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ORIGINAL ARTICLE

The influence of 1.5 and 3 T magnetic resonance unit magnetic fields on the movement of steel-jacketed projectiles in ordnance gelatin

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Abstract

Purpose Ferromagnetic bullets can move in air or gelatin in magnetic resonance (MR) units. According to our experience, ferromagnetic bullets do not always present consistent movement. We examined factors affecting ferromagnetic projectile movement in a 1.5T and a 3T MR unit, focusing in this study on the steel-jacketed Swiss ordnance ammunition 7.5 mm GP11 Suisse.

Methods Five 7.5 mm GP11 Suisse bullets were embedded horizontally and vertically in 10 % ordnance gelatin phantoms. Before and after exposing the bullets to 1.5T (Siemens) and 3T (Philips) MR units each bullet's position was documented by a CT scan. In a second phase, the magnetic polarization of the bullets in relation to the MR units was measured by a dry magnetic portable compass (Suunto).

Results Our results showed that the displacement of the bullets increased when subjected to a stronger magnetic field (max. Movement 1.5T: 24.4 mm vs. 3T: 101.5 mm) and that the position, i.e. orientation of the bullet toward the gantry, strongly influenced its mobility (horizontally embedded projectiles showed poor movement, vertically placed ones strong movement). One of the bullets presented a 180° rotation in the 3T MR unit. Magnetization and changing of the polarization of these ferromagnetic bullets is possible when subjected to MR units.

Conclusion In conclusion, the location of a bullet, and its orientation toward the gantry must be taken into account when assessing the risk of performing an MR examination on a gunshot victim in clinical and in forensic cases.

Keywords MR · Ferromagnetic foreign bodies · Bullets · MR safety

Introduction

In both military and civilian shooting incidents rapid assessment of the injured organs is of paramount importance in the planning of further surgical procedures. Usually such a potentially life-saving diagnostic tool is multislice computed tomography (MSCT). Although this cross-sectional modality is rapid and very accurate regarding the detection and localization of foreign objects such as bullets or bullet fragments, osseous lesions, fluid (blood), and gaseous (air) accumulations, it is however, even in conjunction with angiographic procedures, often insufficient in the depiction of soft tissue and organ lesions in post-mortem imaging. Furthermore magnetic resonance imaging (MRI) is becoming increasingly important in post-mortem forensic examination of gunshot victims.

In depicting soft tissue injuries, MRI is definitely superior to MSCT [1]. However, bullets may contain ferromagnetic components. Indeed, environmental concerns have led to the increasing deployment of steel shot instead of lead [2]. Certain ammunition types may have impurities, which may be ferromagnetic [3], while other ammunition, especially armor-piercing types, possess a

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steel core instead of the more common lead core. However, the most frequent source of ferromagnetic material in Central and Western Europe are steel-jacketed, lead-core bullets.

The problem of such ferromagnetic objects in the strong magnetic force of an MR unit is—besides possible heating [4, 5]—that they may move and dislocate, possibly leading to secondary injuries. This may endanger injured persons with retained ferromagnetic foreign bodies as well as change findings in forensic post-mortem cases, potentially leading to misinterpretation.

The possibility that projectiles may move and dislocate in the static magnetic field of an MR unit has been investigated before; most studies come to the conclusion that patients with bullets containing iron or steel should not undergo MRI [3–6].

Indeed, Teitelbaum et al. [3] showed in their study 24 years ago, that ferromagnetic bullets readily rotate within a gelatin phantom in response to magnetic torque of 1.5T. Based on the results of Teitelbaum et al., a list regarding the safety of pellets and bullets in 1.5T MR units has been compiled [7].

A recent publication [8] examined the torque and translational activity in 1.5, 3, and 7 Tesla MR-units. In this study, 32 different bullets and 7 different shotgun pellets were examined. Of these, 1 bullet possessed a steel core (0.223 WCC 80 armor piercing) and 2 shotgun pellet types were made of steel. These three ammunition types moved in the magnetic field. However, the rest of the projectiles were non-ferromagnetic, and, as expected, did not move. This study was performed by measuring the movement in air, not in tissue or tissue-substitute.

Another study [9] dealing with artifact reduction in an 1.5 MR unit showed a movement of one magnetically attracted projectile (7.5 mm GP 11 Suisse) in ballistic gelatin, and a distinct torque dislocation for elongated magnetically attracted projectiles tested when hand-held.

Therefore we decided to further examine the possible dislocation of projectiles in a magnetic field of 1.5T as well as 3T MR units, focusing on the steel-jacketed Swiss ordnance ammunition 7.5 mm GP 11 Suisse. According to our experience it can readily move in the magnetic field of an MR. In order to analyze the effect under standardized conditions, we subjected five 7.5 mm GP 11 Suisse bullets to 1.5T and 3T MR units. The position of the bullet was determined by CT scanning before and after the exposure. In addition to this, we determined the magnetic force of the bullets after being subjected to the magnetic field of the MR unit and measured the respective magnetic polarization of the bullets in relation to the MR units.

Method and materials

Projectiles

Five 7.5 mm steel-jacketed GP 11 Suisse projectiles with lead cores were included in this study. The bullets weighed, on average, 11.3 g, and measured 7.81 × 34.89 mm.

Ferromagnetic interaction

The magnetic attraction force of the projectiles was measured with a non-ferromagnetic spring scale (D.B.G.M, Germany) with 1 % precision by attaching a small plastic container containing the projectile to the end of a 25 cm long filament (own weight 0.95 g) that was held in the middle upper region of a 1.5T MR unit as described previously [9].

Phantom

Using ordnance gelatin powder (Type 3 Photographic Grade, GELITA AG, Uferstr. 7, 69,412 Eberbach, Germany) we prepared a 10 w/w% ordnance gelatin as described previously [10]. Two projectiles were embedded in a horizontal (tip facing the gantry) position and three other projectiles in a vertical position (tip pointing up) in the middle of the gelatin (approximately 1.5 kg) that was contained within a plastic bucket, which was then allowed to harden at 5 °C. Additionally we placed six lipophilic nitroglycerine capsules (Streuli Pharma AG, Uznach, Switzerland) on the external surface as reference markers (Fig. 1).

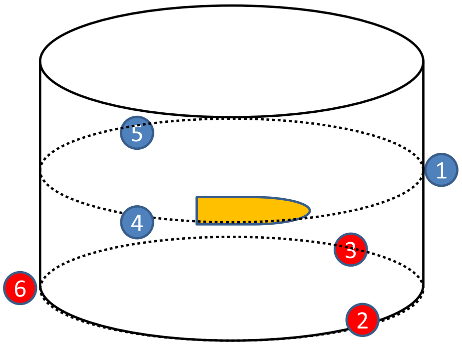

Fig. 1 Schematic depiction of the phantom with the bullet (*yellow*) resting within the bucket filled with gelatin, and the 6 reference points attached to the outside of the bucket. The *blue* reference points are located on a higher level than the *red* ones

Imaging

CT imaging was performed using a 128 slice Dual-source Multi-detector row scanner (Somatom Definition Flash, Siemens Healthcare, Erlangen, Germany).

The gelatin phantoms containing the projectiles were scanned on the CT at 140 kV using a tube current time product of 1200 mAs, a slice collimation of 0.6 mm, a rotation time of 1 s, and a spiral pitch factor of 0.35 mm. For reconstruction of bone and soft tissue convolution kernel (B70 s), a slice thickness of 0.6 mm and increments of 0.4 mm were used.

After CT scanning, the gelatin phantoms underwent initial exposure to a 1.5 Tesla MRI system (Magnetom Aera, Siemens Healthcare).

After that the phantoms underwent a further CT scan prior to being subjected to a 3T MR unit (Philips Achieva, Philips Healthcare, Amsterdam, Netherlands).

Finally, the phantoms underwent a third CT scan.

The workflow for imaging was therefore as follows:

1. 1st CT scan
2. 1.5T MR unit
3. 2nd CT scan
4. 3T MR unit
5. 3rd CT scan

CT data acquisition and measurement

Using a dedicated workstation (Leonardo, Siemens AG Medical Solutions, Erlangen, Germany), a radiologist measured the distances of the tip and base of each projectile to the six nitroglycerine reference markers attached to the outside surface of the bucket. This procedure was performed on the MSCT data in Multiplanar Reconstruction (MPR) acquired before and after MRI.

The difference of the measurements obtained before and after exposure to MR units was then calculated. Negative distances (i.e. −65.1 mm) indicate that the measured survey mark, for example the base of the bullet, moved 65.1 mm toward the reference point, positive distances that the survey mark moved farther away.

Magnetic polarization

After having determined that the 7.5 mm GP 11 Suisse bullets possessed a magnetic force, we determined their magnetic polarization (after demagnetization by hitting on a hard surface).

Determination of polarization was performed using a dry magnetic portable compass (Suunto A-10 IN, Suunto, Vantaa, Finland); before and after submitting the bullet to the magnetic field of a 1.5T and a 3T MR unit, respectively. The polarization of each bullet was measured by determining the movement of a compass needle (indicating the direction of the Earth's magnetic north) held next to the tip or base of the bullet. Positive results indicated a movement of the compass needle toward the measured point (tip or base of the bullet), negative results that the compass needle moved away.

The workflow for polarization determination was therefore as follows:

1. Subjection to static magnetic field (1.5T Magnetom Aera, Siemens Healthcare)
2. Determination of polarization
3. Subjection to static magnetic field (3T Philips Achieva, Philips Healthcare)
4. Determination of polarization

Reproducibility of magnetization

In order to verify the reproducibility of the results of prior measurements, we subjected one bullet (#5) 15 times in the same manner to the gantry of each MR scanner. The bullet was introduced into the gantry horizontally and parallel to the z-axis at the height of the head coil. After each exposition to the magnetic field, the deviation of the compass needle from "zero" due to the magnetic force of the bullet's tip and base was measured as described above.

Properties of the MR unit's static magnetic field

To verify the properties of the static magnetic field of the used MR scanner, the above mentioned needle compass was positioned outside the Faraday cage in front of each scanner. The orientation of the compass needle was documented.

To compare the results of the magnetic polarization and the properties of the individual MR unit's static magnetic field, we additionally checked the properties of a 3T Siemens MR Unit ("Magnetom nVerio," Siemens Healthcare) and again verified the reproducibility of magnetization. The workflow for polarization was the same as mentioned above.

Results

Ferromagnetism

With the spring scale, our bullets displayed an average magnetic force of 500 N in the 1.5T environment.

Magnetic polarization

Before subjection to the magnetic field of the MR units, the bullets displayed a mild magnetic polarization (range −4° to +10°, tip mean 4.33°, base mean −1.66°).

After exposure to 1.5T, the bullets displayed a marked polarization (tip mean −21.6°, base mean 36.4°). All tip results were negative, all base results positive.

The 3T magnetic field polarized the bullets differently; this time, all base results were negative (all results −120°). Detailed results are shown in Table 1.

Interestingly, the compass indicated the "magnetic north" at the gantry entrance of the Siemens 1.5T unit, while it indicated the "magnetic south" close to the Philips 3T unit gantry.

A crosscheck showed spontaneous magnetization of the used bullet type independently of the previously measured attributes. For example, a bullet subjected with the tip toward the gantry in the 1.5T MR unit showed a tip rejecting the compass needle indicating the "magnetic south" whereas the base was attracting it. The same bullet subjected with the base toward the gantry on the same unit, showed an opposing effect at the compass (tip attracts, base rejects).

After subjection to the static magnetic field of the 1.5T (Siemens Magnetom Aera) environment all bullets' tips showed a rejection of the needle "north" whereas the bases attracted it. After exposure to the static magnetic field of the 3T (Philips Achieva) environment, all bullets caused an opposite behavior of the compass needle, the tip attracting the needle much more strongly. The base rejected the needle "north" quickly until the needle "south" was attracted by each bullet's base. After subjection to the 3T (Siemens Magnetom nVerio) environment, the bullet's tip and base showed a similar polarization as after the 1.5T subjection but with a much stronger magnetization. The tip rejected the needle "north" and attracted the needle "south." For detailed results see Table 1.

Reproducibility of magnetization

The repeated subjection to the MR units' static field with measurement of a single bullet revealed similar results as recorded for each of the five bullets. The needle's deviation/attraction was lower after 1.5T and repeatedly reached its maximum after 3T equipment, in both Philips and Siemens MR units. For detailed results see Table 2.

Properties of the MR units' static magnetic fields

The dry needle compass showed a different behavior when comparing the two tested manufacturers' equipment. When measuring the Siemens environment (1.5T), the magnetic north pointed toward the MR gantry. Repeating the experiment on a Philips system (3T), the opposite occurred with the needle indicating the magnetic south pointing toward the gantry.

Deviation/movement

Depending on the initial position of the 7.5 mm GP11 Suisse in the gelatin (see Table 3; Fig. 2), different movements could be observed by CT.

Horizontally placed bullets

The two horizontally placed bullets presented only poor displacement after being subjected to the magnetic field of the 1.5T MR unit, with similar results when subjected to the 3T unit. Maximum movement was 2.3 mm in relationship to one reference point.

Vertically placed bullets

The three vertically placed bullets were less displaced when exposed to the 1.5T magnetic field compared to the 3T magnetic field. Bullet 1 presented a rotation after 1.5T

Table 1 The attraction/repulsion of the compass needle by the tip/base of the used 7.5 mm GP11 Suisse projectiles

Bullet	Post 1.5 T (Siemens, Magnetom Aera)		Post 3 T (Philips, Achieva)		Post 3 T (Siemens, Magnetom Verio)	
	Tip	Base	Tip	Base	Tip	Base
1	−22	36	50	−120	−120	50
2	−20	34	50	−120	−120	50
3	−24	40	50	−120	−120	50
4	−22	38	50	−120	−120	50
5	−20	34	50	−120	−120	50
Mean	−21.6	36.4	50	−120	−120	50

Positive values indicate that the needle was attracted, negative ones that the needle was rejected by the projectile's tip/base

Table 2 The attraction/repulsion of one randomly chosen bullet (bullet No. 5) in different MR units

Bullet no. 5	1.5 T Siemens Magnetom Aera		3T Philips Achieva		3T Siemens Magnetom Verio	
	Gantry: "N"		Gantry: "S"		Gantry: "N"	
Measurement no	Tip	Base	Tip	Base	Tip	Base
#1	−24	38	50	−120	−120	50
#2	−22	36	50	−120	−120	50
#3	−22	36	50	−120	−120	50
#4	−24	38	50	−120	−120	50
#5	−22	34	50	−120	−120	50
#6	−24	38	50	−120	−120	50
#7	−22	38	50	−120	−120	50
#8	−22	34	50	−120	−120	50
#9	−20	34	50	−120	−120	50
#10	−22	36	50	−120	−120	50
#11	−22	34	50	−120	−120	50
#12	−24	38	50	−120	−120	50
#13	−26	38	50	−120	−120	50
#14	−22	40	50	−120	−120	50
#15	−22	36	50	−120	−120	50
Mean	−22.7	36.5	50.0	−120.0	−120.0	50.0
Standard deviation	1.4	1.9	0.0	0.0	0.0	0.0
Median	−22	36	50	−120	−120	50
Max	−20	40	50	−120	−120	50
Min	−26	34	50	−120	−120	50

exposure with the tip having moved away from the gantry and the base toward it. Moreover, this bullet tip presented a major movement of 24.4 mm in relation to one reference point. Bullet 2 rotated into a horizontal position with the tip pointing toward the gantry. Bullet 3 showed a similar movement as bullet 2, however, this bullet did not reach a completely horizontal position. After 3T the first bullet acquired a more or less horizontal position and moved with its base toward the gantry. Bullet 2, which was in a horizontal position after 1.5 T, rotated by almost 180°, with the tip now pointing away from the gantry. The tip moved 101.5 mm in relation to one reference point. Bullet 3 assumed a horizontal position, but moved away from the gantry corresponding to repulsion.

Discussion

Our results confirm that ferromagnetic full metal jacketed bullets with lead cores can be dislodged in ordnance gelatin in the static magnetic field of a MR unit. As expected the stronger magnetic field of a 3T MR unit leads to a greater dislodgement of the bullets than was observed at 1.5T.

We found two other factors potentially influencing the movement of the bullet, namely the original position or rather the orientation toward the gantry, and the magnetic polarization.

All our bullets tended to assume a more or less horizontal position after being subjected to the magnetic fields of 1.5 and 3T MR units. This is not surprising, as a horizontal position parallel to the z-axis presents the most stable position for a longish ferromagnetic body along the magnetic field lines in a stationary magnetic field, thus constituting the local energy minimum. Interestingly, this horizontal position was not uniform; one of the initially vertically placed bullets rotated with the tip pointing away from the gantry as opposed to the other two. This bullet also showed another peculiarity—it moved toward the gantry, whereas the other two moved away from it. These two gantry-repulsing bullets also displayed a completely different movement pattern in order to achieve a horizontal position. One of these bullets performed a 180° rotation, whereas the other one simply tipped further.

Magnetic polarization and resulting attraction or repulsion may in part explain this peculiar behavior. Indeed, our study proves that the bullets, being ferromagnetic objects, became magnetically polarized when being moved in same orientation toward the gantry. The direction of this polarization might differ, depending on the MR unit.

Table 3 The results of the measurements are presented

	Ref. point	1	2	3	4	5	6
Bullet 1 horizontal							
CT2 versus CT1	Tip	0.40	−0.20	−2.30	0.00	−0.20	−0.10
	Base	0.50	−0.10	0.50	0.10	0.00	−0.70
CT3 versus CT2	Tip	−0.20	−0.10	0.70	0.00	−0.10	0.40
	Base	−10.20	−0.10	−0.50	0.30	−0.30	−0.20
CT3 versus CT1	Tip	0.20	−0.30	−1.60	0.00	−0.30	0.30
	Base	−9.70	−0.20	0.00	0.40	−0.30	−0.90
Bullet 2 horizontal							
CT2 versus CT1	Tip	−0.44	0.50	0.00	0.30	0.00	0.40
	Base	0.10	−0.50	0.00	−0.10	0.20	0.30
CT3 versus CT2	Tip	−0.06	−0.20	0.00	3.20	13.30	−0.10
	Base	−0.30	0.40	−0.20	−6.00	−15.10	−0.20
CT3 versus CT1	Tip	−0.50	0.30	0.00	3.50	13.30	0.30
	Base	−0.20	−0.10	−0.20	−6.10	−14.90	0.10
Bullet 1 vertical							
CT2 versus CT1	Tip	−24.40	−4.00	−6.10	−2.00	−2.50	20.10
	Base	13.40	6.60	6.60	−3.70	−4.10	−13.40
CT3 versus CT2	Tip	17.40	19.00	19.70	−17.20	−18.00	−23.10
	Base	32.60	16.20	24.30	−5.70	4.80	−30.30
CT3 versus CT1	Tip	−7.00	15.00	13.60	−19.20	−20.50	−3.00
	Base	46.00	22.80	30.90	−9.40	0.70	−43.70
Bullet 2 vertical							
CT2 versus CT1	Tip	16.50	22.90	18.50	−19.20	−17.80	−22.60
	Base	3.90	−9.50	−7.10	8.20	10.10	−3.20
CT3 versus CT2	Tip	−81.60	1.10	−45.50	76.20	32.40	101.50
	Base	−27.20	15.70	−29.90	12.50	22.40	33.90
CT3 versus CT1	Tip	−65.10	24.00	−27.00	57.00	14.60	78.90
	Base	−23.30	6.20	−37.00	20.70	32.50	30.70
Bullet 3 vertical							
CT2 versus CT1	Tip	11.40	5.00	10.10	−10.00	−5.90	−12.70
	Base	−11.50	−9.40	−16.30	16.00	9.70	7.00
CT3 versus CT2	Tip	−60.50	−4.80	−9.20	34.90	27.30	63.40
	Base	−42.80	10.10	11.80	48.80	52.40	63.20
CT3 versus CT1	Tip	−49.10	0.20	0.90	24.90	21.40	50.70
	Base	−54.30	0.70	−4.50	64.80	62.10	70.20

"CT2 versus CT1" describes the difference between pre- and post-MR-unit exposure at 1.5 T. "CT3 versus CT2" shows the deviation of the position after exposure to the 3 T MR unit relative to the 1.5 T MR. "Ref." means "reference point." All measurements are reported in mm

With the horizontally placed bullets, the tip became negatively ("magnetic south") polarized after exposure to the 1.5T Siemens unit. As no great movement was necessary to reach the horizontal position of these two bullets, the gelatin remained more or less undisturbed. This relative intactness of the gelatin may have prevented the bullet from flipping when subjected to the new magnetic field of the 3T Philips unit, which has a "magnetic south" at the gantry entrance. A probable explanation suggests that the negative—negative repulsion was not sufficient to move the bullet through the gelatin away from the gantry. With the vertically placed bullets, displacement patterns were completely different. Firstly, the initial polarization was not predictable; an unapparent position of the tip slightly closer to the 1.5T Siemens gantry would make it negative and vice versa.

Furthermore, all vertically placed bullets performed a very distinct movement through the gelatin in order to assume a horizontal position. By doing so, the gelatin became cracked, thus facilitating further movements when

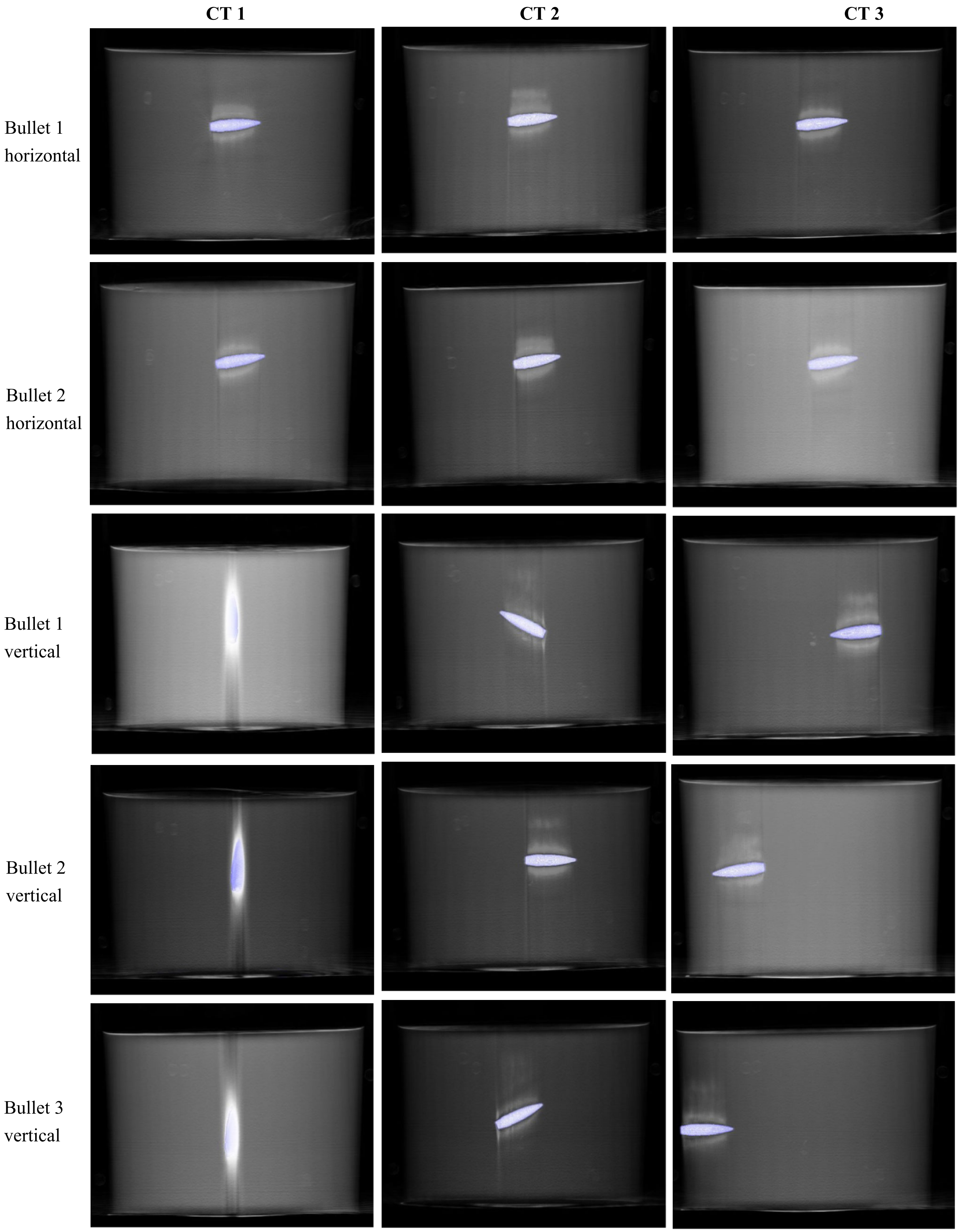

Fig. 2 Demonstration (MPR) of the 7.5 mm GP11 Suisse movement. "CT1" indicates position in relation to the reference points (see Fig. 1) before exposure to MR units, "CT2" the position after 1.5T and "CT3" after 3T unit

subjected to another strong magnetic field. If the tip pointed toward the gantry after being exposed to 1.5T, then the bullet was repelled. However, if the base pointed to the gantry after exposure to 1.5T, the opposite was true.

Therefore, our results prove that ferromagnetic bullets may dislocate when subjected to the magnetic field of MR units. Particularly, the stronger 3T scanners may cause movement of over 10 cm as well as rotational movement, depending on how the bullet is located, which may seriously endanger a patients' life or disturb forensically relevant findings. The movement of the bullet is also influenced by its orientation toward the gantry in the gelatin. Therefore, great caution should be taken in cases of living patients with retained ferromagnetic bullets. MR scanning of such patients should only be performed when absolutely necessary, and then only if the retained bullet is lodged in a less critical location such as a limb. In postmortem cases, the localization of the lodged bullet must be documented with CT prior to MR scanning in order to be able to discriminate between an original bullet path and one caused by the magnetic attraction of the MR unit.

Although ordnance gelatin has proved to be a reliable soft-tissue substitute in shooting reconstructions [10–16], it is unclear whether this substitute is also reliable in low velocity situations. It is possible that the gelatin may perform differently in response to low velocity movements, such as in the present study, for example with an even higher resistance toward movement than in higher velocity settings.

In conclusion, our results confirm that ferromagnetic projectiles may move significantly when subjected to the magnetic field of an MR unit and that his movement increases with the strength of the magnetic field of the MR unit. Furthermore, the position, i.e. orientation of the bullet toward the gantry, as well as altered magnetic properties due to different MR unit polarizations, can affect the behavior of its movement.

Key points

1. Ferromagnetic projectiles may move significantly when subjected to the magnetic field of an MR unit.
2. The movement of ferromagnetic projectiles increases with the strength of the magnetic field of the MR unit.
3. The position, i.e. orientation of the bullet toward the gantry, affects its movement.
4. Different MR unit polarization directions can alter magnetic properties of ferromagnetic objects, causing dissimilar behavior.

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