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Metallic Ballistic Fragments: MR Imaging Safety and Artifacts[1]

The ferromagnetism of various bullets and shotgun pellets was tested in vitro. Magnetic deflection showed that four of 21 metallic specimens tested (all bullets) demonstrated marked ferromagnetism. Three of these four were made outside the United States; two of the four were known to contain steel, and the other two were reportedly either copper or copper-nickel-jacketed lead bullets (indicating that the ferromagnetism was due to impurities in the bullet jackets or cores). Ferromagnetic bullets readily rotated within a gelatin phantom in response to magnetic torque. Nonferromagnetic bullets and pellets demonstrated only mild to moderate metal artifact during spin-echo and gradient-echo magnetic resonance (MR) imaging. However, all four of the ferromagnetic bullets produced severe MR artifacts and image distortion. MR studies of seven patients with retained bullets, pellets, or shrapnel were reviewed. In six of the seven, only mild MR artifacts were seen. Only intracranial shrapnel (presumably steel) in one patient created significant artifact. All seven patients with retained bullets and shotgun pellets were imaged safely with MR. However, caution should be exercised with MR imaging in the presence of metallic foreign bodies, particularly if they are located near vital neural, vascular, or soft-tissue structures.

Index terms: Foreign bodies • Iron • Magnetic resonance (MR), artifact • Magnetic resonance (MR), safety • Trauma

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With the nationwide increase in gang- and drug-related violence, and with the large number of previously wounded war veterans, important questions arise regarding the safety of magnetic resonance (MR) imaging and imaging artifacts in the presence of retained metallic ballistic fragments. To address these questions, we evaluated, in vitro, the ferromagnetism, magnetic torque and migration, and MR imaging artifacts of the types of bullets and shotgun pellets most often encountered in criminal trauma and police action. In addition, we reviewed MR studies of seven patients with retained bullets, pellets, or shrapnel to assess artifact production and any untoward effect resulting from MR imaging in the presence of these metallic foreign bodies.

MATERIALS AND METHODS

Bullets and Pellets

We tested 21 types of the more commonly encountered bullets and shotgun pellets (Table). Seven of the 21 were produced outside the United States. Bullets ranged in caliber (bore diameter in inches of the barrel of the firearm in which the bullet is used) from .357 to .45. The shotgun pellets we tested ranged in diameter from 0.095 inch (shot size 7½) to 0.330 inch (buckshot size 00). Various bullet types were examined, including round-nose, hollow-point, and full-metal-jacket varieties (Fig 1). Bullets were removed from their cartridges with a kinetic bullet puller (Quinetics, San Antonio, Tex). All bullets and pellets were weighed.

Magnetic Deflection, Rotation, and Migration of Bullets and Pellets

All bullets and pellets were suspended by a thread at the magnetic portal of a 1.5-T superconducting MR imaging unit (Gyroscanner; Philips Medical Systems, Shelton, Conn). The deflection angle from the vertical (average of three measurements) and alignment within the static magnetic field (B_0) for each metallic object were noted and recorded. The magnetic deflection force for each object was determined with the equation $F = mg \cdot \tan\theta$, where F = deflection force (dynes), m = mass of object (grams), g = gravitational acceleration constant (980 cm/sec^2), and θ = deflection angle from the vertical.

The above test for ferromagnetism is largely qualitative due to inaccuracies imposed by the wide and unusual spatial variations in the B_0 field that are possibly present at the magnetic portal of an MR unit. This is, however, the method that has been used by previous investigators (1–3). A firm gelatin phantom was prepared for each metallic object with 3.5 g of powdered unflavored gelatin (Knox Gelatine, Englewood Cliffs, NJ) dissolved in each 100 mL of heated water used. Each metal object was centrally fixed within 180 mL of the gelatin mixture in an 8-fl-oz (237-mL) Styrofoam coffee cup. The location and orientation of each object within its phantom was observed and recorded when the gelatin was completely set. The gelatin phantoms with their embedded bullets or pellets underwent MR imaging at 1.5 T, with the phantoms positioned so that the bullets were aligned with their long axis parallel to the B_0 field. Afterward, any longitudinal displacement of a metallic object that had occurred during imaging was measured and recorded. The propensity of a bullet to rotate within its gelatin phantom in response to magnetic torque was assessed by positioning the phantom at the magnetic portal of a 1.5-T MR unit so that the long axis of the bullet was initially per-

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Abbreviations: GRE = gradient echo, SE = spin echo.

Composition, Ferromagnetism, and MR Artifacts of Bullets and Pellets

Metallic Object	Caliber	Composition	Manufacturer	Country of Origin	Mass (g)	Deflection Angle at 1.5 T (degrees)	Deflection Force (dynes × 10⁴)	Artifact SE	Artifact GRE
1	.380 inch (ACP)	Copper cup with plastic cap, lead bullet	Glaser	USA	4.247	0	0	+	+
2	.44-inch magnum (KTW)	Teflon-coated bronze bullet	North American Ordnance	USA	10.679	0	0	+ to ++	++
3	7.62 × 39 mm	Copper-plated, steel-jacketed, steel core bullet	Norinco	China	7.910	>89	>44.4	+++	+++
4	.357 inch (.38 spl)	Copper-jacketed lead bullet	Cascade	USA	9.703	0	0	+	+
5	.357 inch	Lead bullet	Remington	USA	10.202	0	0	+	+
6	.357 inch (.38 spl)	Aluminum-jacketed lead bullet	Winchester	USA	6.139	0	0	+	+
7	9 mm	Copper-jacketed lead bullet	Remington	USA	7.336	0	0	+	+
8	.380 inch (ACP)	Copper-nickel-jacketed lead bullet	Geco	FRG	5.981	80	3.3	+++	+++
9	.357 inch	Nickel-plated, Copper-jacketed lead bullet	Winchester	USA	9.342	0	0	+	+ to ++
10	.357 inch (.38 spl)	Nylon-coated lead bullet	Smith & Wesson (Federal)	USA	10.288	0	0	+	+
11	12 gauge, size: 00	Copper-plated lead shot	Federal	USA	3.479	0	0	+	+
12	7½ shot	Lead shot	Unknown	USA	0.082	0	0	+	+
13	4 shot	Lead shot	Unknown	USA	0.210	0	0	+	+
14	00 buckshot	Lead shot	Unknown	USA	3.385	0	0	+	+
15	.45 inch (ACP)	Steel-jacketed lead bullet	Evansville Ordnance	USA	14.755	75	5.4	+++	+++
16	.357-inch magnum	Copper-jacketed lead bullet	Fiocchi	Italy	9.202	0	0	+	+
17	.357 inch (.38 spl)	Copper-jacketed lead bullet	Hornady	USA	12.715	0	0	+	+ to ++
18	9 mm	Copper-jacketed lead bullet	Norma	Sweden	7.421	81	4.6	+++	+++
19	.357 inch (.38 spl)	Bronze tube, plastic plug	Patton-Morgan	Korea	4.151	0	0	+	+
20	.357 inch (.38 spl)	Copper-coated lead bullet	Patton-Morgan	Korea	10.303	0	0	+	+
21	.45 inch (ACP)	Copper-jacketed lead bullet	Samson	Israel	12.008	0	0	+	+

Note.—SE = spin echo, GRE = gradient echo, ACP = automatic Colt pistol, KTW = Kopsch-Turcus-Ward, spl = special, FRG = Federal Republic of Germany.

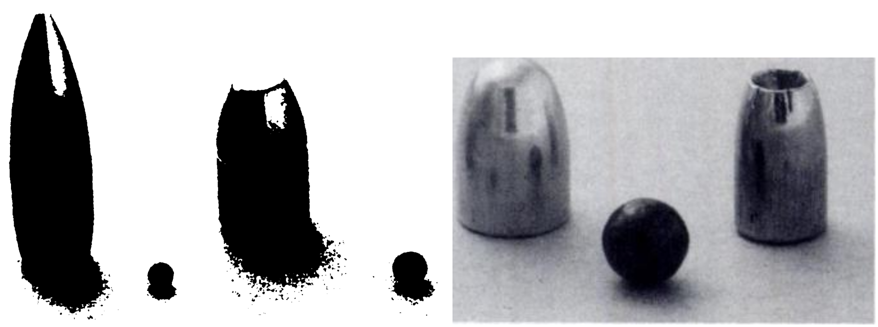


Figure 1. Representative bullets and shotgun pellets examined in this study. Front row (left to right): metallic objects 12, 13, and 14. Second row (left to right): metallic objects 3, 4, 15, and 9 (Table).

pendicular to the direction of the B_0 field. Any rotation of the bullet was observed and recorded. This qualitative technique for assessing torque is suboptimal primarily because torque would be maximal at the center of the magnetic bore. However, we believed that observing rotation at the magnetic portal in a more controlled fashion would be safer, especially when dealing with highly ferromagnetic metallic objects.

MR Imaging of Bullets and Pellets

The gelatin phantoms with their embedded bullets and pellets were imaged with a 1.5-T superconducting MR unit (Philips Medical Systems). Sagittal T1-weighted SE imaging was performed with a 288/28 sequence (repetition time msec/echo time msec), four excitations, a 256 × 256 matrix size, a 35.8-cm field of view, and 5.8-mm-thick imaging sections. Sagittal, single-section GRE imaging (125/18, four excitations, 256 × 256 matrix, 35.8-cm field of view, 5.8-mm-thick sections, and a 38° flip angle) of the embedded bullets and pellets was also performed. The resultant SE and GRE images obtained with the same windowing were examined to assess the level of metal artifact produced by each bullet and pellet. Artifacts were classified as follows: mild (+) = approximately the same size as the metal object; moderate (++) = somewhat larger than the metal object, with little or no significant image distortion; severe (+++) = markedly larger than the object, with image distortion.

MR Imaging of Patients

Over a 3-year period at our institution, seven patients with retained bullets, shotgun pellets, or shrapnel underwent MR imaging of the body regions containing the metallic objects. The five men and two women ranged in age from 18 to 49 years. Locations of ballistic foreign bodies included intraspinous and paraspinous (bullets in two patients), extremity (shotgun pellets in

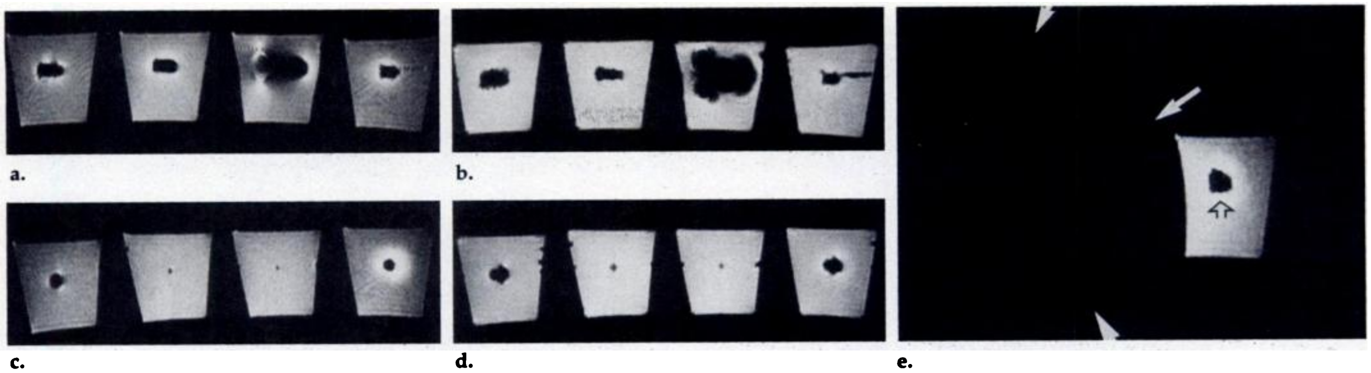


Figure 2. MR images of bullets and pellets in gelatin phantoms. **(a)** T1-weighted SE image of various bullets (left to right, metallic objects 5, 4, 2, and 1 [Table]), with artifact levels of +,+,+ to ++, and + (left to right). Artifacts appear as zones of signal void bordered by crescentic regions of high signal intensity. **(b)** GRE image of same bullets as in **a** demonstrates somewhat greater artifact production by the two bullets on the left. Artifact levels are +,+,++,+ (left to right). **(c)** T1-weighted SE image of shotgun pellets (left to right, metallic objects 14, 13, 12, and 11 [Table]), with an artifact level of + for all pellets. **(d)** GRE image of the same pellets as in **c** demonstrates no significant increase in artifact level for any pellet. **(e)** T1-weighted SE image of ferromagnetic bullet (solid arrows, metallic object 15) and a nonferromagnetic, low-artifact bullet (open arrow, metallic object 21 [Table]). The ferromagnetic bullet creates a severe "black hole" artifact (+++) that obliterates the image of its gelatin phantom and distorts the contour of the adjacent phantom containing the low-artifact bullet.

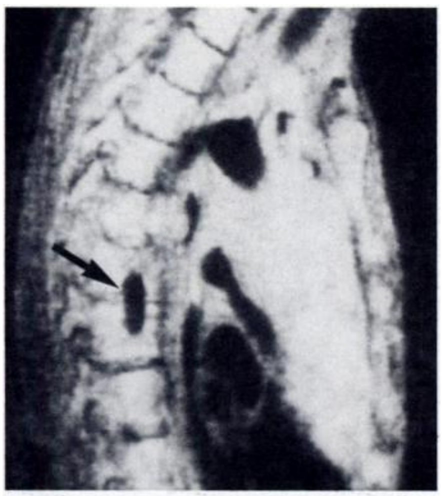


Figure 3. Sagittal T1-weighted SE image, obtained at 0.5 T, of a 48-year-old woman who had a thoracic gunshot wound in the remote past. The MR study was performed to assess for the presence of spinal metastases from squamous cell carcinoma of the lung. The low level of metal artifact created by a retained intraspinous bullet (arrow) does not interfere with evaluation of the thoracic spine or mediastinum.

Figure 4. Cine MR study (GRE imaging at 1.5 T) of the heart in a 26-year-old woman who had a thoracic gunshot wound clearly demonstrates the intramyocardial location of a low-artifact bullet (arrow). A left hemorrhagic pleural effusion is seen as a crescentic zone of high signal intensity (arrowheads). Intracardiac and aortic blood flow are seen as high-signal-intensity areas.

two patients), intramyocardial (bullet in one patient), intrathoracic (bullet in one patient), and intracranial (shrapnel fragments in one patient). MR imaging was performed at either 0.5 T or 1.5 T on superconducting MR units (Philips Medical Systems) with both SE and GRE sequences. The images and records of the MR studies were evaluated retrospectively to assess the level of metal artifact created by the bullets and pellets and to determine if any untoward effect occurred as a result of MR imaging. Artifacts were classified as in the section MR Imaging of Bullets and Pellets.

RESULTS

Four (all bullets) of the 21 samples tested demonstrated marked magnetic deflection (Table). Three of these four bullets were produced outside the United States. Two of the four were known to have a steel core and/or jacket, and two were reported to be either copper or copper-nickel–jacketed lead-core bullets. Ferromagnetism in the latter two bullets was probably due to iron impurities in either the bullet jackets or cores.

The four ferromagnetic bullets aligned with their long axis parallel to the B_0 field. Maximum magnetic torque was exerted on these bullets when they were oriented perpendicular to the B_0 field. All four readily (within seconds) rotated 90° within their gelatin phantoms (to align parallel with the B_0 field) after being positioned perpendicular to the B_0 field. No appreciable longitudinal migration of bullets or pellets within the gelatin phantoms was noted after MR imaging.

Most bullets and all pellets created only mild or moderate (+ or ++) artifact during SE and GRE imaging of phantoms (Table). All these metallic objects were nonferromagnetic. Several of the nonferromagnetic bullets did show a moderate increase in their level of artifact production during GRE imaging (Fig 2a–d). All ferromagnetic bullets created severe black hole artifacts, with significant image distortion (Fig 2e).

Six of the seven patients with retained bullets or pellets demonstrated only mild metal artifact levels during MR imaging. Intrathoracic bullets did not interfere with evaluation of the spine (Fig 3), heart (Fig 4), or pleural cavities (Fig 5). Shotgun pellets within the extremities also produced a low level of artifact (Fig 6). However, a minute intracranial shrapnel fragment (presumably ferromagnetic steel) in one patient resulted in a severe black hole artifact that obliterated the image of much of the left middle cranial fossa (Fig 7). No discomfort or neurologic or vascular sequelae resulted from MR imaging in any of the seven patients.

DISCUSSION

Previous studies that examined MR imaging in the presence of various metallic implants and prostheses (1–13) resulted in several contraindications to MR imaging, including the presence of highly ferromagnetic intracranial aneurysm clips and cardiac pacemakers. However, MR imaging has been performed safely in the presence of weakly ferromagnetic intracranial aneurysm clips (14).

The primary risk of MR imaging in the presence of ferromagnetic bullets and bullet fragments is soft-tissue, vascular, and neural injuries caused by rotation of the metallic objects due to

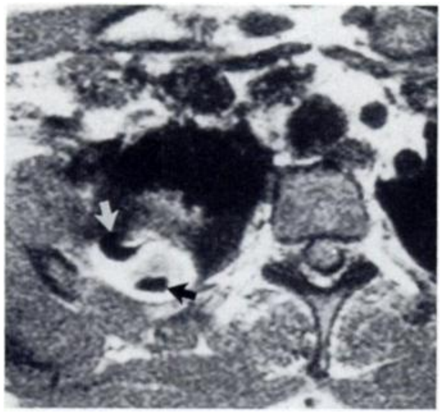
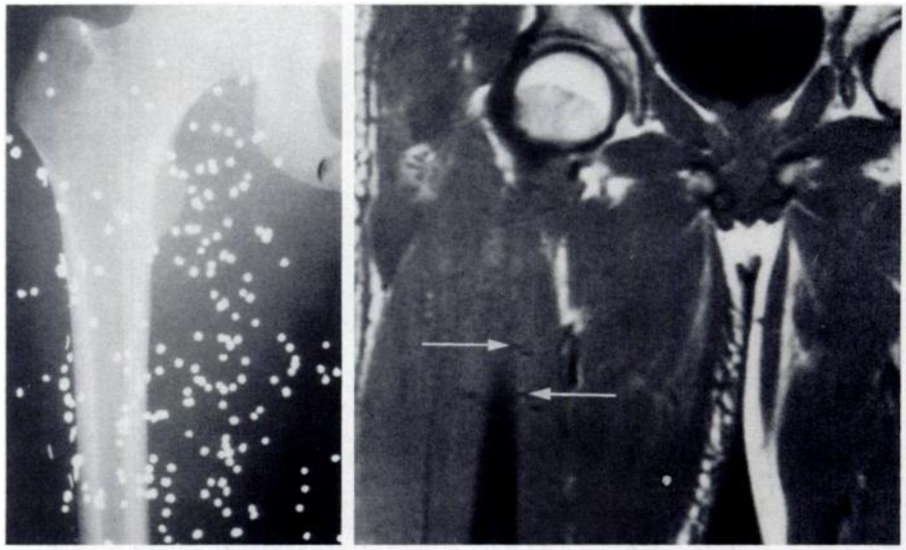


Figure 5. Axial T1-weighted SE image of the chest obtained at 1.5 T demonstrates the presence of retained low-artifact bullet fragments (arrows) within a hemorrhagic right pleural effusion.



a. b.

Figure 6. Images of 18-year-old man who had a shotgun wound to the right thigh. **(a)** Plain radiograph demonstrates numerous shotgun pellets embedded within the soft tissues. **(b)** Coronal T1-weighted SE image of the lower extremities obtained at 1.5 T (a scout image for an MR angiographic examination) reveals scattered minute metal artifacts (arrows) resulting from the pellets.

magnetic torque. Our results suggest that migration of bullets and bullet fragments poses less of a risk. Like metallic implants with a defined long axis (3), bullets align with their long axis parallel to the B_0 field. Torque is maximized when bullets and bullet fragments are oriented perpendicular to the B_0 field.

Gelatin phantoms were used in this study because they provided a convenient means of imaging bullets and pellets. With regard to the role of the phantoms in assessing magnetic torque qualitatively, no attempt was made to closely duplicate the ordnance gelatin used in a previous ballistics study (15), because we believed that no one variety of gelatin would accurately simulate the wide range of densities and resiliences found in various body tissues.

We found that there was significant rotation within the gelatin phantoms for all four ferromagnetic bullets tested. Three of these bullets were made outside the United States, and the other was a military bullet of World War II vintage.

In a previous in vitro study of magnetic torque on bullets (16), commercial sporting bullets were found to be generally nonferromagnetic, whereas military and paramilitary ammunition, particularly from Europe and China, showed varying degrees of ferromagnetism and magnetic torque. Some ferromagnetic bullets, for example, the Norinco 7.62 × 39-mm bullet (copper-plated and steel-jacketed, with a steel core) produced in China for use with the AK-47 assault rifle, are designed to fully penetrate the victim. Bullets of this type are consequently encountered infrequently in patients undergoing MR imaging.

Although none of the shotgun pellets we tested showed magnetic deflection, several varieties of BBs (Daisy, Rogers, Ark; Crosman, East Bloomfield, NY) have been reported to be ferromagnetic (17).

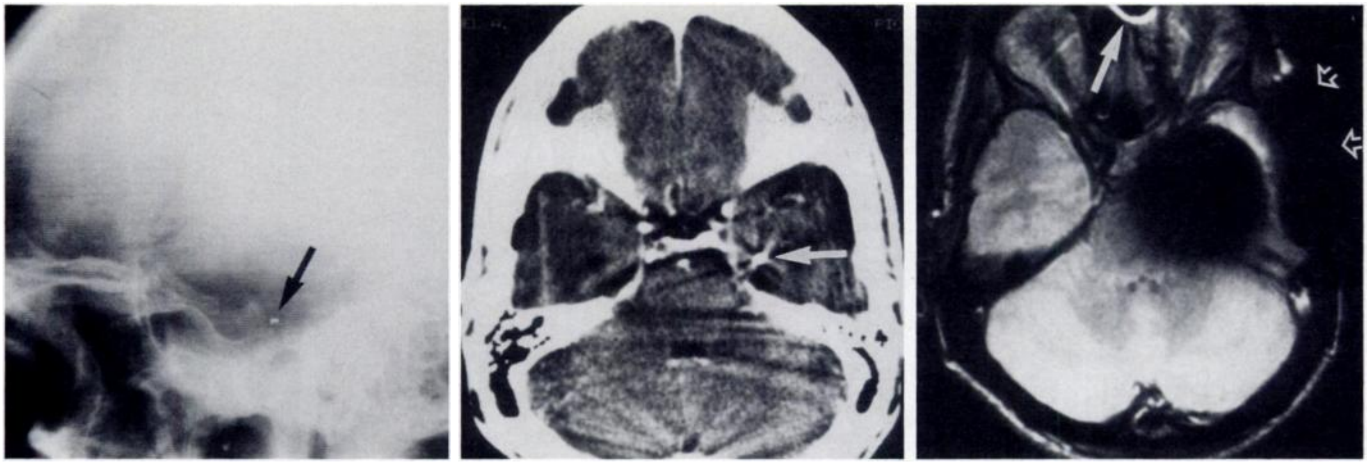
The bullets and pellets we tested were chosen on the basis of local experience with the types of ammunition encountered most frequently in criminal shootings and police actions. In reviewing bullet calibers used in 667 unsolved homicides from the files (past 6 years) of the Los Angeles County Sheriff, the most common caliber of bullet involved was .357 inch (254 homicides), followed by .22 inch (138 homicides), .25 inch (70 homicides), 9 mm (46 homicides), and .32 inch (46 homicides). It is interesting to note that only 37 of 667 (5.5%) of all unsolved homicides were committed with rifles; the remaining 94.5% involved handguns. Police shootings most commonly involved .357-inch (".38 special") and 9-mm hollow-point copper-jacketed lead bullets. We also frequently encountered shotgun wounds of the extremities that involved pellets (either lead or copper-coated lead shot) of various sizes (most commonly "birdshot"). Frequently used in drug-related violence are shotguns and 9-mm semiautomatic pistols. In general, in both domestic and criminal violence, the type of ammunition used most commonly is that which is most readily available over the counter at gun and sporting goods stores.

The most commonly encountered bullets in police, criminal, and wartime gunshot wounds include hollow-point, round-nose, and total-metal-jacket varieties. The hollow-point variety uses a lead core with a concave tip that is inserted into a harder metal jacket (frequently composed of copper or copper and nickel), leaving the concave lead tip exposed (Fig 1). The bullet expands and deforms on impact. Although these bullets are designed to prevent ricochets during police firefights, they are also far more devastating on entry into the victim, causing significant local tissue disruption.

Round-nose bullets may consist of a lead core inserted into the back end of a harder metal jacket (usually copper or copper and nickel), and are also known as full-metal-jacket bullets. These tend to be highly penetrating rounds and are frequently used in hunting weapons and 9-mm semiautomatic pistols. Round-nose bullets may also be composed entirely of lead. Total-metal-jacket bullets consist of a round-nose lead core totally electrocoated with a thin layer of metal (usually copper). They have no practical advantage, but they tend to be cheaper to produce.

Most rifle wounds sustained from the time of World War II through the Vietnam War were caused by copper-jacketed lead, round-nose bullets of .30–.308-inch caliber.

The high degree of ferromagnetism displayed by two bullets in our study, reportedly with lead cores and either a copper or a copper-nickel jacket, strongly suggests that magnetic deflection was due to iron impurities in either the bullet cores or jackets (although nickel, like iron, can exhibit ferromagnetic properties). With regard to metallic artifacts at MR imaging, the greater the ferromagnetism of an object, the larger its black hole artifact and image distortion (3) due to local perturbations in the B_0 and gradient



a. b. c.

Figure 7. Images of 49-year-old man with recent shrapnel injury to the head sustained during guerrilla activity in Central America. **(a)** Lateral plain radiograph of the skull shows a minute shrapnel fragment (arrow) in a parasellar location. **(b)** The intracranial location of this metallic foreign body (arrow) is confirmed with an axial computed tomographic (CT) study of the brain. **(c)** On an axial multiecho SE MR image obtained at 0.5 T, this minute, presumably steel, shrapnel fragment creates a large black hole artifact that strongly suggests the ferromagnetic nature of this fragment. The artifact largely obliterates the image of the sella and left middle cranial fossa. However, MR imaging also shows the presence of additional metallic particles that create significant magnetic susceptibility artifacts in the anterior midline (solid arrow) and left peritemporal area (open arrows). These additional metal particles were not detectable with either plain radiography or CT. No untoward effect occurred as a result of the MR study.

fields. In light of this fact, it can be assumed that the minute metallic fragments that caused the enormous MR artifact in our patient with intracranial shrapnel were probably composed of ferromagnetic steel (Fig 7).

Since shrapnel is generally composed of steel, it may present special problems for MR imaging. This would be most important in cases of head and neck shrapnel wounds. In our patient with intracranial shrapnel, unsuspected facial metallic particles were not detected with plain radiography or CT but were discovered with MR imaging and caused significant artifacts. It is quite possible that intraocular steel particles could also result from head and neck shrapnel wounds. Such ferromagnetic particles can subject patients to the risk of vitreous hemorrhage and possible blindness due to the action of magnetic torque during MR imaging. The risks associated with intracranial metallic fragment rotation are obvious. Although MR imaging resulted in no significant neurologic symptoms in our shrapnel patient, experience in a single patient is insufficient to recommend the routine practice of MR imaging in patients with shrapnel fragments in or near vital neural, vascular, or soft-tissue structures in the head and neck. The risks versus benefits of MR imaging in these cases should be carefully weighed. Perhaps MR imaging could be performed more safely in such cases with ultra-low-field-strength units.

The MR artifact produced by a metallic object is determined not only by the degree of its ferromagnetism but also by its shape and the type of imaging sequence used (3). Longer objects have increased artifact at their ends, and artifact is increased at bends, points, and edges. MR metallic artifacts are accentuated during GRE imaging, largely because of the lack of a 180° refocusing radio-frequency pulse (which is present in SE imaging). This phenomenon is greatly amplified with longer echo times during GRE imaging.

In conclusion, we found that domestically produced bullets and shotgun pellets that would be most likely encountered in criminal and police shootings are nonferromagnetic. In our experience, seven patients with various ballistic metallic fragments were imaged safely and effectively with MR. However, because shrapnel, some bullets made outside the United States, and wartime-vintage bullets can be expected to show varying degrees of ferromagnetism, patients with such ballistic fragments should be considered for MR imaging with caution, particularly if these fragments are located near vital neural, vascular, or soft-tissue structures. Since it is usually impossible to accurately determine the make or caliber of a bullet on the basis of plain radiographs, it is necessary to rely on spent cartridges obtained by investigators at a crime scene to determine the make and caliber of a bullet in an anatomically sensitive area before MR imaging is attempted. ■

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