko MB: Sedation for pediatric patients undergoing CT and MRI. *J Comput Assist Tomogr* 1992; 16:3–6
113. Li W, Wait SD, Ogg RJ, Scoggins MA, Zou P, Wheless J, Boop FA: Functional magnetic resonance imaging of the visual cortex performed in children under sedation to assist in presurgical planning. *J Neurosurg Pediatr* 2013; 11:543–6
114. Machata AM, Kabon B, Willschke H, Prayer D, Marhofer P: Upper airway size and configuration during propofol-based sedation for magnetic resonance imaging: An analysis of 138 infants and children. *Paediatr Anaesth* 2010; 20:994–1000
115. Manuli MA, Davies L: Rectal methohexitol for sedation of children during imaging procedures. *AJR Am J Roentgenol* 1993; 160:577–80
116. Shepherd JK, Hall-Craggs MA, Finn JP, Bingham RM: Sedation in children scanned with high-field magnetic resonance; the experience at the Hospital for Sick Children, Great Ormond Street. *Br J Radiol* 1990; 63:794–7
117. Slovis TL, Parks C, Reneau D, Becker CJ, Hersch J, Carver CD, Ross RD, Tech K, Towbin RB: Pediatric sedation: Short-term effects. *Pediatr Radiol* 1993; 23:345–8
118. Volle E, Park W, Kaufmann HJ: MRI examination and monitoring of pediatric patients under sedation. *Pediatr Radiol* 1996; 26:280–1
119. Greenberg SB, Faerber EN, Aspinall CL, Adams RC: High-dose chloral hydrate sedation for children undergoing MR imaging: Safety and efficacy in relation to age. *AJR Am J Roentgenol* 1993; 161:639–41
120. Kannikeswaran N, Sethuraman U, Sivaswamy L, Chen X, Mahajan PV: Children with and without developmental disabilities: Sedation medication requirements and adverse events related to sedation. *Pediatr Emerg Care* 2012; 28:1036–40
121. Karian VE, Burrows PE, Zurakowski D, Connor L, Mason KP: Sedation for pediatric radiological procedures: Analysis of potential causes of sedation failure and paradoxical reactions. *Pediatr Radiol* 1999; 29:869–73
122. Malviya S, Voepel-Lewis T, Eldevik OP, Rockwell DT, Wong JH, Tait AR: Sedation and general anaesthesia in children undergoing MRI and CT: Adverse events and outcomes. *Br J Anaesth* 2000; 84:743–8
123. Fogel MA, Weinberg PM, Parave E, Harris C, Montenegro L, Harris MA, Concepcion M: Deep sedation for cardiac magnetic resonance imaging: A comparison with cardiac anesthesia. *J Pediatr* 2008; 152:534–9, 539.e1

124. Heng Vong C, Bajard A, Thiesse P, Bouffet E, Seban H, Marec Bérard P: Deep sedation in pediatric imaging: Efficacy and safety of intravenous chlorpromazine. *Pediatr Radiol* 2012; 42:552–61
125. Jain R, Petrillo-Albarano T, Parks WJ, Linzer JF Sr, Stockwell JA: Efficacy and safety of deep sedation by non-anesthesiologists for cardiac MRI in children. *Pediatr Radiol* 2013; 43:605–11
126. Maruf AA, Hossain MD, Ahmed M, Samsad IA: Procedural sedation in children for magnetic resonance imaging—Comparison between ketamine diazepam combination with midazolam fentanyl combination. *Mymensingh Med J* 2010; 19:60–5
127. Tith S, Lalwani K, Fu R: Complications of three deep sedation methods for magnetic resonance imaging. *J Anaesthesiol Clin Pharmacol* 2012; 28:178–84
128. Shorrab AA, Demian AD, Atallah MM: Multidrug intravenous anesthesia for children undergoing MRI: A comparison with general anesthesia. *Paediatr Anaesth* 2007; 17:1187–93
129. Bloomfield EL, Masaryk TJ, Caplin A, Obuchowski NA, Schubert A, Hayden J, Ebrahim ZY, Ruggieri PM, Goske MJ, Ross JS: Intravenous sedation for MR imaging of the brain and spine in children: Pentobarbital *versus* propofol. *Radiology* 1993; 186:93–7
130. Bluemke DA, Breiter SN: Sedation procedures in MR imaging: Safety, effectiveness, and nursing effect on examinations. *Radiology* 2000; 216:645–52
131. Bryan YF, Hoke LK, Taghon TA, Nick TG, Wang Y, Kennedy SM, Furstein JS, Kurth CD: A randomized trial comparing sevoflurane and propofol in children undergoing MRI scans. *Paediatr Anaesth* 2009; 19:672–81
132. Cho JE, Kim WO, Chang DJ, Choi EM, Oh SY, Kil HK: Titrated propofol induction *vs.* continuous infusion in children undergoing magnetic resonance imaging. *Acta Anaesthesiol Scand* 2010; 54:453–7
133. Connor L, Burrows PE, Zurakowski D, Bucci K, Gagnon DA, Mason KP: Effects of IV pentobarbital with and without fentanyl on end-tidal carbon dioxide levels during deep sedation. *AJR Am J Roentgenol* 2003; 181:1691–4
134. De Sanctis Briggs V: Magnetic resonance imaging under sedation in newborns and infants: A study of 640 cases using sevoflurane. *Paediatr Anaesth* 2005; 15:9–15
135. Kaila R, Chen X, Kannikeswaran N: Postdischarge adverse events related to sedation for diagnostic imaging in children. *Pediatr Emerg Care* 2012; 28:796–801
136. Machata AM, Willschke H, Kabon B, Kettner SC, Marhofer P: Propofol-based sedation regimen for infants and children undergoing ambulatory magnetic resonance imaging. *Br J Anaesth* 2008; 101:239–43
137. Mason KP, Sanborn P, Zurakowski D, Karian VE, Connor L, Fontaine PJ, Burrows PE: Superiority of pentobarbital *versus* chloral hydrate for sedation in infants during imaging. *Radiology* 2004; 230:537–42
138. Mason KP, Zurakowski D, Connor L, Karian VE, Fontaine PJ, Sanborn PA, Burrows PE: Infant sedation for MR imaging and CT: Oral *versus* intravenous pentobarbital. *Radiology* 2004; 233:723–8
139. Merola C, Albarracín C, Lebowitz P, Bienkowski RS, Barst SM: An audit of adverse events in children sedated with chloral hydrate or propofol during imaging studies. *Paediatr Anaesth* 1995; 5:375–8
140. Oğurlu M, Orhan ME, Bilgin F, Sızlan A, Yanarateş O, Yilmaz N: Efficacy of different concentrations of sevoflurane administered through a face mask for magnetic resonance imaging in children. *Paediatr Anaesth* 2010; 20:1098–104
141. Pershad J, Wan J, Anghelescu DL: Comparison of propofol with pentobarbital/midazolam/fentanyl sedation for magnetic resonance imaging of the brain in children. *Pediatrics* 2007; 120:e629–36
142. Rangamani S, Varghese J, Li L, Harvey L, Hammel JM, Fletcher SE, Duncan KF, Danford DA, Kutty S: Safety of cardiac magnetic resonance and contrast angiography for neonates and small infants: A 10-year single-institution experience. *Pediatr Radiol* 2012; 42:1339–46
143. Sanborn PA, Michna E, Zurakowski D, Burrows PE, Fontaine PJ, Connor L, Mason KP: Adverse cardiovascular and respiratory events during sedation of pediatric patients for imaging examinations. *Radiology* 2005; 237: 288–94
144. Vade A, Sukhani R, Dolenga M, Habison-Schuck C: Chloral hydrate sedation of children undergoing CT and MR imaging: Safety as judged by American Academy of Pediatrics guidelines. *AJR Am J Roentgenol* 1995; 165:905–9
145. Woodthorpe C, Trigg A, Alison G, Sury M: Nurse led sedation for paediatric MRI: Progress and issues. *Paediatr Nurs* 2007; 19:14–8
146. American Society of Anesthesiologists: Practice advisory for the prevention and management of operating room fires: An updated report. *ANESTHESIOLOGY* 2013; 118:271–90