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MRI issues for ballistic objects: information obtained at 1.5-, 3- and 7-Tesla

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Abstract

BACKGROUND CONTEXT: Few studies exist for magnetic resonance imaging (MRI) issues and ballistics, and there are no studies addressing movement, heating, and artifacts associated with ballistics at 3-tesla (T). Movement because of magnetic field interactions and radiofrequency (RF)-induced heating of retained bullets may injure nearby critical structures. Artifacts may also interfere with the diagnostic use of MRI.

PURPOSE: To investigate these potential hazards of MRI on a sample of bullets and shotgun pellets.

STUDY DESIGN: Laboratory investigation, ex vivo.

METHODS: Thirty-two different bullets and seven different shotgun pellets, commonly encountered in criminal trauma, were assessed relative to 1.5-, 3-, and 7-T magnetic resonance systems. Magnetic field interactions, including translational attraction and torque, were measured. A representative sample of five bullets were then tested for magnetic field interactions, RF-induced heating, and the generation of artifacts at 3-T.

RESULTS: At all static magnetic field strengths, non–steel-containing bullets and pellets exhibited no movement, whereas one steel core bullet and two steel pellets exhibited movement in excess of what might be considered safe for patients in MRI at 1.5-, 3- and 7-Tesla. At 3-T, the maximum temperature increase of five bullets tested was 1.7°C versus background heating of 1.5°C. Of five bullets tested for artifacts, those without a steel core exhibited small signal voids, whereas a single steel core bullet exhibited a very large signal void.

CONCLUSIONS: Ballistics made of lead with copper or alloy jackets appear to be safe with respect to MRI-related movement at 1.5-, 3-, and 7-T static magnetic fields, whereas ballistics containing steel may pose a danger if near critical body structures because of strong magnetic field interactions. Temperature increases of selected ballistics during 3-T MRI was not clinically significant, even for the ferromagnetic projectiles. Finally, ballistics containing steel generated larger

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artifacts when compared with ballistics made of lead with copper and alloy jackets and may impair the diagnostic use of MRI.

Keywords: Magnetic resonance imaging, safety; Heating, MRI; Artifacts, MRI; Bullets; Ballistics

Introduction

In consideration of the prevalence of both civilian and military gunshot injuries resulting in retained bullets, it is important to determine the risks involved with magnetic resonance imaging (MRI) [1]. This is especially relevant because MRI is often used as part of the initial injury workup or as part of the preoperative planning process. Although most small arms ballistics are fabricated using nonferromagnetic materials and, therefore, will not cause patient injuries because of movement or dislodgment in tissue, prior studies demonstrated that many have ferromagnetic impurities [2]. Furthermore, although most shotgun pellets were historically lead based, environmental pollution concerns have led to the introduction of steel-based pellets that may be ferromagnetic [3]. Any retained ballistic object displaying magnetic field interactions, whether because of occult impurities or actual fabrication material (such as steel or nickel), poses a potential risk to soft-tissue, vascular, and neural structures because of migration and torque in association with the powerful static magnetic field encountered during an MRI examination [2–7]. The effect of MRI-induced heating of conductive materials (both ferromagnetic and nonferromagnetic) may also pose a risk [8,9].

With few exceptions, the numerous theoretical risks have not been effectively substantiated in the current literature [2–6,8,9]. The conclusions of prior studies are that, ballistics known to contain iron or nonaustenitic steel should not be allowed in patients referred for MRI examinations, whereas the vast majority of commonly encountered American-made bullets have minimal or no ferromagnetism and are not considered to pose a risk to patients relative to the use of MRI [2–4]. However, these investigations were conducted in the setting of magnetic resonance (MR) systems using static magnetic fields up to 1.5-tesla (T) only. Presently, MRI scanners using magnets with static magnetic fields of 3-T are used clinically, and even 7-T scanners now exist in the research environment. Accordingly, it is critical to understand how retained bullets will behave in the setting of more powerful MRI systems because the outcome of unanticipated behavior of metallic objects near critical anatomic structures could be catastrophic [1,10].

For this investigation, we hypothesize that commonly encountered bullets and shotgun pellets are not subject to magnetic forces sufficient to pose harm to patients undergoing MRI in 1.5-, 3-, and 7-T scanners. The goals of this ex vivo study were to determine the magnetic field interactions (at 1.5-, 3- and 7-T), MRI-induced heating (at 3-T), and image artifacts (at 3-T) for a representative sample of ballistic objects that are commercially available and commonly encountered in criminal trauma.

Materials and methods

Bullets and pellets

Thirty-two different bullets and seven types of shotgun pellets (Table 1) obtained from the San Francisco Police Department underwent MRI evaluations in this study. The samples were representative of those commonly encountered in urban crime-related trauma and hunting accidents. Each bullet and pellet was tested for translational attraction in 1.5-T (Signa; General Electric Healthcare, Milwaukee, WI, USA), 3-T (GE 750; GE Healthcare, Milwaukee, WI, USA), and 7-T (GE 950; GE Healthcare, Milwaukee, WI, USA) MR systems.

Magnetic field interactions

Translational attraction

The deflection-angle method described by New et al. and used in previous similar studies [2,8–16] was used to assess translational attraction for the samples. This method involved suspending the object on a string (20-cm length; weight $<1\%$ of each sample) attached to a stable nonferromagnetic structure fixed with a plastic protractor with 1° graduated markings (Fig. 1). The apparatus was then placed eccentrically near the scanner portal at the experimentally determined point of highest spatial magnetic gradient for each MR system [17]. The deflection angle from the vertical position to the nearest 1° was measured three times, and the mean value was calculated. Following the methodology of previous studies, a deflection greater than 45° was considered to be potentially relevant [10,11].

A single bullet (no. 32) that was found to deflect 90° was retested in a 3-T MR system (Excite, HDx; General Electric Healthcare, Milwaukee, WI, USA) using a digital force gauge (model 475040; Extech Instruments, Waltham, MA, USA) to measure the translational attraction, as previously described [18,19]. The bullet was positioned within the 3-T MR system at the point of highest magnetic spatial gradient to measure a peak translational force.

Torque

Torque was assessed using a qualitative measurement technique used by previous studies, in which each test item was placed on a flat plastic material with a grid etched on the bottom (Fig. 2) [8,14–16]. Each test samples were

Table 1
Description of ballistics tested

No.	Details	Composition	Morphology	Weight (g)	Length (mm)
1	Winchester .22 Super X	Pb core/Cu jacket		2.59	12.0
2	Winchester .22 Super Magnum	Pb core/Cu jacket		2.60	12.5
3	Lake City Manufacturing .22 “C”	All Pb		2.55	12.5
4	Winchester 99 WRA(+)	Pb core/Cu jacket		9.54	29.0
5	Remington-Peters .223	Pb core/Cu jacket		3.61	17.5
6	Winchester .223	Pb core/Cu jacket		4.18	20.5
7	Winchester .300 H&H Magnum WW Super	Pb core/Cu jacket		9.76	26.0
8	Remington-Peters .300 Magnum	Pb core/Cu jacket		11.58	29.5
9	Winchester .308 FC	Pb core/Cu jacket		9.72	26.0
10	Winchester .308 WIN	Pb core/Cu jacket	Lead tip	11.69	28.5
11	Western S&W Long	Pb core/Cu jacket		6.40	15.0
12	Remington-Peters .357 Magnum RP	Pb core/Cu jacket		8.18	14.5
13	Winchester-Western .38 Special WW	All Pb	Wadcutter	9.40	16.0
14	Winchester-Western .38 Special target	All Pb		10.31	18.5
15	Winchester .38 SPL+P	Pb core/Cu jacket		8.04	14.5
16	Remington-Peters .38 SPL+P	All Pb	Wadcutter	9.61	16.0
17	Winchester-Western .38 Auto W-W	Pb core/alloy jacket	Hollow point	5.55	12.0
18	(Unknown) .38 Auto	Pb core/Cu jacket	Hollow point	5.83	11.5
19	(Unknown) .38 Automatic Colt Pistol	Pb core/Cu jacket		5.82	12.0
20	Winchester .40 S&W	Pb core/Cu jacket	Hollow point	10.09	14.0
21	Remington-Peters .40 S&W	Pb core/Cu jacket	Hollow point	11.63	16.0
22	Winchester .40 S&W	Pb core/Cu jacket	Blunt point	11.68	15.0
23	Remington .40 S&W	Pb core/alloy jacket	Hollow point	11.69	16.0
24	Winchester-Western .41 REM Magnum WW Super	Pb core/alloy jacket	Hollow point	11.35	15.5
25	Winchester-Western .41 REM Magnum WW Super	Pb core/Cu jacket	Blunt point	13.65	17.0
26	Winchester-Western .41 REM Magnum WW Super	All Pb	Semiwadcutter	13.73	18.0
27	Lake City .223/8.6 LC	Pb core/Cu jacket		3.55	19.0
28	Winchester 9 mm Luger	Pb core/Cu jacket	Ball tip	7.46	15.0
29	Winchester 9 mm Luger	Pb core/alloy jacket	Hollow point	7.47	14.0
30	Winchester 9 mm Luger	Pb core/Cu jacket	Hollow point	9.53	17.0
31	FC 9 mm Luger	Pb core/Cu jacket	Hollow point	9.55	16.5
32	Western Cartridge Company .223 WCC 80 armor piercing	Steel core/Cu jacket	Teflon tip	4.06	23.0
33	Reminton-Peters 12 gauge R-P #4 shot	All Pb	Spherical	0.22	
34	Winchester 12 gauge Super Double Magnum #2 shot	Cu	Spherical	0.32	
35	Winchester 12 gauge #3 shot	Steel	Spherical	0.19	
36	Kent 20 gauge #2 shot	Steel	Spherical	0.23	
37	Winchester-Western 12 gauge #6 shot	All Pb	Spherical	0.11	
38	Federal 12 gauge 00 buckshot	All Pb	Spherical	3.20	
39	Federal 12 gauge tactical rifle slug	All Pb	Cylindrical	28.33	

Pb, lead; Cu, copper.

oriented 45° to the static magnetic field and then introduced into the center of the bore of the scanner where magnetic torque is the greatest. Any change in orientation of the test sample was judged by an experienced single observer (RDD) according to the following qualitative criteria: 0—no torque; +1—mild torque, object slightly changed orientation but did not align to the magnetic field; +2—moderate torque, object aligned gradually to the magnetic field; +3—strong torque, object aligned rapidly and forcefully to the magnetic field; and +4—very strong torque, object very rapidly and forcefully aligned to the magnetic field [14–16]. Each sample was then moved in 45° increments to encompass the full 360° of rotation in the 1.5-, 3-, and 7-T MR systems. This procedure was conducted three times for each sample, and a mean value of torque was calculated for each bullet. Because rotational force is not relevant in spherical objects [1], shotgun pellets were not evaluated for torque.

MRI-related heating

Experimental setup

Five bullets (nos. 8, 10, 23, 25, and 32), selected to be representative of the various sizes and material compositions of the total number of samples (Fig. 3), were tested for MRI-related heating. This procedure used a plastic head/torso phantom filled to a depth of 9 cm with a semisolid gelled saline that was prepared to simulate the electrical and thermal properties of human tissue [20].

Temperature recording system and placement of thermometry probes

Temperature recordings were obtained by using a fluoroptic thermometry system (Luxtron Model 3100; LumaSense Technologies, Santa Clara, CA, USA) with one probe attached to each end of the bullet (Probe 1 and 2) and a third (Probe 3) attached to the middle (Fig. 4).

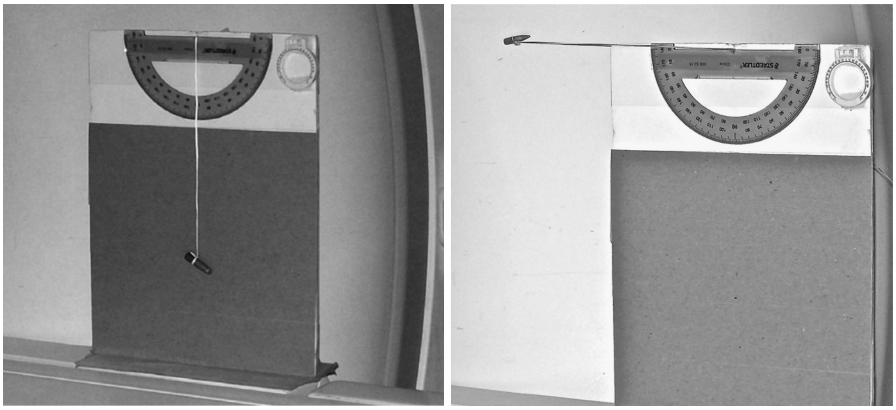

Fig. 1. (Left) Example of deflection angle test performed on Bullet 10. Note the deflection angle of 0° indicating no translational attraction. (Right) Example of deflection angle test performed on Bullet 32. Note the deflection angle of 90°, indicating the presence of substantial translational attraction.

These three probes were placed at positions that would be associated with the greatest amount of heating during MRI. A fourth probe was positioned within the phantom approximately 30 cm directly across from the bullet to record a reference temperature.

MRI conditions

The assessment of MRI-related heating was performed using a 3-T system with a body radiofrequency (RF) coil used to transmit RF energy. Magnetic resonance imaging parameters were selected to generate a relatively high level of RF energy, producing an MRI system-reported whole-body average specific absorption rate of 2.9 W/kg for 15 minutes [16,20]. The landmarking position for the MRI procedure was at the center of the thorax (thus, the center of the bullet) of the head/torso phantom, with section locations selected to encompass the entire area of the bullet [16,20].

MRI protocol

Baseline (pre-MRI) temperatures were recorded at 5-second intervals for 5 minutes, and MRI was then performed for 15 minutes, recording temperatures at 5-second intervals. Post-MRI temperatures were recorded for 2 minutes at 5-second intervals. The highest temperature changes were recorded for each thermometry probe and reported.

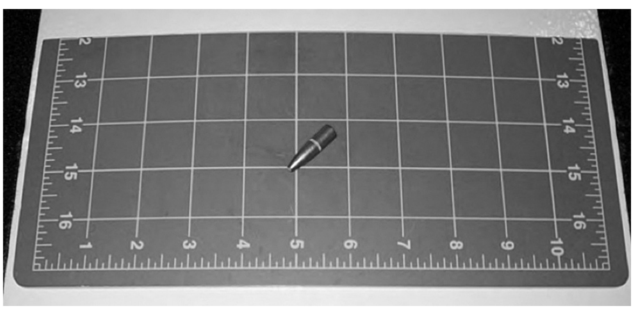

Fig. 2. The experimental setup used for the qualitative assessment of torque for Bullet 10.

The ‘‘background’’ temperature was also recorded in the gelled-saline–filled phantom by repeating the aforementioned protocol with a single probe placed at the position within the gelled-saline phantom corresponding to Probe 3 but without the bullet present.

Artifacts

Artifacts were characterized for five bullets (nos. 8, 10, 23, 25, and 32) selected to be representative of the various sizes and material compositions of our total sample (Fig. 3). All five bullets were attached to a plastic frame and placed inside a gadolinium-doped saline-filled plastic phantom, as previously described (Fig. 5) [15,16]. Magnetic resonance imaging was performed using a 3-T MR system (Excite, Software G3.0-052B; GE Healthcare, Milwaukee, WI, USA), a send-receive RF body coil, and the following pulse sequence: gradient echo pulse sequence; repetition time, 100 milliseconds; echo time, 15 milliseconds; flip angle, 30°; matrix size, 256×256; section thickness, 10 mm; field of view, 48 cm; number of excitations, 2; and bandwidth, 16 kHz. This sequence was chosen to generate an extreme clinical MRI condition [15,16]. The image locations obtained through the bullets represented the largest or worst-case artifacts and were, therefore, selected for evaluation. Planimetry software provided with the MR system was used to measure (accuracy and resolution ±10%) the cross-sectional area of the largest artifact size for the bullets [15,16].

Results

Magnetic field interactions

Table 2 summarizes the findings for magnetic field interactions. The only samples that demonstrated translational attractions at 1.5-T were the Western Cartridge Company 0.223 caliber armor-piercing bullet (no. 32) and the two steel pellets (no. 35 and 36), deflecting 90°. Using the digital force gauge, the peak translational attraction force on

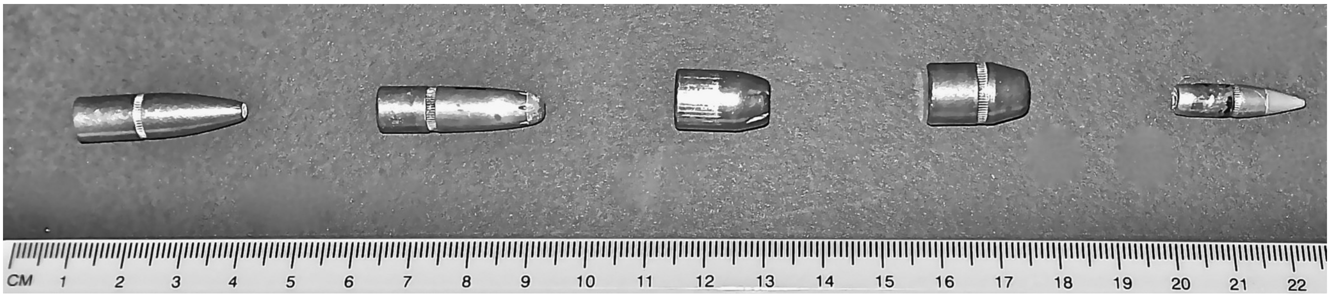

Fig. 3. Five representative bullets that underwent testing for magnetic resonance imaging–related heating and artifacts at 3-T. From left to right, Samples 8, 10, 23, 25, and 32.

Bullet 32 at 3-T MR system was 1.27 N/130 g. All other bullets and shots demonstrated no deflection above 45 degrees in the 1.5-, 3-, or 7-T MR systems. Torque was observed for the Western Cartridge Company 0.223 caliber armor-piercing bullet (no. 32), measuring 4+.

MRI-related heating

Magnetic resonance imaging–related heating experiments performed on the five bullets tested yielded a highest temperature change equal to or less than +1.7°C, with a background temperature rise of 1.5°C in each case (Table 3).

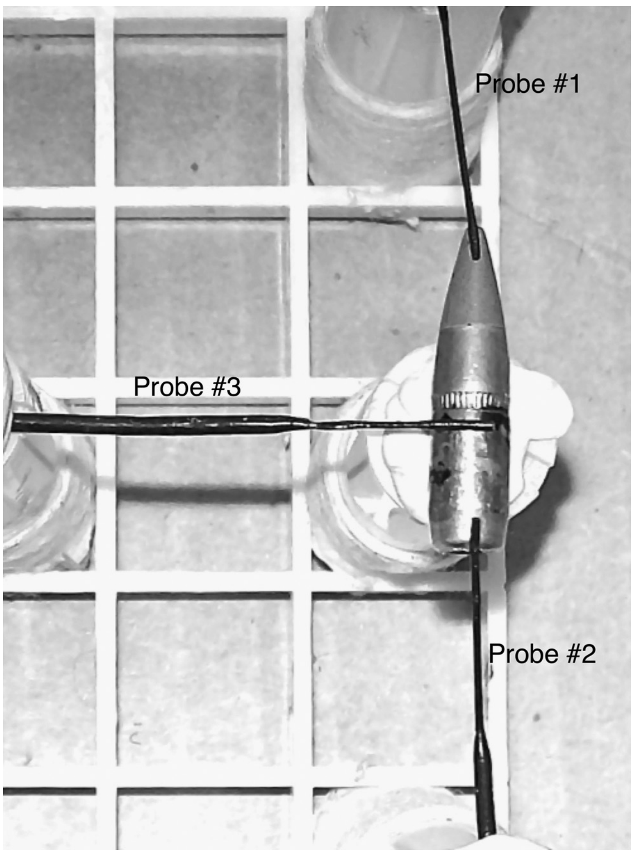

Fig. 4. Position of three fluoroptic thermometry probes used to measure magnetic resonance imaging–related heating on Bullet 32 at 3-T/128-MHz.

Artifact

Artifact results are seen in Fig. 6 and reported in Table 4. In relation to the size and shape of each bullet, the artifact associated with four bullets tested (nos. 8, 10, 23, and 25) was small in size, whereas the artifact associated with Bullet 32 was very large.

Fig. 5. Experimental setup for the evaluation of magnetic resonance imaging–related artifacts at 3-T. Note the five different bullets (Fig. 3) placed on the plastic frame, as follows: top row (left to right): Bullets 23 and 8; middle row (left to right): Bullets 25 and 10; and bottom row: Bullet 32.

Table 2
Summary of magnetic field interactions at 1.5-, 3-, and 7-Tesla

	1.5-Tesla		3-Tesla		7-Tesla	
Item no.	DA	Torque	DA	Torque	DA	Torque
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0
13	0	0	0	0	0	0
14	0	0	0	0	0	0
15	0	0	0	0	0	0
16	0	0	0	0	0	0
17	0	0	0	0	0	0
18	0	0	0	0	0	0
19	0	0	0	0	0	0
20	0	0	0	0	0	0
21	0	0	0	0	0	0
22	0	0	0	0	0	0
23	0	0	0	0	0	0
24	0	0	0	0	0	0
25	0	0	0	0	0	0
26	0	0	0	0	0	0
27	0	0	0	0	0	0
28	0	0	0	0	0	0
29	0	0	0	0	0	0
30	0	0	0	0	0	0
31	0	0	0	0	0	0
32	90 (43)*	4+	90	4+	—	—
33	0	NA	—	NA	—	NA
34	0	NA	—	NA	—	NA
35	90 (29)*	NA	—	NA	—	NA
36	90 (49)*	NA	—	NA	—	NA
37	0	NA	0	NA	0	NA
38	0	NA	0	NA	0	NA
39	0	0	0	0	0	0

DA, deflection angle; NA, not applicable; —, not tested.

* Number in parentheses is DA measured after nonferromagnetic weight added to the sample to obtain a DA between 25° and 65°.

Discussion

Magnetic field interactions

According to American Society for Testing and Materials International guidelines [14], if the deflection angle is less than 45°, magnetically induced translation attraction is less than the force of gravity and, therefore, poses no greater impact than normal daily activity in the earth's gravitational field. In our study, all steel-containing bullets and pellets were highly ferromagnetic, and all presumptively non–steel-containing bullets and pellets were nonferromagnetic. Of the ferromagnetic samples, all deflection angles were 90°, a finding that should raise concern relative to the use of MRI in a patient with a similar retained ballistic object.

Table 3
Summary of MRI-induced heating of five representative bullets at 3-Tesla/64-MHz

Bullet no.	Composition	Δt (°C)	Background Δt (°C)
8	Pb core/Cu jacket	1.7	1.5
10	Pb core/Cu jacket	1.7	1.5
23	Pb core/alloy jacket	1.6	1.5
25	Pb core/Cu jacket	1.6	1.5
32	Steel core/Cu jacket	1.7	1.5

MRI, magnetic resonance imaging; Δt, highest temperature change; Pb, lead.

According to Shellock [1], defining ‘‘unsafe’’ translational attraction is not straightforward. In reality, a retained object may be subject to ‘‘counter forces’’ that can be present in situ [1]. For example, if the object is retained in bone or encapsulated by scar tissue, these may suffice to maintain the object in place even in the presence of a powerful 3-T static magnetic field [1]. Moreover, even significant translational force leading to movement within certain tissues, such as skeletal muscle, may be clinically irrelevant provided there are no adjacent critical nerves or vessels [1]. However, these are only suggested principles. Actually predicting how much force is too much for a given anatomic tissue relative to the presence of a ferromagnetic object is difficult to determine and beyond the scope of this study. An additional factor that must be taken into consideration is the risk of performing the MRI examination relative to the benefit provided to the patient.

MRI-related heating

Magnetic resonance imaging–related heating of a metallic object is related to the material's conductivity, mass,

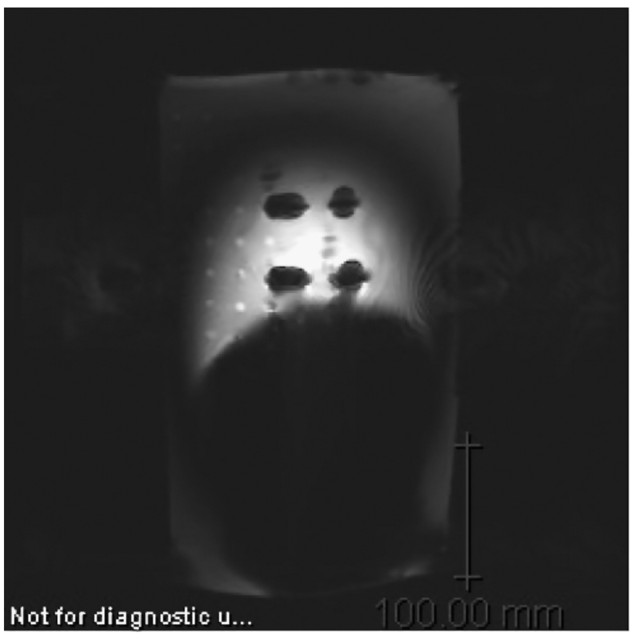

Fig. 6. Magnetic resonance imaging–induced artifact observed for the five different bullets shown in Fig. 5 at 3-T (gradient echo pulse sequence). Note the excessive signal void associated with Bullet 32.

Table 4
Summary of MRI artifacts at 3-Tesla for five different bullets

		Signal void size	
Bullet no.	MRI sequence	Long axis (mm^2)	Short axis (mm^2)
8	GRE	562	333
10	GRE	543	275
23	GRE	395	304
25	GRE	430	300
32	GRE	41,772	30,516

MRI, magnetic resonance imaging; GRE, gradient echo.

length, and shape [1,20]. As such, there is a possibility that a bullet could heat during an MRI examination. Smith et al. [13] found that, of nine bullets tested, there was a temperature increase of 1 to 4°F that was not significantly different from a 2°F temperature rise in a 12-cm^3 control gel phantom [13]. Moreover, these investigators did not find any correlation between bullet composition or weight and change in temperature [13]. Importantly, it is difficult to interpret these findings or to consider them reassuring as the techniques for measuring MRI-induced heating by Smith et al. [13] does not meet the current testing methods, as presented by American Society for Testing and Materials International [20].

Although the results in the present study showed that the temperature of bullets increased up to 0.2°C above background heating in an extreme RF environment, this temperature rise is clinically insignificant [22]. With regard to the potential for substantial MRI-related heating of an object, the length of the item (or bullet in this case) must be resonant with the transmit RF frequency used during the MRI examination [23]. Transmitting RF at 64 MHz (1.5-T) or 128 MHz (3-T) will not create such conditions for objects with lengths that are relatively short (ie, range, 16.0–29.5 mm), like the bullets that underwent evaluation in this study [23].

Artifacts

Artifacts associated with a metallic implant or a retained metallic object are primarily dependent on the magnetic susceptibility of the material, object's dimensions, static magnetic field strength of the MR system, and imaging parameters [1,24,25]. Using a clinical pulse sequence intended to inherently generate large artifact at 3-T, the steel-containing bullet tested (no. 32) caused a very large signal void (loss) that could interfere with the diagnostic interpretation of nearby anatomy but might be inconsequential if the anatomy of interest was located some distance from the bullet. In contrast, the non–steel-containing bullets were associated with small signal voids that would be compatible with visualizing all but contiguous anatomic structures. Importantly, optimization of imaging parameters is typically performed in the clinical setting to minimize artifacts when metallic objects are in the area of interest [25].

Possible limitations

A possible limitation of this study is the somewhat limited number and variety of bullets tested. The test samples were obtained from the San Francisco Police Department to provide a representative sample of those commonly seen in urban criminal trauma and hunting accidents. In comparison to the samples studied by Smith et al. [13] from the Cleveland Police Department, there are obvious differences. Nevertheless, we believe that it would be clearly impractical to test all possible bullet and pellet types available and that our particular collection of ballistics is complimentary to those of prior investigations [2,13].

We recognize that our samples were biased toward non-military bullets manufactured within the United States. The findings of Smith et al. [13] and Teitelbaum et al. [2] suggested that the most likely bullets to be problematic in MRI in terms of translational attraction were foreign made and military ordnance. Foreign-made bullets present a particular challenge because they are likely to have impurities. Future studies could address this issue by focusing on a subset of foreign and military ballistics.

Another possible limitation with respect to our findings on torque and heating is that both phenomena are dependent on the bullet's length. Although we tested bullets in their native form, when a bullet actually enters the body it will occasionally fragment or deform, especially if it has a hollow point. Nevertheless, we believe that our results are relevant because torque is also a function of mass as well as shape and heating a function of length, both of which would be relatively decreased in the multiple pieces generated from a fragmented bullet in situ.

One might criticize the decision to test for magnetic field interactions at 7-T because 7-T scanners are predominantly used for research applications and rarely used to scan patients with metallic implants. However, we believe that these very–high-field scanners may become widely used for clinical purposes in the future and, therefore, these data with respect to retained bullets are potentially relevant.

An additional possible limitation is that, although the findings of this study provide information about how a bullet or a pellet might behave in an MRI environment, it is not a simple matter to apply this in clinical decision making. First, as has been suggested previously, each tissue environment presents different potential safety concerns. For example, a bullet subjected to translational force in the quadriceps muscle is less likely to cause problems than one lying adjacent to the spinal cord or within the brain parenchyma. Furthermore, once present in soft tissue, encapsulation of the foreign body, which happens over time, could well prevent the object from being displaced when subjected to a powerful static magnetic field.

The intent of this investigation was not to provide definitive recommendations for or against the use of MRI with patients who have retained ballistics but rather to generate information with which to help judge the overall risk versus benefit of imaging on a case-by-case basis. Additionally, our finding that lead-only ballistics neither moved nor induced large imaging artifacts raises the question of how a clinician can determine the composition of a retained bullet before imaging. To our knowledge, there is no simple way to do this other than to obtain forensic information from law enforcement involved in the case that may help guide the decision-making process. Interestingly, a recent report from Karacozoff and Shellock [26] suggests that the use of a ferromagnetic detection system designed for identifying external ferromagnetic objects can also detect internal ferromagnetic foreign bodies, like an armor-piercing bullet. Thus, further investigation of using a ferromagnetic detection system as a screening tool for patients with injuries related to ballistic objects referred for MRI examinations is warranted.

Even with the possible limitations stated previously, the results of this investigation contribute to the existing peer-reviewed literature. Although prior studies demonstrated that non–steel-containing bullets were not associated with significant magnetic field interactions in 1.5-T MRI environments, we have shown that this holds true in 3- and 7-T MRI systems, as well [2,13].

Conclusions

Findings from the MRI tests indicated that non–steel-containing bullets and pellets did not exhibit magnetic field interactions at 1.5-, 3-, and 7-T and that both steel-containing and non–steel-containing bullets did not significantly heat, even under extreme MRI conditions at 3-T. Furthermore, steel-containing bullets were likely unsafe for patients referred for MRI because of their potential to move in vivo although this recommendation must be interpreted on a case-by-case basis with respect to the restraining effect of the specific tissue environment, time in situ, proximity of vital or delicate structures, and with careful consideration given to the risk versus benefit for the patient. Artifacts on MR images were associated with both steel-containing and non–steel-containing bullets, but the magnitude was much larger in the former than the latter, which is related to the magnetic susceptibility of the related materials [21].

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