MRI Safety with Orthopedic Implants

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KEYWORDS

• Magnetic resonance imaging • Radiofrequency-induced heating • Implant migration • Torque • Safety

KEY POINTS

- This study reviews the current literature on MRI safety with orthopedic implants.
- MRI is safe in patients with orthopedic implants regarding migration and torque.
- Radiofrequency-induced heating of implants during MRI showed small differences among studies, although not clinically significant.
- Pediatric patients may be at an increased risk for thermal injury if anesthetized and/or unable to report temperature change during MRI.
- A risk-to-benefit ratio should be applied when using MRIs with orthopedic implants in pediatric patients requiring sedation.

INTRODUCTION

MRI is a valuable diagnostic tool, with utility in pediatric and musculoskeletal imaging due to its lack of ionizing radiation and excellent soft tissue contrast. A continual increase in MRI usage has been demonstrated in the United States, with a 5% rise annually, peaking at 118 examinations per 1000 population (64 in an ambulatory setting and 54 in an inpatient hospital setting).[1] Additionally, the United States has the second-most MRI units per capita, with a 188% increase since 1995, reaching 39 per 1 million population in 2015.[2,3] What makes MRI unique is the method by which the images are obtained. MRI uses a magnet to alter proton rotation, producing signals as the protons return to their baseline rotation at differing rates in various tissues of the body. The magnetic fields used to manipulate the protons during the imaging sequence come in varying strengths for different uses; however, nearly all clinically used scanners in the United States are under 3.0 T,[4] and only one 7.0-T scanner has received approval from the United States Food and Drug Administration for clinical use.[5] Scanners with strengths over 3.0 T are routinely used in research; however, this article's focus in on recommendations on clinically relevant field strengths.

MRI is considered safer and is generally preferred in the pediatric population compared with CT scans for advanced imaging because it does not use ionizing radiation. MRI is not without risk, however, and the Food and Drug Administration[6] receives reports of approximately 300 adverse events associated with these examinations annually. Second-degree burns are the most commonly reported problems and are often due to the formation of internal currents (via skin-to-skin contact)[7,8] or from external metallic objects contacting the body (electrocardiogram leads,[9] pulse oximeters,[10] microfiber tech clothing,[11] medical patches,[12] and so forth). Projectile events (objects drawn into the magnetic field), crush injury of the digits by the patient table, patient falls, and hearing loss or tinnitus are the next most commonly reported problems with MRI, all unrelated to the presence of an orthopedic

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implant. Additionally, pediatric patients requiring anesthesia to inhibit movement during the long MRI acquisition time are at higher risk of adverse events during the MRI sequence.[13–15] Over the past several decades, the safety, compatibility, and imaging artifact caused by surgical implants have been tested in numerous in vivo and ex vivo studies. Because MRI units use strong magnets, metal implants pose a particular hazard with their potential for dislodgment, heating of the implant, and possible damage to surrounding tissues. Although newer orthopedic implants seem safe for MRI, concerns remain with the increasing field strength of MRI scanners. Additionally, confusion remains regarding MRI use immediately postoperatively in patients with surgical implants. This study reviews the current literature concerning the safety of MRI in patients with orthopedic implants. Information was sought about displacement, torque, and radiofrequency-induced (RF) heating of orthopedic implants, paying special attention to any articles pertaining to pediatric orthopedics.

LITERATURE SEARCH

This study did not require institutional review board approval. PubMed was searched using the terms, "MRI and Safety and Orthopedic Implant"; "MRI and Safety and Surgical Implants"; "MRI and Safety and Medical Implants"; "MRI and Orthopedic Hardware and Soft Tissue"; "Magnetic Resonance Imaging and Radiofrequency Heating and Metal Implants"; "MRI and Safety and Pediatric and Orthopedics"; and "MRI and Safety and Spinal Implants." Google Scholar was also searched using these terms to capture relevant articles not listed on PubMed. Only articles published within the past decade were reviewed and only those that discussed MRI safety pertaining to orthopedics were included. In addition, the Web site mrisafety.com was reviewed.

LITERATURE SEARCH RESULTS

The PubMed search produced 402 articles. After narrowing the results to the past 10 years, 219 articles remained. After excluding duplicate articles, articles not pertaining to orthopedic implants, and articles discussing topics other than safety, 15 remained for review.[16–30] Implant displacement was discussed in 11 articles,[16–22,26–28,30] RF heating in 13,[16–21,23–25,27,28,30] and torque in 4.[21,22,26,27] Table 1 summarizes the results of the 15 studies.

Implant Displacement

Implant displacement in 1.5-T, 3.0-T, and 7.0-T scanners has been the focus of numerous studies.[16–22,26–28,30] The experimental studies examined the change in the hanging angle of implants in scanners during an imaging sequence compared with prior to imaging (Fig. 1). A displacement angle of 45° indicated that the translational force of the magnet was equivalent to the force of gravity, and an angle over 45° indicated a potential for implant displacement with MRI.[21,29] Overall, significant displacement in orthopedic implants was infrequent. Two studies reported deflection angles over 45° using a 7.0-T MRI.[21,22] In Feng and colleagues'[21] study, 2 stainless-steel implants showed deflection of more than 45° at 7.0 T. Dula and colleagues[22] reported a deflection angle of 55° for the Synergy Hip System (Smith and Nephew, Memphis, TN) (metal not reported). The deflection angle for all other implants reported was well below 45°, with most below 10° (see Table 1). Except for a known ferromagnetic posterior spinal implant with a deflection angle of 65°,[26] all other implants had no significant displacement in 1.5-T and 3.0-T scanners. All studies but 2[19,28] were performed in ex vivo conditions, and the 2 in vivo studies failed to demonstrate any clinically or radiographically significant implant migration. Two studies also found no detrimental effects of MRI on magnetic-controlled growing rods.[27,28]

Torque

Torque describes the rotational displacement and speed at which the implant aligns with the magnetic field. Only 4 studies reported torque values.[21,22,26,27] Feng and colleagues[21] reported 1+ (minimal) torque in 2 titanium implants and 1 titanium alloy implant. Dula and colleagues[22] reported 2+ (moderate) torque in a pyrocarbon knee implant, a Synergy Hip System, and a titanium alloy hip stem with a cobalt-chrome head stem. They also reported 1+ (minimal) torque in a cobalt-chrome staple and an oxidized zirconium knee implant. McComb and colleagues[26] reported 2+ (moderate) torque in 1 highly ferromagnetic posterior spinal implant but deemed the risk to patient safety minimal, given the rigid fixation of the implant.

Radiofrequency-induced Heating

RF heating of implants during MRI sequencing was discussed in 13 of the 15 articles,[16–21,23–25,27–30] with 8 showing a change

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Table 1
Results of reviewed articles

Author	Implant	MRI Field Strength	Deflection Angle	Torque (1–4)	Temperature Change (°C)
Yang et al,[16] 2009	1 Charite (Depuy Spine, Raynham, MA)	<1.5 T	7.5°	NR	0.4
	1 ProDisc-L (Depuy Synthes, Raynham, MA)	<1.5 T	6.0°	NR	0.6
Zou et al,[17] 2015	7 Titanium plates and screws	1.5 T	4.28°	NR	0.48
	7 Stainless-steel plates and screws	1.5 T	7.74°[a]	NR	0.74[b]
Kumar et al,[18] 2006	6 Stainless-steel	0.25 T and 1.0 T	0°	NR	NR
	3 Femoral prostheses		0°		—
	1 Condylar blade plate		0°		—
	1 Femoral nail		Significant (at 1.0 T)		—
	1 Ex fix clamp		0°		—
	5 Titanium		—		NR
	1 Femoral prosthesis		—		—
	1 Shoulder hemiprosthesis		—		—
	1 Tibial buttress plate		—		—
	1 Femoral recon nail		—		—
	1 Tibial nail		0°		NR
	1 Cobalt-chrome femoral prosthesis		0°		—
	1 Carbon fiber ex fix rod		0°		NR
	2 Stainless-steel hip prostheses		NR		0.1–0.2
	1 Titanium plate		NR		0.1
Makhdom et al,[19] 2015	19 Stainless-steel Fassier-Duval rod (Pega Medical, Laval, Canada)	1.5 T	0°	NR	0

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Table 1
(continued)

Author	Implant	MRI Field Strength	Deflection Angle	Torque (1–4)	Temperature Change (°C)
Tsukimura et al,[20] 2017	4 Pure titanium rods	3.0 T 7.0 T	1.0°–2.0° at 3.0 T	NR	0.2–0.5 at 3T
			5.0°–6.2° at 7.0 T		−0.2–0.4 at 7 T
	4 Titanium alloy rods		1.0°–2.3° at 3.0 T		−0.3–0.3 at 3 T
			5.7°–7.7° at 7.0 T		−0.2–0.2 at 7 T
	4 Cobalt-chrome rods		5.0°–6.0° at 3.0 T		0.1–0.4 at 3 T
			17.8°–21° at 7.0 T		0–0.6 at 7T
	1 Titanium alloy/cobalt-chrome screw		3.2° at 3.0 T		0.2 at 3 T
			10.0° at 7.0 T		−0.3 at 7 T
	1 Titanium alloy cross-link bridge		2.2° at 3.0 T		0 at 3 T
			6.7° at 7.0 T		−0.2 at 7 T
Feng et al,[21] 2015	10 Stainless-steel	7.0 T	16°–47° (5 implants >44)	0	−0.54–0.41 (2 implants)
	6 Titanium		1°–44° (1 implant 44)	1 (2 implants)	0.21 (1 implant)
	4 Titanium alloy		0°–7°	—	—
	2 Cobalt-chrome		1°–2°	1 (1 implant)	
	2 Aluminum oxide		0°–17°	—	—
	1 Vitallium		18°	—	—
Dula et al,[22] 2014	PEEK HTO plate	7.0 T	0°	0	NR
	PEEK distal radius plate		0°	0	
	Pyrocarbon knee implant		0°	2	
	Cobalt-chrome staple		23°	1	
	Oxidized zirconium knee implant		5°	1	
	Synergy Hip System		55°	2	
	Titanium alloy hip stem and cobalt-chrome-molybdenum hip stem		45°	2	
	Titanium and silver-plated cannulated screw		8°	0	

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Muranaka et al,[23] 2011; Muranaka et al,[24] 2007; Muranaka et al,[25] 2010	Stainless-steel humeral implant	1.5 T	NR	NR	6.4–14.7 (depending on absorption rate, angle, and location)
	1 Cobalt-chrome hip implant				9.0
	1 Titanium alloy hip implant				5.3
McComb et al,[26] 2009	Posterior spinal fixator (Anatomica, Gothenburg, Sweden) with fixation blocks, expansion screws, and spindle bolt Highly ferromagnetic components	1.5 T and 3.0 T	65°	4	NR
Budd et al,[27] 2016	2 Magnetic-controlled growing rods	1.5 T	0°	0	No detectable heating
Schroeder et al,[28] 2018	28 Stainless-steel plates and screws in pediatric patients with DDH	1.5 T	No implant migration or loosening	NR	No thermal effects to soft-tissues noted
Poon et al,[29] 2017	3 Magnetic-controlled growing rods	1.5 T	NR	NR	0.39–1.61
Mansour et al,[30] 2009	4 Steinmann pins (varying sizes)	1.5 T	<10°	NR	<3
	Tractor bow (external for traction)		<45°	NR	1.9
	Kirschner wire bow (external for traction)		Highly ferromagnetic removed from study	—	—

Abbreviations: DDH, developmental hip dislocation; ex fix, external fixation; HTO, high tibial osteotomy; PEEK, polyetheretherketone; 1 torque, mild or low; 2 torque, moderate; greater than 3 torque, high; NR, not reported.

[a] The difference in value between the titanium implants and stainless-steel implants was significant ($P<.001$).

[b] There was an absence of blood circulation in the cadaver swine leg tested. In humans, this value would be lower.

Fig. 1. Demonstration of the experimental setup used to assess hanging angle displacement of implants during an imaging sequence. (*From* Zou YF, Chu B, Wang CB, et al. Evaluation of MR issues for the latest standard brands of orthopedic metal implants: plates and screws. Eur J Radiol 2015;84(3):451; with permission.)

of less than 1°C.[16–21,27,28] Only 5 studies showed more than 1°C change.[23–25,29,30] Muranaka and colleagues[23–25] found increases from 5.3°C to 14.7°C in a stainless-steel humeral implant and cobalt-chrome and titanium hip implants. These experiments were performed in a laboratory setting using a tissue-equivalent, gel-filled polypropylene model. The humeral implant showed a 12.3°C increase at 2-cm depth after a 15-minute 1.5-T MRI sequence.[23] In these studies, implants deeper (6 cm) in the model had less temperature rise (<5.0°C), and the edges of the implants demonstrated the most volatile temperature increases (14.7°C). The maximum temperature rise was noted when the implant tip was parallel with the static magnetic field, and when the implant was moved away from the center of the irradiation coil (static magnetic field), less temperature rise was noted.

DISCUSSION

The concerns of MRI in patients with metal implants are centered on theoretic migration and RF heating of implants, causing damage to surrounding tissues. Numerous studies examining the safety of surgical implants have been published over the past 3 decades, concluding that most passive (no power associated with their operation) nonferromagnetic or weakly ferromagnetic implants are safe for patients in any setting requiring an MRI at 1.5 T or less.[31–34] The results of this review are similar. In general, MRI with field strengths up to 7.0 T can safely be used in patients with orthopedic implants, because the risk of implant-based complications is extremely low.

In this review, 3 of the studies cited areas of concern regarding displacement of orthopedic implants during MRI.[21,22,26] In total, 4 implants violated the previously stated goals for deflection angles being below 45°. The clinical relevance of orthopedic implant migration during MRI remains in doubt, however, and the results of this review support the assessment that in vivo orthopedic implants are likely unaffected by translational forces (even if they exceed 45° under experimental protocols) because they are firmly fixed to bone or are sutured in place, providing sufficient counter-force during imaging.[30] Additionally, in the 2 in vivo studies of this cohort, no clinical or radiographic evidence of implant migration was found after 1.5-T MRI sequencing in osteogenesis imperfecta patients with Fassier-Duval rods[19] or in 28 pediatric patients with developmental hip dysplasia treated with osteotomy and stainless-steel fixation,[28] thus supporting the hypothesis of rigid implant fixation being sufficient to secure the implants in place.

Concerns also exist in the literature regarding RF heating of orthopedic implants. RF heating theoretically occurs due to eddy currents in implants paralleling the static magnetic field of the scanner and causes heating and tissue damage.[17,18,25] Of this cohort, 5 studies reported temperature increases beyond the accepted range of 1°C, and 3 studies reported temperature increases of 5.3°C to 14.7°C.[23–25,29,30] These 3 outliers were ex vivo studies using a tissue-equivalent model with "the same electrical properties of muscle" and failed to document the baseline temperature change of the model during imaging without hardware implanted.[23–25] This lack of a control group calls into question if the temperature increases were due to baseline heating of the model or to RF

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heating of the implant. Although the results of these 3 studies are alarming, the insufficiencies in their methods breed skepticism regarding their clinical utility. All other studies of the cohort found the temperature change to be negligible, and both in vivo studies had zero patients reporting issues relating to RF heating or subjective burning.[19,28] In short, fears of temperature increases and subsequent tissue damage from RF heating may be unfounded, as suggested by the other studies.[19,28,30]

The effect of magnetic field strength has been studied. Although nearly all clinically used scanners in the United States are 3.0 T or below, 3 studies included in this cohort were performed at 7.0 T,[20–22] a strength often reserved for research purposes. Displacement forces generally increased with increasing magnetic field strength, but most implants remained in their accepted ranges at 7.0 T. RF heating was not associated with field strength, and did not demonstrate increases in temperature with increasing field strength.[20] With recent approval of the first clinical 7.0-T scanner in the United States,[5] little evidence supports limiting clinical use of MRI due to magnetic field strength.

Confusion remains regarding the use of MRI immediately postoperatively, and there is a paucity of recent literature discussing this issue in correlation with orthopedic implants. Shellock[31] stated that patients with passive nonferromagnetic implants can safely undergo MRI at 1.5 T or less immediately postoperatively, but if an implant is weakly magnetic, practitioners should wait 6 weeks to 8 weeks after the procedure. This statement was referring to coils, filters, and stents, however, that could migrate due to their lack of rigid fixation, not orthopedic implants affixed to bone or when displacement is not a problem.[30] Furthermore, other articles have not reported adverse events related to early postoperative MRI (2 hours–1 day) in the presence of implants,[28,32] and early postoperative MRI remains the standard of care after spinal surgery in patients with postoperative neurologic changes.[35–37]

Image artifact in patients with metal implants does not pose a direct hazard to the patient but can lead to misinterpretation of the results. All metals generate image artifact regardless of their ferromagnetic properties and become an issue if the area of interest is near the implant. Although artifact was outside the scope of this study, 7 articles directly discussed artifact distortion with orthopedic implants.[16–19,23,27,28] In 2 in vivo studies,[19,28] image distortion was not present, although it was problematic in other studies.[16–18,23,27] Modifications of MR pulse sequences and optimization of scanning parameters, however, such as field of view, fast spin-echo, and short-tau inversion recovery, can minimize image distortion.[17,18] The ordering practitioner should weigh the benefits of each imaging sequence in relation to the possible image distortion of the implant. Also, the presence of bullets, shrapnel, and other foreign bodies was not examined in this study, but these articles may pose a threat of migration during imaging.[38–40] Clinical judgment and appropriate caution are warranted when foreign bodies are located near vital organs or the spine. As with all metallic implants, the composition of the foreign bodies affects the possible MRI interactions, with steel objects posing the greatest risk.

In the United States, the use of MRI continues to increase, with minimal associated adverse events. MRIs have a positive risk-to-benefit ratio, with 118 annual examinations per 1000 population in the United States[1] and only 300 adverse events.[6] Appropriate caution remains necessary, however, when ordering MRI in children. Pediatric patients are more likely to require sedation to inhibit movement, thus leaving them unable to express any possible issues that might arise during scanning or during recovery.[13–15]

The limitations of this study include that most of articles examined were laboratory-based studies, with only 2 retrospective clinical studies.[19,28] Additionally, only 2 studies[19,28] focused on pediatric patients. Lastly, zero reports of thermal burns via orthopedic implants or instances of implant migration have been published in the past 10 years, so the true risk of MRI is difficult to determine.

In summary, MRI is safe after orthopedic device implantation and can be performed postoperatively with little concern regarding implant migration. There is conflicting information regarding RF heating of implants, and various implant and patient-specific factors are involved with this phenomenon. Although implants pose minimal risk to patients, individual assessment of implant properties and MRI-related interactions is warranted and can be easily investigated. A risk-to-benefit ratio should be applied when deciding to use MRI in pediatric patients. If the information gained from the MRI is more valuable than the potential risk of anesthesia, migration, or heating, which is extremely low, then the study is likely warranted.

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