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MR of Ballistic Materials: Imaging Artifacts and Potential Hazards

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The most common ballistic materials available in the urban setting were studied for their MR effects on deflection force, rotation, heating, and imaging artifacts at 1.5 T to determine the potential efficacy and safety for imaging patients with ballistic injuries. The 28 missiles tested covered the range of bullet types and materials suggested by the Cleveland Police Department. The deflection force was measured by the New method. Rotation was evaluated 30 min after bullets had been placed in a 10% (weight per weight) ballistic gelatin designed to simulate brain tissue, with the long axis of the bullet placed parallel and perpendicular to the Z axis of the magnet. Heating was measured with alcohol thermometers by imaging for 1 hr alternatively with gradient-echo and spin-echo sequences (RF absorption = 0.033 and 0.326 w/kg respectively). Image artifacts on routine sequences were evaluated. All the steel-containing bullets except for the Winchester armor-piercing 38 caliber exhibited deflection. A nonsteel 7.38-mm Mauser also deflected. Deflection range was 514 to 15,504 dynes. Rotation occurred when the bullets were not parallel to the Z axis. Temperature changes were not significant. Deflecting projectiles resulted in obliteration of the image. The artifacts from other projectiles were small but varied by content. The artifact of the Winchester armor-piercing 38-caliber bullet was similar to those without steel.

Bullets that contain steel or ferromagnetic contaminates such as nickel can be rotated within the MR unit. Ferromagnetic contaminants do not allow nonsteel bullets to be imaged with confidence; the potential rotation and movement of these missiles results in a relative contraindication to MR, although location within the body and time since injury may be modifying conditions. Missiles with nonaustenitic steel or nickel in the area of interest make images useless, while projectiles without these materials cause minimal image distortion and signal void.

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CT has been proved valuable in the examination of patients who have sustained ballistic injuries, especially in the brain [1–4]. The need for MR evaluation of patients with ballistic injuries is increasing. More than 20,000 Americans are killed by handguns each year, and every 2½ min someone is injured by a handgun [5]. A recent study sites the MR imaging of seven patients with retained projectiles without incident and also reports the rotation of several bullet types within the field [6]. The present study was undertaken as preliminary work to examining patients with retained projectiles. The most common ballistic materials available in the urban setting were studied for deflection force, rotation, heating, and imaging artifact on a high-field system.

Background

The components of a handgun or rifle bullet may vary by their location within the bullet (Fig. 1). In general, the bullet can be a solid metal or compartmented. Compartmented bullets have varying materials in the tip, body, and/or core. An

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outer jacket or coating may be present. The tip may be a solid material, which is lead and some base metal. Soft tips indicate that more pure lead has been used to increase expansion. The "hollow-point" tip is usually soft lead with a depression, which results in controlled expansion for increased damage on contact with soft tissues.

The core of the bullet may be solid metal (i.e., lead) or a cylinder filled with a mixture of elements, such as Teflon and lead, or with exploding pellets surrounded by mercury and powder with a lead base. Solid metal lead-base bullets are primarily made of lead/antimony alloys. Arsenic is usually present, and the quantity of antimony and arsenic increases with increasing caliber (W. Smith, Remington Fire Arms, personal communication). Trace metals in lead bullets can include tin, silver, gold, nickel, platinum, and bismuth (Table 1). The steel of steel-jacketed and steel-load bullets may vary by manufacturer, the nature of which is proprietory. In general, they are composed of tungsten steel with nickel or of carbide steel. An outer jacket may be present to improve the piercing ability of the bullet; the composition of this jacket is typically 90% or more copper with a small amount of zinc. A full metal jacket or case covers the whole bullet, including the tip. A semijacketed case leaves the tip exposed. The jackets are generally made of a copper/zinc alloy. Steel and Teflon coating are used on armor-piercing bullets. A coating may be used in lieu of, or in addition to, a jacket, which is essentially a dry lubricant known as gilding; this is usually a copper/zinc alloy and is thinner than a jacket. The Luboloy (Winchester and Western) coating is basically copper. Shot is made of steel or lead. The use of steel shot is still minimal but is increasing as local and federal guidelines change to protect water fowl areas from lead poisoning. The shot is usually round but recently has been made in cube shapes. Buckshot indicates a larger-gauge shot projectile. A slug is a very large cap of lead.

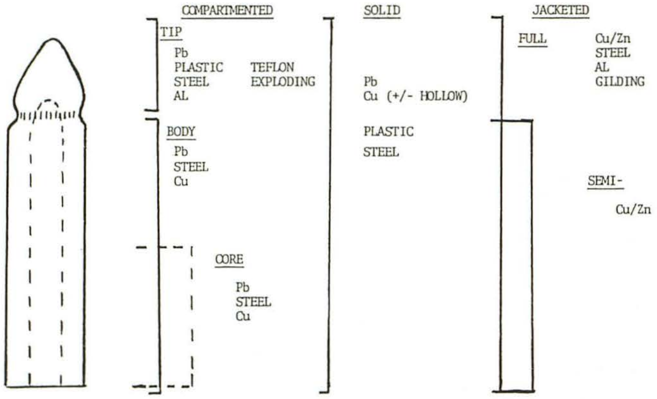

Fig. 1.—Anatomy of a bullet. The metals within different compartments or parts of the bullet may vary.

TABLE 1: Magnetic Susceptibility of Metals Found in Ballistic Materials[a]

Metal	Magnetic Susceptibility[b]
Aluminum (Al)	+16.5
Al_2O_3	−37
Antimony (Sb) s	−99.0
Arsenic (As) s	−5.5–−23.7
Bismuth (Bi) s	−280.1
Copper (Cu) s	−5.46
CuO[c]	+250
$CuCl_2$	−1020
Gold (Au) s	
Lead (Pb) s	−23.0
PbO[c]	−42
Nickel (Ni)	(Ferromagnetic)
Nickel compounds	+190 = +6145
Platinum s	+201.9
Silver (Ag) s	−19.5
Tin (Sn) s	−37.0–+3.1
Tungsten (W) s	+59
Zinc (Zn) s	−11.4

[a] From [11].
[b] Dimensionless units (10^6 cgs system).
[c] Will be formed at various concentrations depending on conditions.
Note.—s = solid.

Materials and Methods

A collection of bullets and shot containing the most common types of ballistic materials in the urban setting as well as a range of materials found in bullet composition was compiled by the ballistics section of the forensic laboratory of the Cleveland Police Department (Table 2). The ballistic materials used were nondeformed and without cartridges. The deflection force of the materials was determined by the New method [7] at the fringe field of a 1.5-T MR unit (Picker International, Highland Heights, OH). This method was chosen to maintain consistency with other papers on metallic projectiles in MR systems. The deflection force was determined by the equation $F = mg \sin \phi / \cos \phi$, where the deflection force (F) equals the product of the mass of the bullet in grams (m), the gravitational acceleration constant (g) (980 cm/sec^2), and the deflection angle from the vertical (ϕ). F is the force in dynes in cgs units. Rotation was studied by placing the bullets in a 10% weight per weight ballistic gelatin (Kind and Knox Co., Saddlebrook, NJ, Type A, 250 Bloom Gelatin) to simulate brain tissue. To test for rotation, the long axis of the bullets was placed parallel and perpendicular to the Z axis at the center of the magnet's cylinder for 30 min. Evaluation of potential heating was performed on a limited number of 38- and 25-caliber bullets. Heating effects were determined by placing the bullets in contact with the bulb of alcohol thermometers within a 12-cm^3 block of gel. The thermometers had 1°F increments. Imaging sequences of a gradient-echo (GRE) (500/18 [TR/TE], 20° flip angle) and multiecho spin-echo (SE) series (2000/20,100) were alternated for 1 hr. Standard software estimated the RF deposition for these sequences to be 0.003 and 0.326 w/kg, respectively, with a 30-cm field of view (FOV), 192 × 256 matrix, and two excitations. The maximum system gradient strength was 1 mT/m. Projectiles in the ballistic gelatin were imaged in the vertical plane orthogonal to the Z axis of the magnet using saline bags to help RF tuning (Fig. 2). To evaluate image artifacts, the projectiles were separated into categories of copper-jacketed, nonsteel; non-copper-jacketed, nonsteel; and those with any steel component. Imaging was performed with the materials within the gel, in a 25-cm quadrature head coil. Sequences included SE 500/26 and 1800/100, and GRE 550/13/15°, with a 192 × 192 matrix, 20-cm FOV, one excitation, and 3.5-mm slice thickness. A single 12-gauge (0.160-mm) steel shot (#28) was also imaged at a 25-cm FOV with the SE 550/26 sequence. Horizontal frequency encoding was used in all imaging.

TABLE 2: Data Summary of the Most Common Projectiles Available in the Urban Setting[a]

Bullet No.	Caliber	Manufacturer	Weight (g)	Deflection (dynes)	Tip	Body	Core	Covering		
								Gild	SMC	FMC
Copper-Jacketed NonSteel Bullets										
1.	.25 auto	Rem	50	—	Pb (r)	Pb	Pb			Cu
2.	.32 auto	Rem	71	—	Pb (r)	Pb	Pb			Cu
3.	.45	Win				Pb	Pb			Cu
4.	.38 SP semiwadcutter	USAC	158	—	Pb (r)	Pb	Pb			Cu
5.	7.38-mm Mauser	Century Arm	86	1691	Pb (r)	Pb	Pb			Cu
6.	.38 SP	Spur	125	—	Pb (h)	Pb	Pb		Cu	
7.	.38 SP + P	Rem	125	—	Pb (h)	Pb	Pb		Cu	
8.	.38 SP	Win super X	125	—	Pb (h)	Pb	Pb		Cu	
9.	.38 Glasser safety slug	W & W	54	—	Teflon (h)	Pb	Pb Pellet/Teflon		Cu	
10.	.44 semiwadcutter	Rem	224	—	Pb (h)	Pb	Pb		Cu	
11.	.22 (rifle)	Rem	40	—	Pb (r)	Pb	Pb		Cu-Gild	
12.	.22 (rifle)	Win	40	—	Pb (r)	Pb	Pb		Luboloy	
Non–Copper-Jacketed NonSteel Bullets										
13.	.38 SP	CCI (Blazer)	158	—	Pb (h)	Pb	Pb			
14.	.38 SP wadcutter	Fed	148	—	—	Pb	Pb			
15.	.38 SP semiwadcutter	S & W (nyclad)	158	—	Pb (h)	Pb	Pb			
16.	.45			—	Pb (h)	Pb				
17.	.22 (rifle)	Win	38	—	Pb (r)	Pb	Pb			
18.	9 mm	Bat		—	Plastic (r)	Cu	Cu			
19.	.38 JSP + P	PMC (tubular)	66	—	—	Cu-hollow	(None)			
20.	.357 silver-tip	Win	125	—	Al (h)	Pb	Pb			Al
21.	Slug	Rem	443	—	N/A	Pb				
22.	18 shot	Rem	52	—	N/A	Pb	Pb			
Steel-Containing Bullets										
23.	.25 auto	Gego	50	514	Steel (r)	Steel	Steel			Steel
24.	.30-06	Win (armor piercing)	164	5887	Pb (p)	Pb	Steel			Steel
25.	.38 SP	KTW (armor piercing)	88	10,180	Pb (p)	Pb	Carbide steel	Cu		
26.	.38	Win (armor piercing)	66	0	Pb (p)	Pb	Steel		Cu	
27.	7.62 × 39 mm	Chinese military	122	15,504	Pb (p)	Pb	Steel	Cu		
28.	12-gauge shot (0.162 mm)	Rem	3.8	Not tested	N/A		Steel			

[a] Suggested by the Ballistic Section, Cleveland Police Department Forensic Laboratory.

Note.—r = round, p = pointed, h = hollow, Gild = gilding (dry lubricant), SMC = semijacketed case, FMC = full metal jacket or case, SP = special, P = plus powder, JSP = jacketed soft point, Bat (USA), CCI = Cascade Cartridge Industry (USA), Fed = Federal Arms (USA), Gego (Germany), KTW (USA), PMC = Pan Metal Co. (Korea), Spur (USA), Rem = Remington Arms (USA), S & W = Smith and Wesson (USA), W & W = Winchester and Western (USA), Win = Winchester (USA), USAC = United States of America Cartridge (USA).

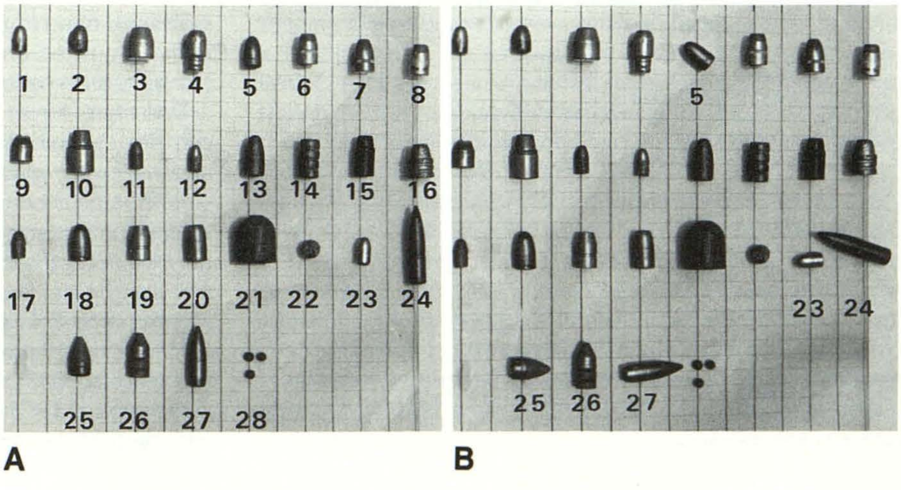

Fig. 2.—*A*, Projectiles oriented along the Z axis of the magnet did not move after 30 min.

B, Placement of the projectile axis perpendicular to the Z axis resulted in 90° rotation for the following steel-containing projectiles: the Gego 25-caliber automatic (#23), the KTW armor-piercing (#25), and the 7.62 × 39 mm Chinese military (#27); and 60° rotation for the .30-06 Winchester armor-piercing (#24). The steel-cored Winchester armor-piercing (#26) did not rotate, while the nonsteel Century Arm 7.38 Mauser (#5) rotated 45°.

Results

As noted in Table 2, there was no deflection force on the lead bullets except for #5. All the steel-containing bullets except for the Winchester armor-piercing 38 caliber (#26) exhibited deflection. The steel shot was not tested.

Deflection forces exhibited by the steel-containing bullets ranged from 514 dynes for the Gego 25-caliber automatic all steel (#23) to 15,504 dynes for the steel-core 7.62 × 39 mm Chinese military issue (#27). The 7.38-mm Mauser (#5), which theoretically contains no ferromagnetic materials, deflected to 1691 dynes. The identity of the Century Arm 7.38-mm Mauser (#5) and the 38-caliber Winchester armor-piercing (#26) bullets were confirmed and retested with no change in results.

Rotation did not occur when the ballistic materials were aligned with the Z axis of the magnet (Fig. 2). Rotation of the bullets that had shown deflection forces occurred when the bullets were arranged perpendicular to the Z axis. After 30 min, 90° rotation was present in the Gego 25-caliber automatic (#23), the 7.62 × 39 mm Chinese military issue (#27), and the 38 special KTW armor-piercing bullet (#25). The .30-06 Winchester armor-piercing bullet (#24) rotated 60° and the 7.38 Century Arm Mauser (#5) rotated 45°. The 12-gauge 0.160-mm steel shot (#28) did not move.

The temperature change in the 12-cm^3 control gel rose 2°F; temperature changes in the bullets ranged from 1–4°F (Table 3). The small range of temperature changes relative to the control gel was not significant, and no correlation was made between bullet content or size and the change in temperature.

There was extensive image artifact in the presence of steel-containing bullets, except for #26. The single 0.160-mm steel shot resulted in approximately 14 cm of field distortion on SE imaging (550/20) (Fig. 3). Copper-jacketed nonsteel bullets showed no field distortion except for the 7.38 Mauser (#5), which distorted the image (Fig. 4). Nonsteel projectiles had signal void at the site of the bullet with a thin perimeter of field distortion that was bright on SE sequences. GRE images had slightly more artifact, making surface features less recognizable, but they had less bright perimeter artifact than SE images (Fig. 5). The copper-bodied bullets (#18 and #19) showed a significantly brighter perimeter artifact. The aluminum tip of the .357 silver-tipped Winchester (#20) resulted in field distortion of 3.5–7 cm for SE and GRE images, respectively.

TABLE 3: Temperature Changes in Bullets vs Control Gel

Material[a]	Temperature Change[b] (°F)
38 Caliber	
Lead, copper jacket	
#4	4
#8	2
Lead, nonjacketed	
#13	2
#14	2
Steel core #26	2
All copper #19	2
Lead/Teflon #9	2
25 Caliber	
All steel #23	1
Lead, jacketed #1	3
12 cm^3 control gel	2

[a] Numbers refer to corresponding bullet numbers in Table 1.

[b] Temperature changes of selected projectiles imaged for 1 hr did not differ significantly from the control.

Discussion

Safety is the primary concern when considering MR imaging of a patient who has been shot. As with other metallic foreign objects or prostheses, movement, rotation, and heating of bullets or shot pose potential dangers to tissue.

The possibility that the bullet or shot in a patient contains steel is increasing. Although most American-made handgun bullets contain lead and lead/copper combinations, in recent years the ammunition market has been filled with inexpensive imported bullets that make use of available steel. The prevalence of assault-style weapons also adds to the number of ballistic materials that may contain steel. Changes in fowl hunting guidelines have resulted in the replacement of lead shot with steel in an effort to reduce fish and water contamination.

Trace elements and ferromagnetic "contaminants" may cause rotation and movement of bullets that are expected to be nonferromagnetic by component specifications (Table 2). Nickel is a frequent trace element in lead bullets and can be ferromagnetic; therefore, knowledge of the bullet type does not eliminate risk of rotation. Although elemental nickel and some nickel alloys are ferromagnetic [8], nickel is also a component of stabilized steel in a nonferromagnetic form [7]. Steel-containing bullets may not react to the field if the content is austenitic steel. Knowledge of the exact type of bullet, such as is available in an accidental shooting, could significantly impact the decision to do clinical MR imaging.

The possibility of rotation of steel-containing bullets that are not parallel to the Z axis of the magnet could be hazardous, depending on several factors, such as the type of tissue around the object (i.e., solid parenchyma versus a fluid-filled cavity), the proximity and fragility of vital tissue (i.e., arteries, nerves, and eyes), and the length of time the bullet has been in the body. However, fibrosis around a foreign object in the brain, eye, or other vital soft tissue can be weak [9]. The possibility of up to 90° rotation of a ferromagnetic object, as in the simulated brain tissue in the experiment, results in a strong relative contraindication to MR imaging.

Deflection force was studied as opposed to the more complex measurements needed to determine torque. Ballistic materials within patients can be deformed with unpredictable variations, and since the geometry of objects alters the torque, in vivo factors are not reproducible. The fringe field of the MR unit is the location of greatest magnetic field gradient and may be the location of the greatest expected deflection of ferrous materials [8, 10, and Cohen JE et al. paper presented at the Society of Magnetic Resonance in Medicine, Amsterdam, 1989]. An accurate description of torque requires knowledge of (1) the object's magnetic susceptibility, which may be field dependent; (2) the grad (first spatial derivative)

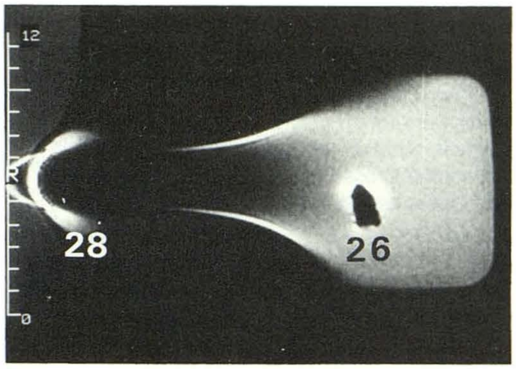

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Fig. 3.—A single 0.160-mm 12-gauge steel shot results in approximately 14 cm of field distortion. The steel shot was on the left. On the right is #26, the .30-06 Winchester armor-piercing bullet, which has a steel core but had no deflection. Note the perimeter artifact caused by the copper jacket. (MR image 500/30/1.)

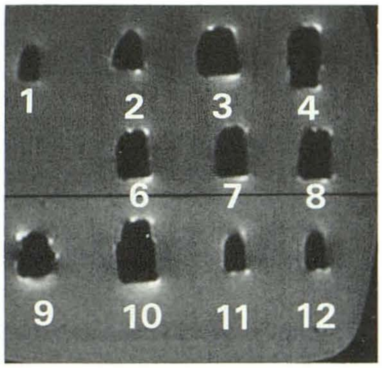

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Fig. 4.—Copper-jacketed nonsteel bullets. Composite image shows minimal bright perimeter artifact on spin-echo MR imaging (550/26/11). (7.38 Mauser [#5] not shown owing to large artifact.)

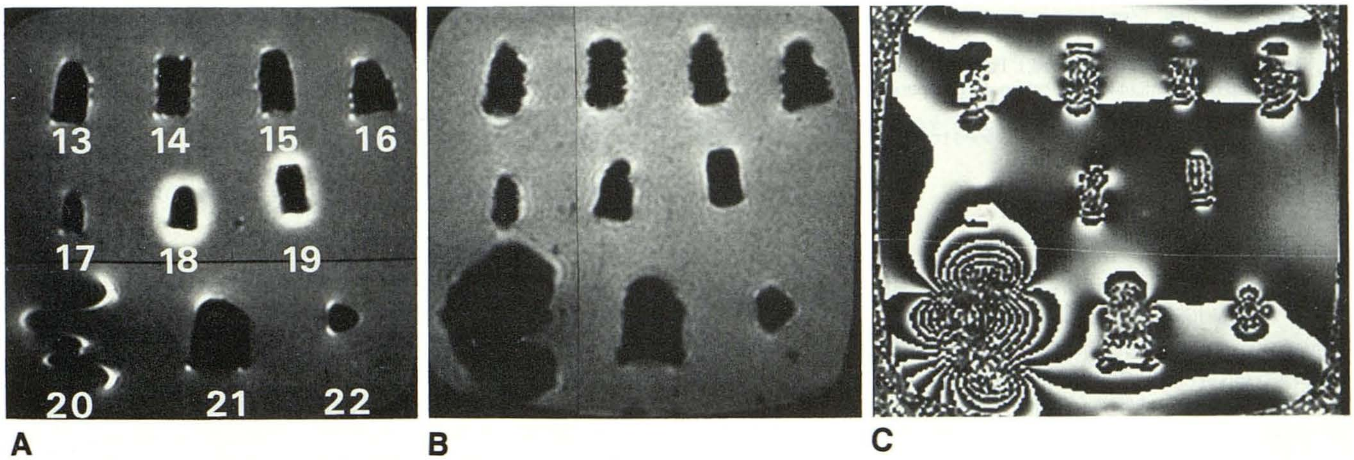

Fig. 5.—Nonjacketed nonsteel bullets.

***A*, Spin-echo MR image (550/26) of the copper-body bullets (#18 and #19) shows significantly brighter perimeter artifact than do comparable images of the all-lead bullets. The aluminum-tipped .357 silver-tipped Winchester (#20) distorts 3.5 cm of the field.**

***B*, On gradient-echo imaging (550/13/15°) the copper-body bullets did not differ in the artifact produced from those of lead, but all showed some shape distortion. The aluminum-tipped #20 distorts 4.8 cm of the field.**

***C*, Phase image of *B* shows distortion at #20 is about 7 cm. All images at 20-cm field of view, 192 × 192 matrix, and one excitation.**

of the field; and (3) the field itself [10 and Cohen JE, SMRM paper]. Although torque was not directly measured, the results of the rotation experiments could be interpreted in terms of a threshold of torque large enough to cause rotation. This interpretation was not attempted because of the possibility of significant errors in applying this analysis to in vivo situations [11].

The change in temperature demonstrated could not be judged significant considering the rise in temperature in the control gel. The gelatin that contained the ballistic sample did not allow for distribution of heat over a large volume or stabilization by circulating blood. The area of contact between the bullet and thermometer was admittedly small. To date, no clinically significant heating has been detected in small metallic objects or implants [12, 13].

Image distortion by bullets depends on the amount and relative magnetic susceptibility of the metal components (e.g., oxides) (Table 1), the object's shape, the mode of postprocessing [12, 14], and the pulse sequence. GRE images yield larger artifacts owing to their greater sensitivity to local field distortion. The magnetic susceptibility of the metal, whether ferromagnetic or nonferromagnetic, can affect the image, but the effect is much greater for ferromagnetic materials [15] (Fig. 3).

In conclusion, the potential hazard to patient safety in MR imaging of persons who have retained bullet or shot material is multifactorial. The rotation and movement of bullets containing ferromagnetic materials is a realistic concern, as shown in the simulated brain tissue of these tests. The presence of a ballistic projectile should be viewed as a relative contraindication to MR imaging dependent on the following: the type and location of the projectile, proximity and fragility of vital tissue, time since injury, and clinical value of MR. When imaging projectiles of unknown metal content, it should be assumed that they contain steel, and that there is the attendant risk. Imaging of nonferromagnetic bullets is not contraindicated by the degree of image artifact, but it should still be approached with caution since technical specifications may not indicate small amounts of ferromagnetic contaminants, such as nickel.

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