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ORIGINAL ARTICLE

Movement of steel-jacketed projectiles in biological tissue in the magnetic field of a 3-T magnetic resonance unit

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Abstract
Purpose The fact that ferromagnetic bullets can move in air or gelatine when subjected to magnetic resonance (MR) units is well known. A previous study showed that the movement of 7.5-mm GP 11 Suisse bullets also depends on their orientation toward the gantry. In order to compare the movement in gelatine to that in real tissue, we decided to measure the movement of these bullets, as well as 9-mm Luger bullets, in the brain and liver.
Methods The GP 11 and 9-mm Luger bullets were inserted into the fresh calf brain or pig liver either vertically or horizontally in the *x*- or *z*-axis to the gantry. Before and after exposure to a 3-T MR unit, their position was documented by CT.
Results GP 11 bullets rotated more readily and in general proved to be more mobile than the 9-mm Luger. All GP 11 bullets and a large amount of the 9-mm Luger bullets exited the brain. Sliding toward the gantry was easier for 9-mm Luger bullets in the brain than in the liver.
Conclusions The orientation of a ferromagnetic object influences its mobility in a strong magnetic field. Tipping is easier than sliding for longish ferromagnetic projectiles, probably due to the lesser tissue resistance. The bullets moved more readily in biological tissue, especially brain tissue, compared to gelatine, thus implying that gelatine is not a suitable substitute for soft tissues when examining the movement of ferromagnetic objects in MR units.

Keywords MR · Ferromagnetic foreign bodies · Bullets · MR safety · Biological tissue

In loving memory of my father Werner Bolliger, PhD, 1941–2016

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Introduction

For the planning of further surgical procedures in gunshot injuries, a rapid assessment of the damage within the patient is crucial. Where financially and logistically possible, multislice computed tomography (MSCT) has replaced plain X-ray imaging as a diagnostic tool for the assessment of such injuries.

MSCT is rapid and very accurate in detecting foreign objects, such as bullets or bullet fragments, fractures, gas and the source of haemodynamic relevant haemorrhage, but it is—even combined with angiography—often insufficient in assessing the extent of damage to soft tissues and internal organs due to artefacts arising from the bullet itself.

Magnetic resonance imaging (MRI), on the other hand, although not the method of choice for detecting fractures and metallic foreign bodies, is superior to MSCT in showing soft-tissue and organ lesions [1]. Postmortem diffusion tensor imaging with fibre tracking is also useful in assessing axonal changes in traumatic brain injury [2].

A major drawback of MRI lies, however, in the very nature of this examination technique, namely magnetism, or rather the strong magnetic attraction that is generated by these units. Besides possible heating [3, 4], a danger Dedini et al. [5] could disprove, ferromagnetic foreign bodies may move within patients undergoing MRI and possibly endanger their lives. Indeed, due to this danger, most studies advise that patients with retained ferromagnetic bullets should not undergo MRI [3, 4, 6–8].

On the other hand, in postmortem examinations, where MRI is becoming increasingly applied, shifting bullets may change findings, thus, if no previous CT was performed, possibly giving rise to a misinterpretation of findings.

Teitelbaum et al. [6] showed this movement in their landmark study over a quarter of a century ago. In their study, they demonstrated that ferromagnetic bullets readily rotate within a gelatine phantom in response to magnetic torque of 1.5 T. These results gave rise to a list regarding the safety of pellets and bullets in 1.5-T MR units [9].

Dedini et al. [4] examined bullet movement further. Instead of observing the movement in gelatine or biological tissue, this group studied the movement of bullets subjected to 1.5-, 3- and 7 T MRI units in air. Of the 32 different bullets and shotgun pellets tested, 3 were ferromagnetic and moved when subjected to the respective magnetic fields of the MR units.

Using gelatine phantoms, Eggert et al. [10] confirmed that ferromagnetic military ordnance ammunition, namely the 7.5-mm GP 11 Suisse bullets, may move significantly in the magnetic field of an MR unit. Unsurprisingly, they showed that the stronger the magnetic field, the more the ferromagnetic bullet moved. In addition to this, it could also be shown that the position, i.e. orientation of the bullet toward the gantry, will also affect its willingness to move and that different MR unit polarizations can cause dissimilar movement behaviour.

Summarising the above, several groups [6, 11–13], using a 1.5-T and/or 3-T MR unit with various bullets and bullet fragments embedded in gelatine, showed that ferromagnetic bullets may indeed move in response to the magnetic field of an MR unit. Other groups [5, 14] confirmed this with bullets moving in air.

Eggert [10], again using gelatine-embedded bullets as in Teitelbaum's original research over 25 years ago, further discovered that the orientation of the bullet affect their movement.

Although ordnance gelatine is a reliable substitute for soft tissues in ballistic experiments [15–25], it is very well possible that it reacts differently to movements at low velocities, as would be the case in a bullet moving due to a magnetic field. For this reason, we decided to examine the movement properties of the ferromagnetic bullets 7.5-mm GP 11 Suisse and full metal-jacketed (FMJ) 9-mm Luger bullets in biological material, namely the brain and liver in dependence to their respective orientation to the MR unit gantry.

Material and method

Fresh whole calf brains (size approximately 10 × 10 × 6 cm) and fresh whole pig livers (size approximately 17 × 17 × 6 cm) were obtained from a local abattoir.

In each of these specimens, which was placed in a plastic bucket and embedded within a tissue paper in order to avoid movement of the organ, one steel-jacketed projectile—either 7.5-mm GP 11 Suisse (Norma Precision AB, Amotfors, Sweden) or 9-mm Luger FMJ (RUAG Ammotec Schweiz AG, Winterthur, Switzerland)—was inserted from above in a right angle from the gantry-facing side of the organ as centrally in the tissue as possible (Fig. 1). The orientation of the projectiles was as follows:

- Vertically, with the tip pointing upward (vertical)
- Horizontally in direction of the gantry (horizontal longitudinal)
- Horizontally in a 90° angle to the gantry (horizontal transverse)

Six lipophilic nitroglycerine capsules (Streuli Pharma AG, Uznach, Switzerland) were placed on the outside of the bucket as reference points as described previously [10].

The thus created phantoms then underwent CT imaging. CT was performed with a 128-slice dual-source multidetector row scanner (Somatom Definition Flash, Siemens Healthcare, Erlangen, Germany) as described previously [8].

The distance of either the tip or the base of each projectile from the reference points was then measured.

The phantoms were then exposed to a 3-T MRI system (Philips Achieva, Philips Healthcare, The Netherlands). The gantry entrance of the MRI system was stated as "magnetic south" by Eggert et al. [10]. Each plastic bucket was fixed on the MR table using restraining straps at a distance of approximately 1.5 m from the gantry entrance. Then, the phantom was exposed to the force of the magnetic field by moving the MR table into the gantry until the bucket was located in the middle of the MR bore and back out again. No coil was used and no imaging was performed. After this, the phantoms were

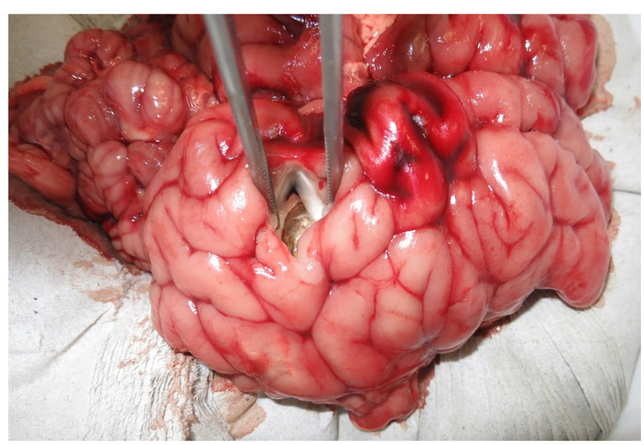

Fig. 1 Insertion of a 9-mm Luger bullet through a small incision into a horizontal transverse position. The brain will be moved toward the right to the gantry

Table 1 7.5-mm GP 11 Suisse in pig liver. The movement after being exposed to the magnetic field of the 3-T unit with regard to the reference points (first row) is given in centimetres. "Exit" indicates that the bullet slipped out of the liver. Negative values mean that the bullet moved toward the reference point and positive ones that the bullet moved away

		Vertical						Horizontal longitudinal						Horizontal transverse					
Bullet		1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
No. 1	Tip	1	0	0	−0.1	0	−0.8	−0.2	−0.2	−0.1	−0.2	0.1	0.4	−2.8	−3.5	0.5	−0.5	3	4.2
	Base	−0.9	−0.5	−0.5	0.7	0.5	1.3	0	−0.2	0.2	−0.1	0.2	0.1	−0.3	1	−2.7	2.7	−0.8	−0.3
No. 2	Tip	−1.3	−0.5	−0.2	0.7	0.9	1.5	−1.1	−1.1	−0.2	0	0.4	1.2	1.3	−1.2	3.3	−2.9	1.4	−0.6
	Base	0.2	0.3	0	−0.4	−0.6	−0.4	−0.6	−1.9	0.1	−0.4	1	1.3	−1.7	−1.4	−0.5	1.2	0.7	2
No. 3	Tip	Exit	Exit	Exit	Exit	Exit	Exit	−2.6	−1.6	−1.3	0.4	0.4	2.7	−3.2	−2.5	1.3	1.6	3.4	4.9
	Base	Exit	Exit	Exit	Exit	Exit	Exit	−2.4	−2.9	−1.5	−0.7	0.4	2.6	−1.9	−0.5	−2.8	3	−0.2	1.6
No. 4	Tip	Exit	Exit	Exit	Exit	Exit	Exit	−2.7	−1.2	−2.3	1.5	0.8	3.1	−1.3	−0.6	−0.7	0.9	0.7	1.5
	Base	Exit	Exit	Exit	Exit	Exit	Exit	−2.5	−2.7	−1.7	−0.8	0.9	2.4	−0.4	0.2	−0.7	0.3	−0.4	−0.2
No. 5	Tip	Exit	Exit	Exit	Exit	Exit	Exit	−0.7	−0.8	−0.4	0.4	0.4	0.9	0.1	−0.2	0.4	−0.2	0.2	0.1
	Base	Exit	Exit	Exit	Exit	Exit	Exit	−0.5	−0.3	−0.6	0.6	0	−0.3	0.5	0.5	0.3	−0.3	−0.1	−0.3

then subjected to a final CT scan as described before and the position of the bullet measured as described above.

The absolute movement of the projectiles was determined by simple subtraction of measured values before and after exposing to the MR scanner according to the distances of each of the reference points from the projectile.

Results

Neither the projectiles inserted into the brains nor those inserted into the livers exited the organ via the initial incision made to place the projectile into the organ but moved through unharmed tissue.

Liver

The 7.5-mm GP 11 Suisse slipped out of the liver in three out of five of the "vertical" cases (Table 1). However, in the remaining two "vertical" cases, there was only a maximum movement of 1.5 cm (tip). "Horizontal transverse" 7.5-mm GP 11 bullets rotated into the direction of the gantry moving as much as 3.5 cm (bullet no. 1) and as little as 0.5 cm (bullet no. 5). "Horizontal longitudinal" 7.5-mm GP 11 bullets did not move as much as the "vertical" and the "horizontal transverse" ones did; indeed, only two bullets (no. 3 and 4) moved more than 1.1 cm, namely 2.7 and 3.1 cm, respectively (Fig. 2).

The 9-mm Luger FMJ bullets proved to be more stable (Table 2); the "vertical" group displayed a maximum

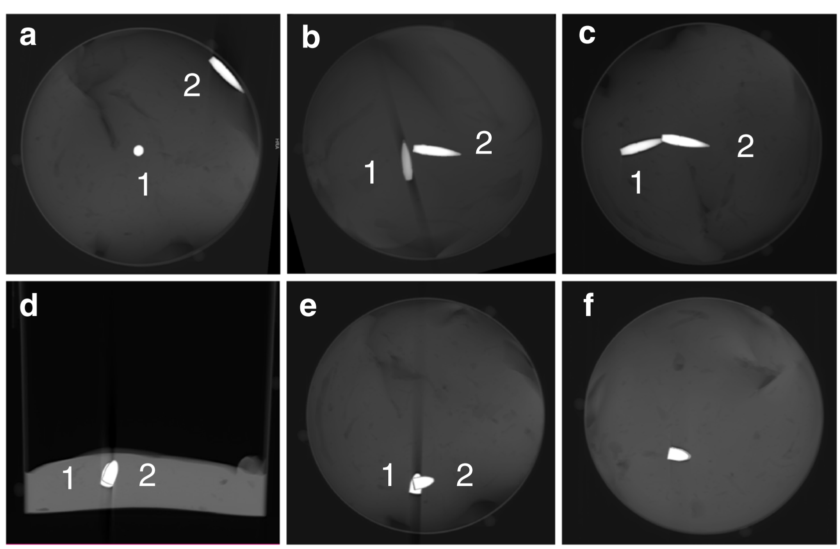

Fig. 2 Movement in the liver, fused CT images. The gantry is on the *right*. No. «*1*» depicts the original orientation, no. «*2*» after 3-T MR exposure. All images except **d** (lateral view) are viewed from above. **a** GP 11, initially vertical, **b** horizontal transverse and **c** horizontal longitudinal orientation, and **d** 9-mm Luger, initially vertical, **e** horizontal transverse and **f** horizontal longitudinal (here, there is hardly any visible movement) orientation

Table 2 9-mm Luger FMJ in pig liver in analogy to Table 1

		Vertical						Horizontal longitudinal						Horizontal transverse					
Bullet		1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
No. 1	Tip	0	−0.4	0	0	0.1	0.1	0.1	0.1	0.1	−0.1	−0.1	0	−0.2	0	0	0	0.1	0
	Base	0.2	0	0.1	−0.2	−0.1	−0.1	−0.1	0	0	0	−0.1	0.1	−0.4	0	0	0.1	−0.1	0.1
No. 2	Tip	−0.6	−0.3	−0.3	1	1.2	1.2	0	0	0	0	0	0.1	0	0.1	−0.2	−0.1	−0.1	−0.2
	Base	−0.3	−0.1	0.1	−0.3	−0.4	−0.1	−0.1	0	0	0	−0.1	0.1	−0.1	0	0.1	0	0.2	0
No. 3	Tip	−0.4	−0.3	−0.2	0	0.2	0.2	−0.1	0.2	0	0	−0.1	0	−0.2	0	0	0.1	0	0.2
	Base	0	0.1	−0.1	0	−0.2	−0.1	0	−0.2	−0.1	−0.1	0	0.1	−0.3	−0.1	0	0.2	0	−1.7
No. 4	Tip	−0.7	−0.2	−0.2	0.6	0.1	0.7	0.1	0.1	−0.2	0.1	−0.1	0	−0.7	−1.5	0.2	−0.3	1	1.4
	Base	−0.5	0.2	−0.1	−0.1	−0.3	−0.1	0	0	−0.2	0	−0.1	0	−0.2	0.1	−0.5	0.2	−0.4	−0.2
No. 5	Tip	−0.4	−0.4	−0.1	0.4	0.9	0.7	−0.1	0.1	0	−0.1	−0.1	0	−0.3	0.4	−1.1	1	0.2	1
	Base	0.4	0.4	0.1	−0.4	−0.3	−0.4	0	0.2	0	0.1	−0.1	−0.1	0.4	−0.3	0.5	−0.3	−0.1	−0.6

movement of 1.2 cm. "Horizontal longitudinal" 9-mm Luger FMJ bullets hardly moved at all; indeed, the maximum movement was 0.2 cm. However, the "horizontal transverse" bullets tended to move more freely. Bullet no. 3 of this group managed to move as much as 1.7 cm (Fig. 3).

Brain

All 7.5-mm GP 11 bullets slipped out of the brain.

Of the "vertical" 9-mm Luger FMJ group (Table 3), one bullet (no. 1) slipped out of the brain and the other four were less mobile, with maximum movements raging between 0.7 and 1.3 cm. In the "horizontal longitudinal" 9-mm Luger FMJ group, only one (bullet no. 1) remained in the brain (maximum deviation 0.6 cm), whereas the others all slipped out. All the "horizontal transverse" bullets remained within the brain, with maximum deviations ranging from 0.9 to 2.1 cm.

Discussion

Our results confirmed the conclusions of our previous study regarding the significance of the orientation of the bullet with regard to its mobility when subjected to the strong magnetic field of a 3-T MR unit.

In this study, the phantoms were moved into the bore and back out again. No imaging was performed as the spatial gradient of static magnetic field (B_0) is indicative of the attraction force on magnetic objects. This spatial gradient is symmetric around the *z*-axis of the MR scanner and its values are the highest at the entrance of the bore. These values (T/m) are described as dB/dx referring to static magnetic field strength over space per unit length [26]. In this study, the maximum spatial gradient of $B_{0,}$ occurring along the length of a cylindrical tube around the *z*-axis, was 5.5 T/m according to a tube diameter of 30 cm, which represents the position of the phantom. According the technical description of the MR scanner, 8.6 T/m occurs according to a diameter of 60 cm (maximum bore-diameter at the centre). Thus, apart from tissue, the position of the bullet inside the body is significant, as the attraction force increases at the outer range of the maximum bore diameter at the centre. The vertically placed 7.5-mm GP 11 Suisse moved more frequently in the pig liver than horizontally placed ones. Of the latter groups, the transverse bullets moved most, tipping along their axes in direction of the gantry. Interestingly, the longitudinally placed bullets, despite their

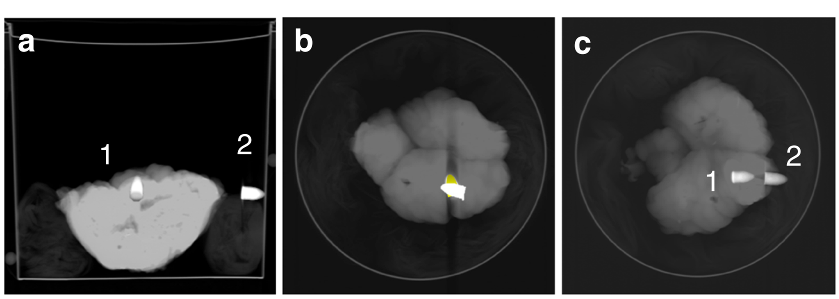

Fig. 3 Movement of 9-mm Luger in the brain, fused CT images. The gantry is on the *right*. No. «*1*» depicts the original orientation, no. «*2*» after 3-T MR exposure. The *yellow bullet* is the original position in **b**. **a** Initially vertical, lateral view, **b** horizontal transverse and **c** horizontal longitudinal orientation

Table 3 9-mm Luger FMJ in calf brain in analogy to Tables 1 and 2."Exit" indicates that the bullet slipped out of the brain

		Vertical						Horizontal longitudinal						Horizontal transverse					
Bullet		1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
No. 1	Tip	Exit	Exit	Exit	Exit	Exit	Exit	−0.4	0.0	−0.1	−0.3	0.3	0.6	−0.6	−1.4	0.5	0.2	1.5	1.2
	Base	Exit	Exit	Exit	Exit	Exit	Exit	−0.6	−0.2	−0.4	0.5	0.2	0.6	0.1	0.6	−0.3	0.3	−0.7	−0.4
No. 2	Tip	0.7	−0.3	−0.1	−0.3	0.1	−1.0	Exit	Exit	Exit	Exit	Exit	Exit	0.9	−0.5	1.1	0.0	0.6	−0.4
	Base	−0.4	−0.1	−0.5	0.5	0.0	0.3	Exit	Exit	Exit	Exit	Exit	Exit	−0.9	−0.1	−0.3	−0.4	0.1	0.7
No. 3	Tip	0.8	0.2	−0.2	−0.1	−0.1	−1.0	Exit	Exit	Exit	Exit	Exit	Exit	0.4	−0.3	0.8	−0.9	0.4	−0.6
	Base	−0.6	−0.3	−0.1	0.1	0.1	0.2	Exit	Exit	Exit	Exit	Exit	Exit	−0.6	−0.1	−0.4	0.7	0.1	0.4
No. 4	Tip	0.7	−0.2	−0.1	0.1	0.2	−1.0	Exit	Exit	Exit	Exit	Exit	Exit	−0.9	−0.5	0.1	0.3	2.1	1.1
	Base	−1.3	−0.1	0.2	−0.3	0.4	1.1	Exit	Exit	Exit	Exit	Exit	Exit	0.4	0.8	−0.7	0.6	−0.6	−0.3
No. 5	Tip	0.7	0.1	−0.3	0.1	−0.2	−1.0	Exit	Exit	Exit	Exit	Exit	Exit	−0.6	−1.1	0.7	−0.3	1.1	1.1
	Base	−0.7	0.1	−0.1	−0.1	0.0	0.4	Exit	Exit	Exit	Exit	Exit	Exit	0.3	0.5	−0.1	0.0	−0.5	−0.5

aerodynamic build, moved less than the transversely placed bullets.

9-mm Luger FMJ partially reflected the results witnessed in the 7.5-mm GP 11 Suisse group. Although the vertically placed bullets moved, they did so less readily than their GP 11 counterparts. Of the horizontally oriented bullets, the transverse ones were again more mobile than the longitudinal ones.

We conclude from these results that tipping of a bullet contributes more to the movement of a bullet in MR than horizontal sliding in the *Y*-axis of liver tissue. This would explain why the longer 7.5-mm GP 11 Suisse bullets moved most in the vertical and horizontal transverse position, as the bullet aligns itself in the magnetic field. This tipping, or rotation, is less evident in the shorter 9-mm Luger projectiles, which therefore possess a lesser torque than their longer counterparts.

In calf brain, which obviously constitutes a softer tissue than pig liver, the longitudinally placed bullets managed to slide along the *Y*-axis, probably due to the lesser tissue resistance.

According to Eggert et al. [10], the maximum movement of vertically placed bullets in gelatine ranged up to 7.8 cm. This movement may mean that in the case of a calf brain, the bullet would slip out of the brain. However, horizontally placed 7.5-mm GP 11 bullets moved only as much as 0.97 cm, a distance which should not have permitted a slipping out of the brain in the present study. These results obtained from gelatine models would imply that horizontally placed bullets should not slip out of the brain. However, regardless of the orientation of the bullet, every 7.5-mm GP 11 Suisse exited the calf brain. This means that bullets retained in biological material, especially the brain and to a lesser extent the liver, move far more when exposed to the magnetic field of a 3-T MR unit than such embedded in gelatine.

As the pig livers were more or less the same size as the phantoms used by Eggert et al. [10] and in both studies, the projectiles were placed more or less in the middle of the phantom; we do not believe that the size of the phantom played a role in the mobility of the projectiles in the livers of our study. Although the brains were significantly smaller than the phantoms of Eggert et al., the position of the projectile entering the magnetic field of the gantry—the most relevant feature—was the same. Therefore, we believe that our results in biological tissue are comparable to those acquired using the same experimental setup in ballistic gelatine.

As most studies in the past quarter of a century concerning movement of ferromagnetic projectiles in MR units were performed in gelatine, these results should be treated with utmost caution. In real biological tissue, they may move far more readily than in gelatine.

It seems that gelatine, although an adequate soft-tissue substitute in ballistic experiments, is not an ideal soft-tissue substitute when examining the movement of ferromagnetic projectiles in the magnetic field of an MR unit. Ferromagnetic objects seem to tip more readily than slide along the magnetic field through the viscous soft tissue of the brain and liver, as well as gelatine.

Conclusions

- Gelatine is not an adequate soft-tissue substitute for measuring the movement of ferromagnetic objects in the magnetic field of an MR unit
- The movement of ferromagnetic objects subjected to 3-T MR units depends on the bullet shape and the surrounding tissue
- Tipping is easier than sliding for longish ferromagnetic objects subjected to 3-T MR units

- The orientation of a ferromagnetic object influences its mobility in a strong magnetic field

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