Emergency Radiology (2020) 27:527–532
https://doi.org/10.1007/s10140-020-01781-6

REVIEW ARTICLE

MR imaging in the presence of ballistic debris of unknown composition: a review of the literature and practical approach

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Received: 10 February 2020 / Accepted: 16 April 2020 / Published online: 17 May 2020

Abstract

Due to a combination of increasing indications for MR imaging, increased MRI accessibility, and extensive global armed conflict over the last few decades, an increasing number of patients now and in the future will present with retained metallic ballistic debris of unknown composition. To date, there are no guidelines on how to safely image these patients which may result in patients who would benefit from MRI not receiving it. In this article, we review the current literature pertaining to the MRI safety of retained ballistic materials and present the process we use to safely image these patients.

Keywords Ballistic debris · GSW · Bullet · MRI · Gunshot wounds · Shotgun wounds

Introduction

"The magnet is always on" is a sign commonly posted on the door leading to zone 4 of the MR environment. It is an important reminder that within zone 4 is a magnetic field that is between 10,000 and 100,000 times stronger than the average background magnetic field [17, 27] and that failure to abide by safety protocols may result in injury or death. Therefore, all patients entering the MRI environment are screened and required to change out of street clothes into hospital gowns. One of the common screening questions is "Do you have any retained bullets?". This is a question to which most patients answer "No." However, there are a small minority that answers in the affirmative, resulting in much consternation among the screening technologists and the radiologists who must ultimately decide if the patient is safe to enter the MR environment. The authors expect that this will become an increasingly common problem given increases in violent crime, the global armed conflicts that have been ongoing over the last 20 years, as well as an aging population that includes veterans of prior wars. To date, there is no comprehensive protocol for MR imaging of these patients. In this article, we review the literature surrounding the safety of MRI in the presence of ballistic debris and offer a protocol with which patients who have retained ballistic debris of unknown composition can safely be introduced into the MRI environment.

Essentials:
- Most, but not all, retained ballistic debris is MRI safe.
- Material decomposition dual-energy CT scanning holds future promise in determining whether retained ballistic material has ferromagnetic properties.
- Patients with retained ballistic debris of unknown composition adjacent to critical neurovascular structures should be introduced into the magnetic field in an orientation that would result in the metal moving away from the structure of concern should it move.

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Background

In 2018, in the USA, there were 118.9 MRI exams per 1000 population [18]. When extrapolated to the US population of 2018 [28], this works out to almost 39 million MRI examinations and consequently screening questionnaires performed that year. It is unfortunately not possible to determine the number of MRI examinations safely performed on patients with retained ballistic material or the number of patients who were either appropriately or inappropriately denied access to MRI as a result of their retained ballistic material. Additionally, there are no published reports from that year of patients experiencing an injury attributable to the presence of retained ballistic fragments.

The presence of any metal in a patient set to undergo MRI elicits concern due to the risk the metal will experience translation forces and/or torque as it interacts with MRI's static and variable magnetic fields [4, 6, 11, 21, 24, 27]. Additionally, heating of ballistic fragments is a concern as the changing magnetic fields induced by gradient coils can induce electrical currents within conductive materials [24, 27].

Ballistic debris comes in two forms—bullets and pellets. Handguns and rifles fire a single projectile which can either remain intact or variably disintegrate upon contact with flesh, bone, and intervening structures [25]. Shotguns fire a spreading cloud of pellets which come in a variety of sizes and materials. Handgun and rifle bullets are typically constructed of copper, lead, or a combination thereof although some newer bullets have polymer components and a small subset of bullets have a steel jacket or core. Shotgun pellets are round ball bearings and are made of a wide variety of materials although a single shotgun wound will almost always contain ballistic material of uniform composition. Shotgun pellets are composed of one or more of a combination of lead, steel, tungsten, bismuth, nickel, tin, iron, and various polymers [2]. While most ballistic materials are not magnetic, those containing iron and nickel are and must be correctly identified to mitigate against potential patient harm.

Is ballistic material MRI safe?

Any metal within a patient raises concerns for heating and movement, but this concern is exponentially higher when that metal is close to or within critical or fragile structures such as the globes, brain, spinal cord, major nerves, or blood vessels [6]. Handgun and rifle bullets can usually be identified on radiographs or a scout CT image as when they remain intact they are morphologically similar in patient tissues to their appearance pre-firing (Fig. 1). An intact bullet may represent one (where a lead core is) clad entirely in either steel or copper, known as a full metal jacket (FMJ) [29] or had low energy at time of penetration and remained intact [15]. Bullets that do not remain intact are usually made entirely of lead or only partially clad in copper [7]. Bullets that remain intact and bullets that fragment can both contain steel cores susceptible to magnetic effects. Shotguns fire numerous pellets at the same time and characteristically appear as multiple round metal foci clustered about the site of and deep to the site of injury on radiography and CT (Fig. 2) [29]. Pellets that fragment into multiple irregular non-rounded shapes are likely made of lead, whereas pellets that remain round and regular are likely made of a steel alloy [14].

In 1989, Ebraheim et al. reported the use of MRI in a patient with ballistic fragments adjacent to the cervical spinal cord—one of the first reported cases of a bullet being imaged with MRI adjacent to a critical structure [8]. In this case, the bullet was made of lead, a non-ferromagnetic material which resulted in no-effect other than image degradation by signal drop-out at the site of the retained ballistic material. A subsequent study by Teitelbaum et al. [26] found that most American-made civilian market ammunition does not contain ferromagnetic materials. However, they and others have reported that bullets produced outside of the USA and military ammunition can contain varying degrees of ferromagnetic materials [1], and thus while unlikely to be a problem, patients with retained bullets should be imaged with caution. In the intervening 30 years, a lot has changed. The end of the Cold War has made military surplus ammunition both cheap and abundant in the civilian market, and the Internet has made it readily available. Thus, any given bullet has a higher likelihood of being of Eastern European or Asian origin and/or having been produced for military use. Recognizing this, recent research has examined the effects of MRI on bullets used by the military and law enforcement [5] as well as armor-piercing bullets [17]. This research confirmed that non-ferromagnetic bullets are MRI safe at 1.5-3 T but also demonstrated that bullets and shotgun pellets containing ferromagnetic materials are subject to significant motion at diagnostic MRI magnetic field strengths [3, 5, 9, 17]. The most recent research has indicated that MRI should be considered safe in patients, when the bullets with which they have been shot are known to be MRI safe [13]. In the setting of victims of violence, this is not usually feasible. Thus, the ability to identify the composition of ballistic debris has recently become a topic of interest.

Identifying the composition of ballistic material

The American College of Radiology recommends the use of ferromagnetic discriminating metal detectors (FDMD) as an adjunct to a thorough screening examination, and there are numerous commercial products available to screen patients for metal prior to their entry into the MRI environment. This has been shown effective in some studies; however, this is of limited utility in detecting smaller foci of ferromagnetic debris [10], and the detectors are not designed to detect metal internal to the patient [16].

Recently published work has focused on the use of dual-energy CT (DECT) material decomposition modeling to differentiate between ferromagnetic and non-ferromagnetic ballistic debris in vitro [12, 19, 22, 30]. In 2014, Winklhofer et al. in a proof-of-concept experiment demonstrated that DECT was capable of distinguishing ferromagnetic from non-ferromagnetic materials. However, their study noted that determining the composition of a jacketed bullet's jacket was limited [30]. In 2019, Gascho et al. determined that it was possible to differentiate between bullets composed of copper and zinc from lead-cored bullets irrespective of their jacketing material. However, they also demonstrated an inability to

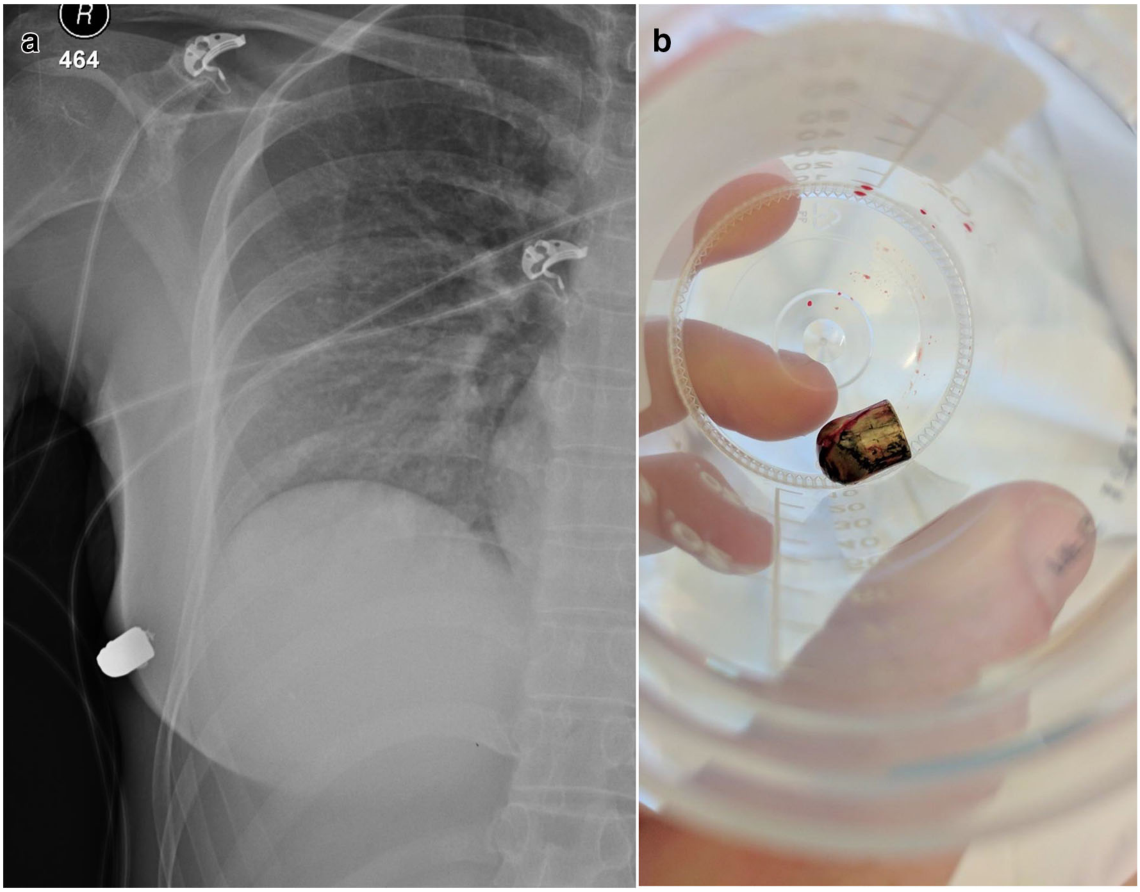

Fig. 1 30-year-old female sustained a single bullet wound to the anterior thoracic wall, and a PA chest radiograph was acquired in the trauma bay. Lodged within the patient's right breast is an intact bullet, an appearance characteristic of full metal–jacketed bullets. The bullet was subsequently removed and is show in panel **B**. Note how the bullet's appearance on radiograph is the same as the bullet after it has been retrieved

differentiate between bullets with ferromagnetic and non-ferromagnetic jackets [12]. Ognard et al. showed results similar to Winklhofer et al. using an automated and manual segmentation approach [19]. While these studies serve as an excellent starting point for future research, all of these studies took place in phantoms or devitalized tissues and used uniform bullets that had not been subject to the deformation seen in bullets delivered at high velocity into

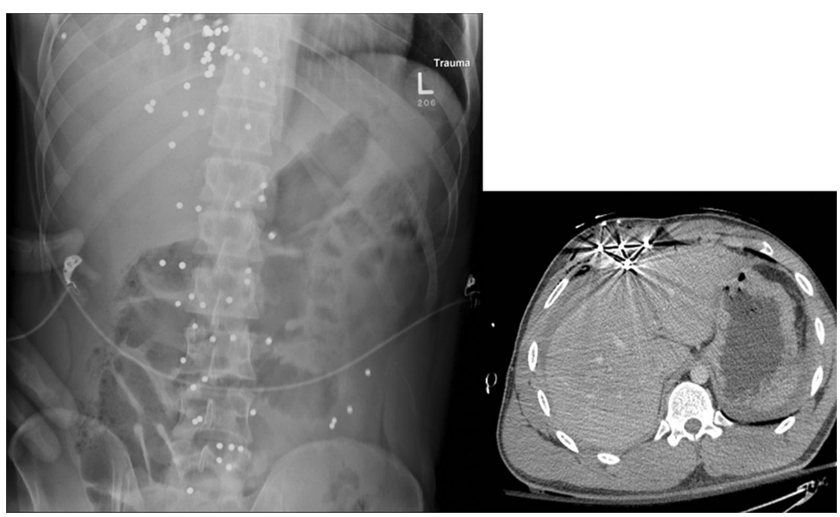

Fig. 2 Abdominal trauma bay radiograph and subsequently acquired axial CT image in a male patient who has suffered an anterior shotgun wound. Numerous round metal shotgun pellets are lodged within the anterior soft tissues. Should this patient require MRI, the safest course of action would be to sample one of the subdermal pellets

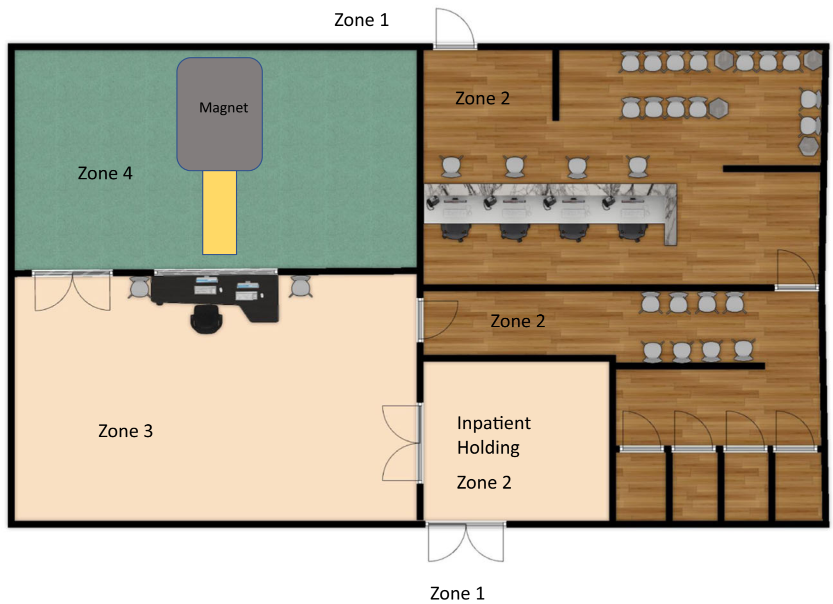

Fig. 3 An idealized MRI suite layout. Door between different zones with the exception of the door between zones one and two should be pass card or key controlled to prevent the free movement of people between zones

living tissues. Although DECT material decomposition holds much promise, it is not yet ready for clinical use.

A common sense protocol for imaging patients with ballistic debris of uncertain composition

The American College of Radiology has divided the MRI environment into 4 “safety zones” [10, 23] (Figs. 3 and 4). Zone 1 is defined as the region leading to the MRI environment that is accessible to the general public. Zone 2 is the boundary between the highly controlled environment of zones 3 and 4 and the universally accessible zone 1. It is in zone 2 that patients change out of their street clothes and are screened for MRI compatibility. Patients do not move beyond zone 2 until after completion of screening and vetting by MRI personnel. If a metal detector is being used as part of the patient screening process, it should be positioned between zones 2 and 3. Zone 3 is the antechamber to the MRI environment, and no person or materials should have access to this zone without appropriate screening due to the risk of magnetic projectiles entering zone 4, the MRI chamber itself.

In zone 2, if a patient screens positive for retained ballistic debris, the technologist conducting the screening should alert the supervising radiologist, as ultimately the determination of patient MRI compatibility and the responsibility for patient safety rests with the radiologist. When informed of a patient with retained ballistic debris of unknown composition (RBUC), the radiologist must determine if the information being sought by MRI can be acquired by other means. If MRI is the only method by which the information sought can be acquired or the use of ionizing radiation is not desirable (pregnant or pediatric patient), the radiologist should review any prior imaging available to determine the appearance, position, and, if possible, the composition of the RBUC. Fortunately, in patients with GSW, there is almost always prior imaging available, and the MRI exam may need to be rescheduled in order to acquire this imaging. In the case of emergency imaging and/or the absence of prior imaging, radiographs should be performed to localize the RBUC. If the radiographs demonstrate RBUC in an extremity and not in an expected location where it could be contacting neurovascular structures, the patient should be advised of the risk of pain and metal fragment movement. The patient should be further advised that should they feel discomfort while being introduced into the magnetic field, or at any time during the exam, the MRI exam can be terminated. In patients with RBUC in the chest, abdomen, or adjacent to a neurovascular structure, low-dose CT imaging may need to be performed to better localize and analyze the RBUC. Once the RBUC is localized, the radiologist should perform an analysis of the adjacent structures and the risks associated with metal movement. It is important to note that there are anatomic structures that do not contain nociceptors, and this must be considered in consenting the patient. The patient should then be informed of the risks associated with debris movement and informed consent acquired accordingly. For example, if metal debris is adjacent to the sciatic nerve, the patient should be questioned with respect to current symptoms of sciatic nerve irritation and consented for the risk of damage to the sciatic nerve. Only if the patient consents to proceed with the examination should he or she should be brought into zone 3. In the setting of RBUC, we image our patients on the 1.5-T magnet.

Once the patient is in zone 3, an explanation of what motion of the RBUC might feel like should be provided. The

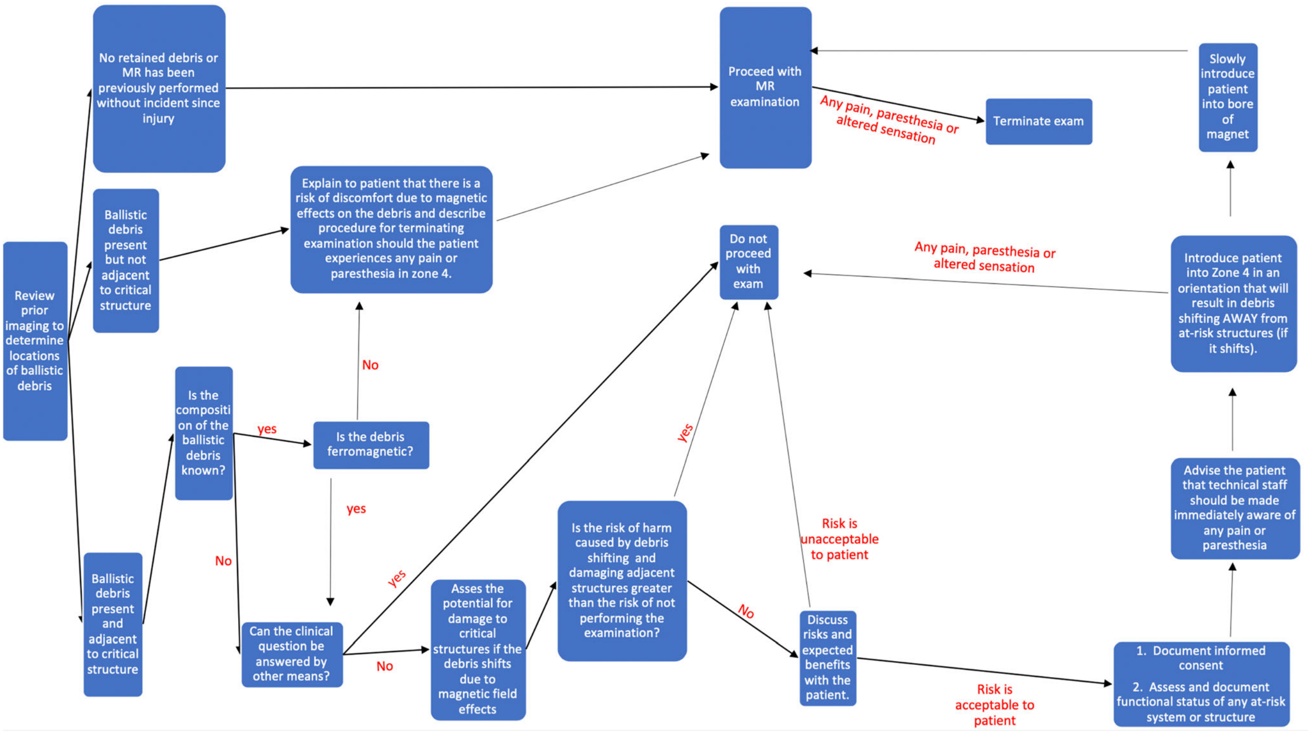

Fig. 4 A decision tree laying out the steps in the decision-making pathway for a patient who has been previously identified as having suffered a ballistic injury during pre-MRI screening

patient should also be made aware of the procedures for terminating the examination should they experience any pain or discomfort, numbness, or tingling. Only at this point should the patient be brought into zone 4. Introducing the patient into zone 4 is the time of highest patient risk as the magnetic field is strongest at the entrance to the bore of the MRI [20]. To this end, we advocate moving the patient into the magnetic field in an orientation whereby the RBUC, should it move under the influence of the magnetic field, will be pulled *away* from critical structures. The patient should be walked (or rolled) slowly toward the bore of the MRI and queried about altered sensation, pain, and discomfort. Should any be experienced, the patient should not proceed with the examination. If asymptomatic, the patient should be placed on the MRI table and manually moved into the bore so that they are positioned similarly to their expected orientation during scanning. If the patient remains asymptomatic at this point, under the influence of the static magnetic field, then they are unlikely to experience symptoms during the course of their examination even under the influence of the less powerful gradient magnetic fields, and the examination should proceed unless terminated by the patient. This is summarized in Fig. 4.

Following the completion of an uneventful examination, the patient should be provided with a note stating that their ballistic debris should not preclude the future use of MRI. This should also be explicitly stated in the final report of the examination. This will prevent future imaging examinations from being unnecessarily delayed or canceled.

Conclusions

MRI is a key diagnostic modality in many disease processes, and unnecessarily denying patients access to MRI may adversely affect their care. Although the majority of ballistic debris is MRI safe, in the interest of patient safety, we must assume that RBUC is not MRI safe until proven otherwise. As DECT technology advances, it may in the future be possible to determine the ferromagnetism of retained ballistic material; however, this technology has not yet been reached a level suitable for clinical use. To this end, we provide a proposed protocol by which patients with retained ballistic debris can be introduced in a stepwise manner (that reduces risk) into the MRI environment. This protocol is only utilizable in the conscious patient, and although this is a protocol that we have successfully utilized, each clinician must determine its suitability for use in their patients and patient population.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Alvis-Miranda HR, Rubiano AM, Agrawal A et al (2016) Craniocerebral gunshot injuries; a review of the current literature. Bull Emerg Trauma 4:65–74

2. Bochynski P, Kuliczkowski M, Karpiewska A et al (2016) Hunting shot - evolution of manufacturing technology. Arch Med Sadowej Kryminol 66:41–64
3. Dedini RD, Karacozoff AM, Shellock FG, Xu D, McClellan RT, Pekmezci M (2013) MRI issues for ballistic objects: information obtained at 1.5-, 3- and 7-Tesla. Spine J 13:815–822
4. Dempsey MF, Condon B, Hadley DM (2002) MRI safety review. Semin Ultrasound CT MR 23:392–401
5. Diallo I, Auffret M, Attar L, Bouvard E, Rousset J, Salem DB (2016) Magnetic field interactions of military and law enforcement bullets at 1.5 and 3 Tesla. Mil Med 181:710–713
6. Dill T (2008) Contraindications to magnetic resonance imaging: non-invasive imaging. Heart 94:943–948
7. Ditkofsky N, Elbanna KY, Robins J, Ali IT, O'Keeffe M, Berger FH (2018) Ballistic injury imaging: the basics. Curr Radiol Rep 6:45
8. Ebraheim NA, Savolaine ER, Jackson WT, Andreshak TG, Rayport M (1989) Magnetic resonance imaging in the evaluation of a gunshot wound to the cervical spine. J Orthop Trauma 3:19–22
9. Eggert S, Kubik-Huch RA, Klarhofer M et al (2015) Fairly direct hit! Advances in imaging of shotgun projectiles in MRI. Eur Radiol 25:2745–2753
10. Expert Panel On MRS, Kanal E, Barkovich AJ et al (2013) ACR guidance document on MR safe practices: 2013. J Magn Reson Imaging 37:501–530
11. Finitsis SN, Falcone S, Green BA (1999) MR of the spine in the presence of metallic bullet fragments: is the benefit worth the risk? AJNR Am J Neuroradiol 20:354–356
12. Gascho D, Zoelch N, Richter H, Buehlmann A, Wyss P, Schaerli S (2019) Identification of bullets based on their metallic components and X-ray attenuation characteristics at different energy levels on CT. AJR Am J Roentgenol 213:W105–W113
13. Hackenbroch C, Wafa M, Klinger S, Mauer UM (2019) Magnetic resonance imaging in the presence of projectiles and projectile fragments: artefacts, image quality, rotation and movement. Magn Reson Imaging 57:143–150
14. Hollerman JJ, Fackler ML, Coldwell DM, Ben-Menachem Y (1990) Gunshot wounds: 1. Bullets, ballistics, and mechanisms of injury. AJR Am J Roentgenol 155:685–690
15. Hollerman JJ, Fackler ML, Coldwell DM, Ben-Menachem Y (1990) Gunshot wounds: 2. Radiology. AJR Am J Roentgenol 155:691–702
16. James CA, Karacozoff A, Shellock FG (2013) Undisclosed and undetected foreign bodies during MRI screening resulting in a potentially serious outcome. Magn Reson Imaging 31:630–633
17. Karacozoff AM, Pekmezci M, Shellock FG (2013) Armor-piercing bullet: 3-T MRI findings and identification by a ferromagnetic detection system. Mil Med 178:e380–e385
18. Oecd (2019) Magnetic resonance imaging (MRI) exams (indicator)
19. Ognard J, Dissaux B, Diallo I, Attar L, Saccardy C, Ben Salem D (2019) Manual and fully automated segmentation to determine the ferromagnetic status of bullets using computed tomography dual-energy index: a phantom study. J Comput Assist Tomogr 43:799–804
20. Panych LP, Kimbrell VK, Mukundan S Jr, Madore B (2020) Relative Magnetic force measures and their potential role in MRI safety practice. J Magn Reson Imaging 51:1260–1271
21. Panych LP, Madore B (2018) The physics of MRI safety. J Magn Reson Imaging 47:28–43
22. Patino M, Prochowski A, Agrawal MD, Simeone FJ, Gupta R, Hahn PF, Sahani DV (2016) Material separation using dual-energy CT: current and emerging applications. Radiographics 36:1087–1105
23. ACR Committee on MR Safety, Greenberg TD, Hoff MN, Gilk TB, Jackson EF, Kanal E, McKinney AM, Och JG, Pedrosa I, Rampulla TL, Reeder SB, Rogg JM, Shellock FG, Watson RE, Weinreb JC, Hernandez D (2020) ACR guidance document on MR safe practices: updates and critical information 2019. J Magn Reson Imaging 51:331–338
24. Schenck JF (2000) Safety of strong, static magnetic fields. J Magn Reson Imaging 12:2–19
25. Stefanopoulos PK, Pinialidis DE, Hadjigeorgiou GF, Filippakis KN (2017) Wound ballistics 101: the mechanisms of soft tissue wounding by bullets. Eur J Trauma Emerg Surg 43:579–586
26. Teitelbaum GP, Yee CA, Van Horn DD et al (1990) Metallic ballistic fragments: MR imaging safety and artifacts. Radiology 175:855–859
27. Tsai LL, Grant AK, Mortele KJ, Kung JW, Smith MP (2015) A practical guide to MR imaging safety: what radiologists need to know. Radiographics 35:1722–1737
28. U.S. Census Bureau PD (2019) Annual estimates of the resident population: April 1, 2010 to July 1, 2018. In:U.S. Census Bureau, Population Division
29. Wilson AJ (1999) Gunshot injuries: what does a radiologist need to know? Radiographics 19:1358–1368
30. Winklhofer S, Stolzmann P, Meier A, Schweitzer W, Morsbach F, Flach P, Kneubuehl BP, Alkadhi H, Thali M, Ruder T (2014) Added value of dual-energy computed tomography versus single-energy computed tomography in assessing ferromagnetic properties of ballistic projectiles: implications for magnetic resonance imaging of gunshot victims. Investig Radiol 49:431–437