Common Healthcare Related Instruments Subjected To Magnetic Attraction Study (CHRISTMAS): prospective in situ experimental study

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ABSTRACT

OBJECTIVE
To investigate the behaviour of common healthcare related objects in a 3 tesla (T) MRI (magnetic resonance imaging) scanner, examining their ability to self-propel towards the scanner bore and their potential for tissue penetration.

DESIGN
Prospective in situ experimental study.

SETTING
Clinical 3 T MRI scanner. Customised rig designed and built to guide objects towards the scanner bore.

PARTICIPANTS
12 categories of objects commonly found in hospitals, or on patients or healthcare professionals, or near an MRI scanning room. Human tissue penetration simulated with ballistic gel (Federal Bureau of Investigation and North Atlantic Treaty Organisation graded).

MAIN OUTCOME MEASURES
SANTA (site where applied newtonian mechanics triggers acceleration) measurements and depth of tissue penetration of the objects.

RESULTS
SANTA measurements ranged from 0 cm for the 20 pence, 50 pence, and £2 coins to 152-161 cm for a knife and the biscuit tins. One penny, two pence, five pence, and 10 pence coins showed self-propulsion and acceleration towards the scanner bore at a distance >100 cm from the gantry entry point. Linear regression analysis showed no apparent correlation between the weight of the objects and their SANTA measurements ($R^2<0.1$). Only five objects penetrated the ballistic gel (simulated human tissue). The deepest penetration was by the knife (5.5 cm), closely followed by the teaspoon (5.0 cm), fork (4.0 cm), spoon (3.5 cm), and a 10 pence coin (0.5 cm). Although the biscuit tins did not penetrate the simulated human tissue, they exerted substantial impact force which could potentially cause bone fractures. A smartphone, digital thermometer, metallic credit card, and pen torch remained fully functional after several passes into the MRI scanner. No discernible loss of image quality for the MRI scanner after the experiments was found.

CONCLUSIONS
The study highlights the potential for harm (major tissue damage and bone fractures) when commonly found objects in a healthcare setting are unintentionally brought into the MRI scanner room. Patients and healthcare professionals need to be aware of the dangers associated with bringing ferromagnetic objects into the MRI environment.

WHAT IS ALREADY KNOWN ABOUT THIS TOPIC
Ferromagnetic objects near an MRI (magnetic resonance imaging) scanner, when captured by the magnetic fringe field, can self-propel towards the scanner bore

Patient injury, equipment damage, and even deaths have occurred after ferromagnetic objects were unintentionally brought into the scanner room

WHAT DOES THIS STUDY ADDS
Controlled experiments with smaller ferromagnetic objects can be safely conducted under appropriate safety measures without damage to clinical MRI scanners

Hospital cutlery utensils and even a 10 pence coin can potentially cause major tissue damage and small biscuit tins could fracture bones

Small electrical equipment, such as smartphones and pen torches, and contactless credit cards might remain fully functional after multiple passes into a 3 tesla MRI scanner

Introduction
The introduction of MRI (magnetic resonance imaging) has provided healthcare professionals with unparalleled, cross sectional image definition of soft tissues without the need for ionising radiation. Clinical MRI scanners use superconducting magnets with field strengths of 1.5 or 3 tesla (T), which are 3-6 times the field strength of industrial electromagnets used to move and lift scrap metal.[1] One of the main risks associated with superconducting magnets is that the magnetic field is permanently switched on. Any ferromagnetic object brought into the fringe field of an MRI machine is immediately attracted towards the scanner bore. This effect requires strict safety precautions, including signage on the doors of magnet rooms. In most clinical scanners, a line is drawn on the floor around the magnet to indicate the limit of the fringe field (5 gauss), within which a risk to cardiac pacemakers and other implanted medical devices exists. Despite extensive warning signs, verbal checks, and training for healthcare professionals, multiple incidents of ferromagnetic objects entering the scanning rooms, even if unintentionally, by both patients and healthcare professionals have occurred.

Despite shielding, MRI magnets have a rapid increase in field strength as ferromagnetic objects get closer in proximity.[2] Any ferromagnetic object will become a projectile when the force of attraction exceeds resistance to motion, with rapid acceleration towards the scanner bore.[3] This effect poses a serious hazard, because objects with high kinetic energy have been reported to cause extensive damage to the magnet and, more concerningly, patient injury or death from blunt force trauma.[4]

Over a 10 year period, the US Food and Drug Administration received 1568 adverse reports related to MRI systems.[5] Although most were related to thermal injuries, several media reports have highlighted incidents related to MRI leading to deaths, including from projectile objects.[4 6] A recent incident involved a pistol being smuggled into the magnet room, which was subsequently attracted to the magnet and self-discharged, causing the individual's death.[7] Innumerable anecdotal stories exist from MRI radiographers, physicists, and service engineers about small objects becoming lodged inside MRI magnets, and a YouTube video shows the attractive force of a 4 T magnet on a stapler, wrench, and small chair.[8] We, however, could not identify reliable peer reviewed literature related to projectile incidents.

In this study, we investigated the potential risk of injury from 12 metallic objects in one of three categories: known to have been unintentionally brought into an MRI scanner room, known to have been nearly brought into an MRI scanner room, and could potentially have been brought into our hospitals' MRI magnet rooms over the past 12 years. We designed and implemented an experimental test rig to facilitate a safe and controlled experiment to investigate the behaviour of the metallic objects when bought close to a 3 T magnet. See the visual summary at the end of the paper for an overview of the study and its findings.

Methods

Magnetic resonance imaging scanner

In this experiment, we used a Siemens Magnetron Skylar Tim Dot system MRI scanner (3 T, 12 years and 3 months old) in an electronically shielded room on the third floor of the hospital.

Electromagnetic launch funnel

A test rig, termed the electromagnetic launch funnel (ELF, fig 1), was built to safely guide objects into the centre of the magnet bore, while simultaneously estimating the force of impact at the isocentre. The entire ELF was designed to slide along the MRI system couch inside the bore.

The base and support structure of the ELF were constructed with non-ferromagnetic material consisting of high density extruded polystyrene foam boards joined together with a polyvinyl acetate based glue (Elmer's glue, Elmers, Westerville, OH, USA). High density extruded polystyrene was chosen because of its light weight and high rigidity for construction, and its potential to absorb impact because of its closed cell structure.

The simulated human tissue target[9 10] was 10% synthetic gelatine ballistic gel for projectiles (Clear Ballistics, SC, USA), graded by the Federal Bureau of Investigation and the North Atlantic Treaty Organisation. The ballistic gel was sited at the entrance of the scanner bore. The batch of ballistic gel used was manufactured on 7 December 2021 and graded with a penetration rating of 3.25 inches with a 0.177 alloy steel ball bearing at 590 feet per second. The ballistic gel block was surrounded on four sides by high density foam and the top was covered by a 2 mm thick acrylic panel to allow visualisation of any penetration (fig 1). To direct the objects towards the ballistic gel, we used interchangeable acrylic tubes, set into high density foam supports. Two large bore tubes were made from 5 mm thick acrylic with inner diameters of 110 mm and 50 mm. A smaller bore tube was made of 3 mm acrylic with an inner diameter of 34 mm.

A modified Whipple shield was then constructed around the junction of the acrylic tube and ballistic gel target with a primary layer of 2 mm acrylic panels secured at the joints with Gorilla crystal tape (Gorilla Glue Company, OH, USA). The secondary layer consisted of a prefabricated 3 mm thick acrylic isolation dome designed for use as a barrier shield in an MRI magnet[11] with the front panel removed (fig 1). This layer was further reinforced with custom cut 40 mm thick high density extruded polystyrene foam on the rear panel. A final layer of protection between the dome and the MRI bore wall was provided by a 900 mm × 600 mm × 3 mm self-healing cutting mat (Suremark, Singapore) which was draped over the dome. Sandbags were placed on the acrylic tubes for stability and to prevent movement.

Objects

Twelve categories of objects (table 1) were introduced into the MRI scanner under controlled conditions. The chosen objects were representative of objects that were unintentionally carried, or nearly carried, or could potentially be carried into the MRI room at our institutions. All objects and the MRI scanner were confirmed to be in full working condition before the study.

Weighing in

All objects to be launched by the ELF, excluding the chair because of its size, were weighed on an A&D GF 200 precision weighing scale (range 0-200 g, accuracy ±0.001 g; A&D, Tokyo, Japan). Measurements were performed in a draft free room. The scale was set on a solid surface and aligned horizontally with a spirit level. The scale was re-zeroed between measurements of each object. Final weight was recorded after at least five seconds to allow the scales to settle. The ELF was weighed on a SECA 769 electronic clinical weighing scale (weight range 0-200 kg, accuracy ±100 g; SECA, Hamburg, Germany).

Site where applied newtonian mechanics triggers acceleration

The site where applied newtonian mechanics triggers acceleration (SANTA) is the point where the attraction of the magnetic field overcomes the static friction of the object at rest, resulting in acceleration towards the magnet. SANTA values were measured as the distance

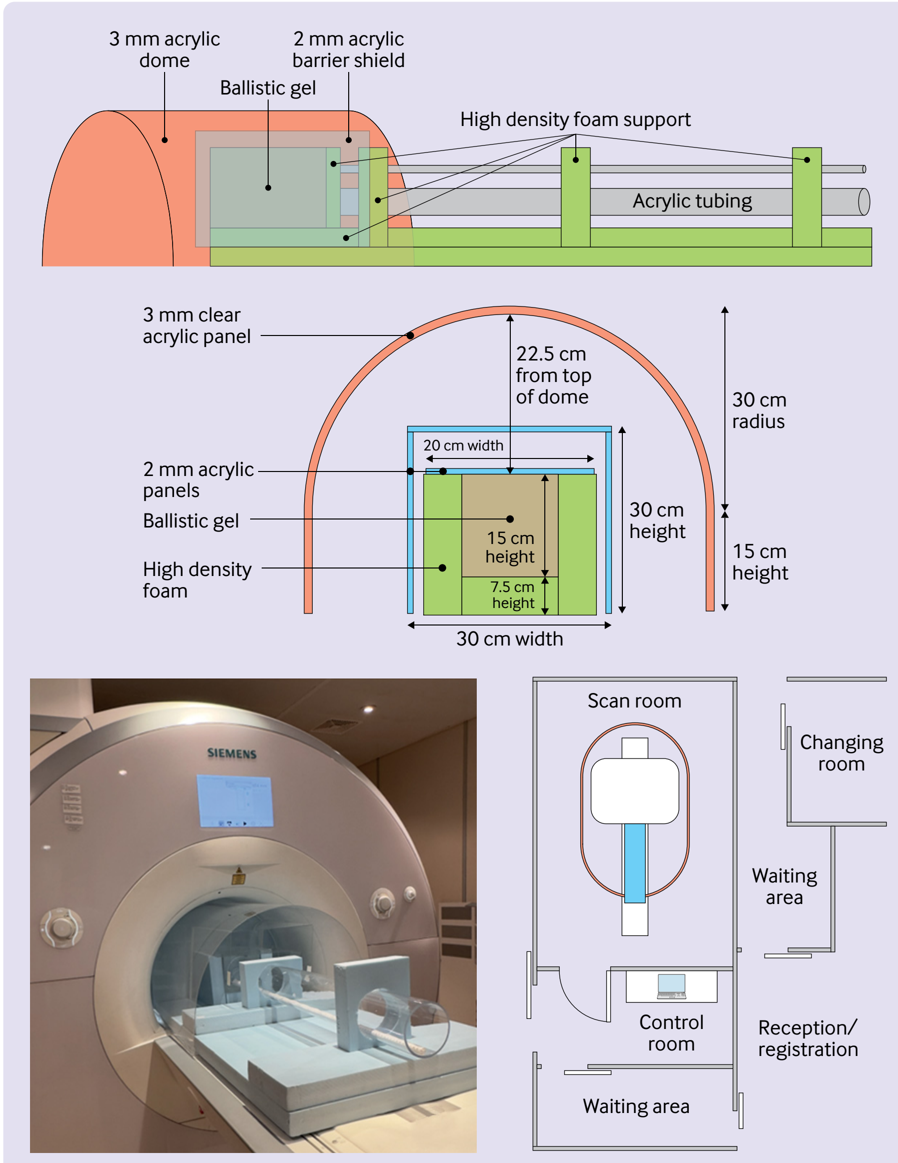

Fig 1 | Electromagnetic launch funnel (ELF). Schematic lateral (top) and frontal (middle) projections of the ELF. Position of ELF within the 3 tesla (T) MRI (magnetic resonance imaging) scanner (bottom, left). The additional layer of protection provided by a self-healing cutting mat between the ELF acrylic dome and the scanner casing is not shown in this image of the MRI scanner. Scale schematic drawing of the layout of the 3 T MRI scanning room (bottom, right). The red line represents the 5 gauss line (magnetic fringe field) drawn on the floor of the room. The blue rectangle represents the location of the ELF during the experiments

between the tip of the acrylic rod pusher and entrance to the magnet bore.

The first 11 objects were carefully inserted into the far end of the smallest acrylic tube that freely fitted into the ELF. Each object was advanced at a rate of about 5 mm per second with a solid 100 cm × 1 cm diameter acrylic rod and an Ikea in-store measuring tape to go (Ikea, Delf, Netherlands) until it reached SANTA. On reaching SANTA, the object accelerated towards the simulated patient (ballistic gel).

The office chair was too large to be introduced by the ELF. The seating component and arms of the chair were tied securely to the wheeled base of the chair with 3 mm diameter Cordelette with a rating of 2.5 kilonewtons (kN) (Decathlon, Villeneuve-d'Ascq, France). The chair was then secured with 6 mm diameter Cordelette with a rating of 9.0 kN (Decathlon). Adequate slack was maintained to facilitate the chair's reach to the front panel of the gantry. The opposing end of the Cordelette was doubly secured, one tied to the MRI room door and the other anchored to a point on the external wall of the scanner room.

To simulate previous incidents where non-MRI safe or conditional chairs with wheels were brought into MRI rooms, the most direct path between the entrance door and the front entry of the magnet bore was chosen as the direction of travel. The chair was advanced at about 1 cm intervals with three second pauses between each movement, towards the front of the magnet bore. The SANTA for the chair was the point at which the chair was noted to freely move towards the bore. To

Table 1 | 12 categories of objects introduced into the 3 tesla MRI (magnetic resonance imaging) magnet

Object and subcategory by category No	Model and brand	Comments
1: Mobile phone:		
Smart phone	Apple iPhone 6 model A1586 (Apple, CA, USA)	Plastic screen protector in place, no phone casing
2: Pen torch	BMA branded pen torch (British Medical Association, London, UK)	2 AAA batteries in place
3: Stethoscope	Generic unbranded stethoscope	From resus trolley in MRI waiting room
4: Pen:		
Ball point pen	BIC Cristal Clic 0.8 mm (BIC, Clichy, France)	Black ink
5: Badge holder:		
Pulley system	Durable (Hunke & Jochheim, Iserlohn, Germany)	
6: Thermometer:		
Digital, sublingual	MC103 (Omron, Kyoto, Japan)	
7: Scissors:		
Nursing safety scissors	Spirit bandage scissors 15 cm (Spirit Medical, Taipei City, Taiwan Republic of China)	
8: Bank card:		
Credit card	The Platinum Charge Card (American Express, NY, USA)	
9: Coins:		
£2	2010 vintage	
£1	2006 vintage	
50 pence	2014 vintage	
20 pence	1982 vintage	
10 pence	2014 vintage	
5 pence	2014 vintage	
2 pence	2011 vintage	
1 penny	1993 vintage	
10: Cutlery:		
Fork	NHS property	Temporary loan from radiology day unit
Spoon	NHS property	Temporary loan from radiology day unit
Knife	NHS property	Temporary loan from radiology day unit
Teaspoon	NHS property	Temporary loan from radiology day unit
11: Biscuit tin:		
Shortbread	Betty's Yorkshire shortbread tin 220 g (Harrogate, UK)	Empty tin. Contents repurposed by research team for sustenance
Christmas biscuits	Christmas orange and chocolate biscuits tin 125 g (Fortnum and Mason's, London, UK)	Empty tin. Contents repurposed by research team for temporary elevation of dopamine
12: Chair:		
Office chair	Millberget swivel chair 404.893.95 (Ikea, Delft, Netherlands)	

prevent unintentional launch of the chair into the MRI gantry, two study members were ready to stop the chair by the sidearms as soon as SANTA was reached.

Tissue penetration

After the launch of each object, the acrylic tubing was removed and a visual inspection was performed to determine the location of the object (fig 2). Any object adherent to the ballistic gel was held firmly by a study team member with their dominant hand, with their elbow anchored on the base of the ELF to prevent further movement. Care was taken not to apply pressure to the object in the direction of the gel block. Two other study team members retrieved the ELF by sliding it (without the acrylic tubing) out of the magnet and beyond the 5 gauss line of the magnet fringe field. Outside the 5 gauss line, the first team member gently released their hold on the object. Any object that fell onto the ELF with no residual laceration of the ballistic gel was considered to be non-penetrating.

For experiments where objects were considered to have penetrated the ballistic gel, the ELF was retrieved into the waiting area outside the magnet room. The modified Whipple shield was then removed, and the slab of ballistic gel was retrieved from the ELF and placed onto the control room table for further examination. The depth of penetration of the object was then measured with a disposable wound measurement marker (UrgoClean Ag, Urgo Medical, Loughborough, UK) (supplementary fig 1).

Static friction forces on the ELF

The static friction of the ELF was measured by securing 3 mm Cordelette to the scanner end of the ELF and the Cordelette was threaded through the bore to the back of the scanner room. The ELF was then set in its normal position. A portable digital handheld travel luggage or fishing electronic scale (range 0-50 kg, accuracy ±10 g; Rhorawill, Amazon.com) was attached to the end of the Cordelette and set to display the maximal weight measured. Gentle and gradual traction was applied to the ELF assembly from the attached weighing scale until movement of the ELF was noted. The maximal weight reading

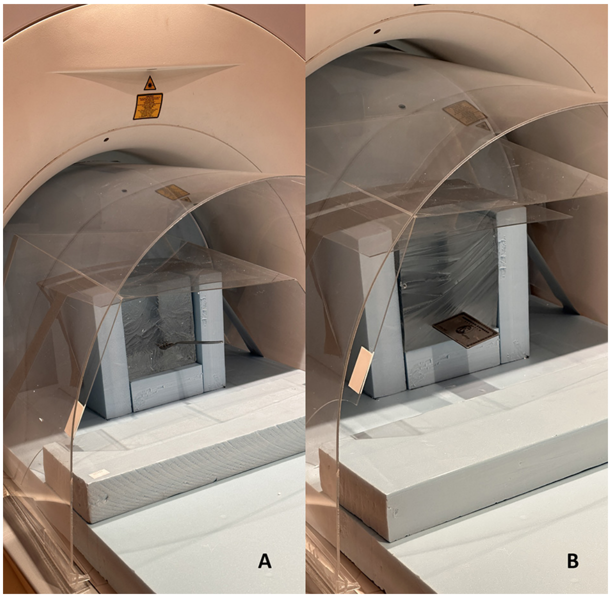

Fig 2 | Adherence of objects onto the ballistic gel. (A) Penetration of a fork into ballistic gel. (B) Metallic credit card adherent to the ballistic gel at the level of the scanner gantry inlet after removal of the guiding and protective acrylic tubing. The metallic credit card did not penetrate the gel

on the scale was taken as the static force of friction between the scanner bed and the ELF.

SANTA relation with weight

SANTA measurements were plotted against object weight on a scatter chart. The swivel chair was excluded from this calculation to reduce confounding. This confounding was because of the difference in the magnetic field lines that the chair was subjected to (at an angle to the bore) compared with the rest of the objects that were in line with the direction of the static magnetic field.

Table 2 | Measured weight of objects used in the study

Object	Weight (g)
Apple iPhone 6, model A1586	131.025
BMA branded pen torch (including batteries)	27.301
Generic unbranded stethoscope	76.982
BIC Crystal Clic 0.8 mm ball point pen	6.943
Badge pulley holder	20.307
Thermometer	12.641
Nursing safety scissors	31.600
Metallic credit card	18.512
Coin type:	
£2	11.988
£1	8.808
50 pence	7.952
20 pence	5.024
10 pence	6.577
5 pence	3.241
2 pence	7.125
1 penny	3.533
Cutlery:	
Fork	32.988
Spoon	27.860
Knife	41.408
Teaspoon	14.178
Biscuit tin (empty):	
Betty's Yorkshire shortbread 220 g	121.375
Fortnum and Mason's Christmas biscuits 125 g	92.140
Office chair:	
Cordelettes (3 mm) to tie swivel	63.650
Cordelettes (6 mm) to tie swivel	132.586

Patient and public involvement

We did not involve patients or the public in this study because of safety concerns. The potential risk of individuals attempting to replicate the study, particularly by bringing small metallic objects into the MRI scanner room, led to limitations on external involvement.

Results

Weighing in

Table 2 shows the measured weight of the objects used in the experiment. The ELF rig base without the interchangeable acrylic tubes weighed 13.6 kg. The large (110 mm) bore acrylic tube with high density foam support weighed 2.2 kg.

Site where applied newtonian mechanics triggers acceleration

SANTA values for the objects introduced from the ELF were measured by two researchers to the nearest centimetre. Objects where SANTA was never reached before their leading edge touched the ballistic gel were given a value of zero. Figure 3 shows the results plotted on a scale figure, and individual values are given in the supplementary table.

An accurate SANTA measurement for the armchair could not be determined because of the 360 degree swivel and the five legs on dual castors. The experiment was therefore repeated multiple times with the chair in various rotations and the presumed SANTA was taken from the level of the hydraulic component representing the centre of the chair. On all rotations, no independent movement of the chair was noted when the hydraulic component was outside the 5 gauss line. Independent movement of the chair towards the magnet core occurred when the hydraulic component had just crossed the 5 gauss line.

Tissue penetration

Only five objects penetrated the ballistic gel. The deepest penetration was by the knife, at 5.5 cm (supplementary fig 1), closely followed by the teaspoon (5.0 cm), fork (4.0 cm), spoon (3.5 cm), and 10 pence coin (0.5 cm). The other objects caused no tissue penetration, but we saw occasional indentation of the ballistic gel by smaller objects or a dent in some of the objects themselves (fig 4). For the two empty biscuit tins, we saw high acceleration and impact against the ballistic gel block, resulting in the movement of the ELF deeper into the MRI scanner as well as breakage of the inner layer of the modified Whipple shield (supplementary video).

Functionality of electronic equipment

The iPhone 6 retained both calling and smart phone functionality, despite more than three passes from the ELF to the front of the 3 T MRI scanner (fig 5).

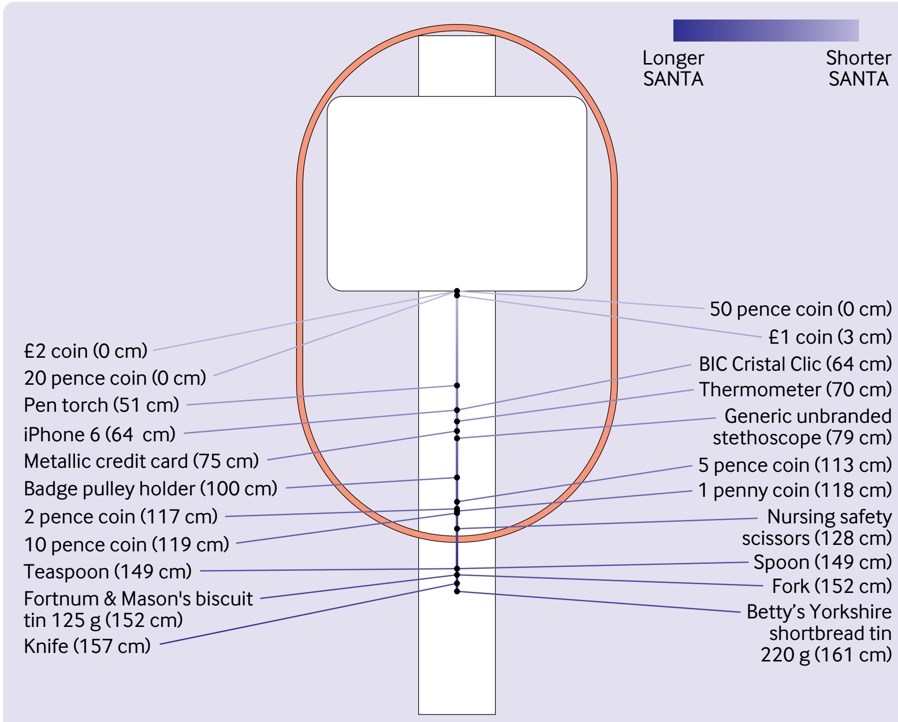

Fig 3 | Measurement of site where applied newtonian mechanics triggers acceleration (SANTA). Magnified view of the MRI (magnetic resonance imaging) room layout, with SANTA values of the objects drawn to scale along the launch axis

The internal memory of the iPhone was intact, with no corruption of old photos dating back to Christmas 2018 (fig 5). The camera continued to focus and could resolve small line pairs on a piece of fabric (fig 5). The video recording and replay functions were unaffected. The pen torch remained functional with no qualitative change in the brightness of the light (fig 6). The digital thermometer was turned on after the experiment and the liquid crystal display was still fully functional (fig 6). The metallic credit card was fully functional after the experiment, with successful purchase of Burger King soft serve ice creams by using the contactless payment function on a self-service terminal. Despite the multitude of objects introduced into the scanner from the ELF, we found no discernible loss of MRI image quality after the study (supplementary fig 2).

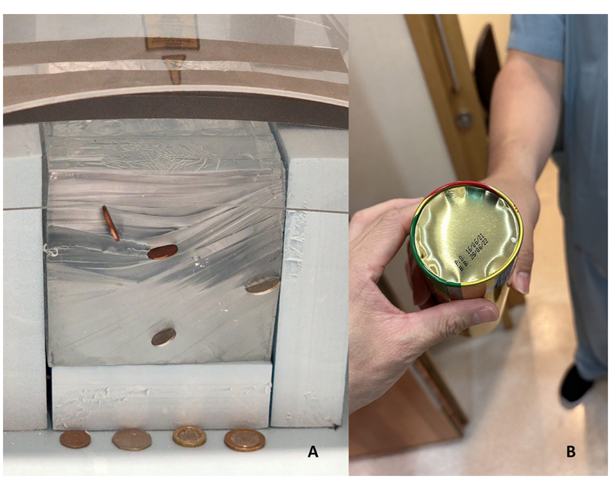

Fig 4 | Deformation of the ballistic gel by the objects. (A) Reconstructed summary appearance of the coins tested in the study with the ballistic gel at the gantry of the scanner. The 20 pence, 50 pence, and £2 coins did not have any recordable site where applied newtonian mechanics triggers acceleration (SANTA) and fell to the base level of the electromagnetic launch funnel (ELF) when the protective acrylic tubing was removed. The £1 coin had a SANTA value of 3 cm, but the electromagnetic attraction was insufficient against the pull of gravity and it also fell onto the base of the ELF. The one penny, two pence, and five pence coins adhered to the ballistic gel after removal of the acrylic tubing and seemed to be indenting or deforming the ballistic gel. These coins did not penetrate the ballistic gel, however, and fell onto the base of the ELF when it was retrieved past the 5 gauss line. The 10 pence coin partially penetrated the ballistic gel, measured at 0.5 cm. (B) Deformation of the base of the Fortnum and Mason's biscuit tin

Static friction forces on ELF

The static frictional force between the ELF and scanner bed was measured at 33.84 N.

SANTA's weight

Linear regression analysis showed no apparent correlation between the weight of the objects and their SANTA measurements, with an R^2 value of <0.1 (supplementary fig 3).

Discussion

Principal findings

By conducting our CHRISTMAS, we showed the projectile risk of objects commonly found near a clinical MRI scanner. Our findings suggested no clear relation between the weight of the objects and their minimal safe distance. Among the objects that were identified as projectiles, some had the potential to cause tissue penetration. This effect supports professional recommendations and best practices that patients and

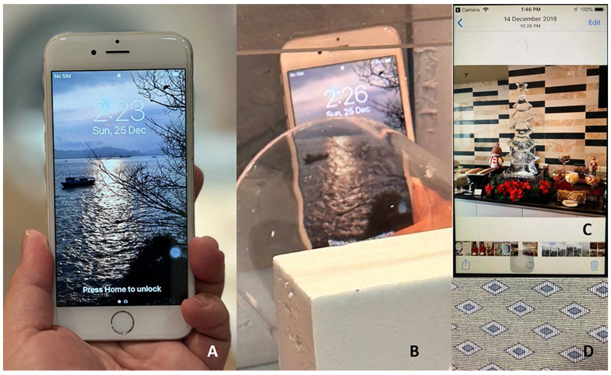

Fig 5 | Functionality of smartphone (iPhone 6) before and after multiple passes into the 3 Tesla MRI (magnetic resonance imaging) scanner. (A) Screen of the iPhone 6 at the scanner room entry point, immediately before the experiment. (B) Screen of the iPhone 6 at the scanner gantry, immediately after the first pass from the electromagnetic launch funnel (ELF) to the front of the MRI scanner. (C) Old photograph taken four years ago, viewed on the Apple photos app with no data corruption several weeks after the experiment. (D) Camera of the iPhone 6 was fully functional with the ability to focus and resolve small line pairs on fabric

members of staff should receive extensive warnings and checklists before being allowed into the MRI room.

Strengths and limitations of this study

Preventable MRI incidents continue to occur around the world, and this study will help raise awareness of the dangers of common healthcare related objects in the vicinity of an MRI scanner. The study had several technical limitations. Firstly, although an FBI and NATO graded ballistic gel was used to simulate human tissue penetration, the gel was previously only validated in limited scenarios of a high impact wound penetration profile and tissue disruption, and therefore might not fully apply to the lower impact projectiles in this study. Also, other confounding factors, such as clothing, skin type, and thickness, are likely to reduce actual tissue penetration. A second limitation of the study was the angle of approach to the magnet bore. The selected objects were placed in line with the primary magnetic field, which would have increased SANTA values compared with real world scenarios where objects are more likely to be introduced at an angle. As such, the same objects would probably be under a lower magnetic attractive force at the same distance from the magnet bore.

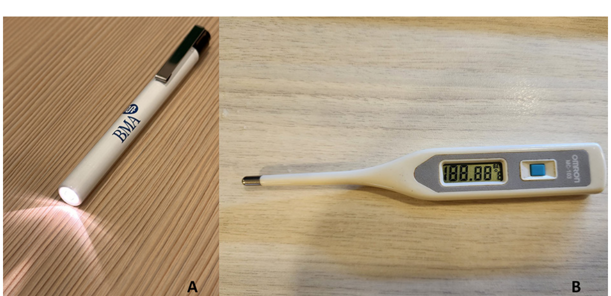

Fig 6 | Functionality of pen torch and digital thermometer. The pen torch remained fully functional after the experiment, with no discernible loss of brightness of the light (A). The digital thermometer similarly was fully functional with no damage to the liquid crystal display (B)

Comparison with other studies

To the best of our knowledge, no study has evaluated the putative projectile risk of small metallic objects within the vicinity of a clinical MRI scanner.

Policy implications

Warning signs are usually visible from the registration areas to the changing areas, and even on the door of the magnet room. Staff members also routinely check if patients are carrying magnetic or metallic objects before entering the MRI room. At our institutions, physical checklists must be signed by a trained member of staff before the patient is allowed to enter the magnet room. As an added security measure, we have also trialled wall mounted ferromagnetic detection systems; handheld ferromagnetic detection systems are available at all scanner sites. Despite these efforts, small injuries and near misses have still occurred over the past 12 years, attributable to a multitude of human factors, including warning and alert fatigue.[12]

Some near misses originate from miscommunication between patients and staff. For example, in at least two incidents, patients reported that they were carrying only paper money and no metallic objects. In one instance, the member of staff prepared the patient for the examination and as the patient entered the magnet bore, coins were pulled from the patient's pockets and became affixed to the magnet bore. On further questioning, the patient disclosed that their paper money referred to coinage they required to purchase a newspaper. We presume that these scenarios occur more frequently than reported by staff because coins are commonly found by service engineers under the patient's bed during MRI servicing.

Other incidents might be related to a temporary lapse in judgment of patients and staff members. Patients are advised to change into hospital gowns for their examinations, but occasionally, at the patient's insistence, they are allowed to wear their own pyjamas, sweat pants, or gym shorts if they confirm that their clothing has no metal objects. This scenario is common for a scan of an extremity where their torso will not be within the bore. Coins, paperclips, metallic microfibres woven into shirts and undergarments, and even a switch blade have been brought into the scanner bore in these instances.

Patients' routines and habits can also contribute towards these incidents. Patients declaring that they are not wearing any jewellery or other metallic objects, but forgetting about a pendant or religious token which they always carry, is not uncommon, especially if the pendant is not attached by a metallic chain. These objects are usually detected after the patient enters the scanner because the patient feels the magnetic pull on the object or the radiographer notes distorted images.

That the highly ferromagnetic cutlery utensils (fork, spoon, knife, and teaspoon) could penetrate the skin is not surprising. We found that the knife had the deepest tissue penetration. Given the huge potential for harm, we strongly recommend that care is taken by the clinical teams to be extra vigilant when attempting to scan patients with altered mental states (eg, patients who are drowsy, confused, or unconscious). The use of handheld ferromagnetic detection systems should always be performed on these patients because cutlery could be unintentionally dropped and hidden within the folds of the bedsheets.

Many of the other objects in our study were included because they are commonly carried or attached to junior doctors, especially house officers and senior house officers. These doctors are often the first responders to a crash call in the hospital and, in their eagerness to help the patient, are at risk of forgetting to remove metallic objects before entering the MRI room. These metallic objects include pen torches, pens, and badge holders, which are often given to house officers when they join a medical defence union. We were pleasantly surprised at the resilience of the pen torch, badge holder, and thermometer in our study, which all survived intact. In contrast, previously, a pager belonging to one of the authors was unintentionally brought into the MRI magnet room and was irreparably damaged with near complete loss of audible volume.

The generic stethoscope as well as the nursing scissors, despite having large SANTA values, did not cause penetrating damage to the ballistic gel. We presume that the small plastic tip on the blunted end of the nursing scissors prevented penetration into the simulated tissue by reducing the force per unit area and potentially absorbing some of the impact kinetic energy. For the stethoscope, the actual SANTA outside of the experimental set-up could potentially be much higher. We believe that placement of the stethoscope within the acrylic tubing allowed for substantially increased surface contact between the ELF tubing surface and the rubber based tubing of the stethoscope, and hence substantially increasing friction. A very different scenario could occur if a junior doctor was wearing the stethoscope around their neck or if the stethoscope was lying on a patient's bed. We were surprised to find that the iPhone 6 and credit card were still fully functional after several passes into the MRI scanner. We had anticipated finding some damage to the iPhone screen, speaker, or electronics based on forum threads on Apple[13] and Quora.[14 15]

One penny and two pence coins have been made from copper plated steel since September 1992,[16 17] and five pence and 10 pence coins have been made of nickel plated steel since 2012.[18 19] Given the steel base of the coins, we were not surprised that the one penny, two pence, five pence, and 10 pence coins were ferromagnetic. The 20 pence and 50 pence coins were made of cupro-nickel,[20 21] which is non-ferromagnetic, and showed no magnetic attraction. The £1 coin was made of nickel-brass,[22] but although the magnetic attraction force to overcome the frictional resistance between the coin and the acrylic tubing was sufficient, the force was insufficient against gravity. The £2 coin was made from a combination of nickel-brass for the outer rim and cupro-nickel for the core.[23] The weight of the coin at almost 12 g was likely far greater than the magnetic attraction force towards the 3 T magnet.

Although the two biscuit tins did not penetrate the simulated human tissue, sufficient force existed to cause a dent in the base of the tin as well as moving the whole ELF deeper into the bore of the magnet. Reports that as little as 375 J/m^2 of surface tension is needed to break normal human tibial and femoral diaphyses[24] suggests a high possibility of bone breakage for patients or staff in the way of these biscuit tins if unintentionally brought into the scanner room and accelerated towards the bore of the magnet. Given that the attractive force on a ferromagnetic object is proportional to the strength of the static magnetic field, the introduction of 7 T magnets (now available commercially) into clinical practice could have a higher potential risk of injury because the SANTA values of the objects could be more than double.

Conclusions

We wish to emphasise that the experiments were conducted after exceptionally detailed planning (over more than three years) and overengineered safety precautions. We hope that the initial findings from these 12 categories of objects will support the development of other real world studies on the interactions between modern MRI scanners and healthcare related objects. We look forward to further research in this area of MRI safety but would strongly caution against attempting to replicate these experiments without extensive safety precautions, especially in a clinical MRI scanner.

Given the substantial potential for harm from the shortbread and Christmas biscuit tins, we suggest limiting Christmas or seasonal treats for the MRI team in the control and magnet rooms to confectionery in plastic tubs (eg, Heroes, Celebrations, and Quality Street), or to pandoro and panettone in their paper boxes. Posher treats in their collectable or seasonal tins should be stored in the staff pantry and never allowed anywhere near the magnet and control rooms.

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Contributors: All authors made substantial contributions to the conception and design. All authors were involved in conducting the literature review and practical research component. Initial plans for the electromagnetic launch funnel (ELF) were developed by SJO. KLC managed and was responsible for the results database. MG and JH performed the physics calculations and statistical analyses. The original draft was prepared by SJO. All authors contributed to data analysis and interpretation, critically revised the manuscript, gave final approval of the version to be published, and agreed to be accountable for all aspects of the work. SJO is the guarantor (the contributor who accepts full responsibility for the finished article, had access

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Competing interests: All authors have completed the ICMJE uniform disclosure form at www.icmje.org/disclosure-of-interest/ and declare: no support from any organisation for the submitted work; no financial relationships with any organisations that might have an interest in the submitted work in the previous three years; no other relationships or activities that could appear to have influenced the submitted work.

Ethical approval: Not required.

Data sharing: Additional data are available on reasonable request from the corresponding author.

The lead author (SJO) affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned have been explained.

Dissemination to participants and related patient and public communities: Data obtained from this study will be presented in MRI and patient safety talks and presented in local and international scientific meetings. Media obtained during the course of the study will be used for patient safety education material.

Provenance and peer review: Not commissioned; externally peer reviewed

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Supplementary information: Additional table and figures thebmj Xmas Visual summary

CHRISTMAS experiment

Common Healthcare Related Instruments Subjected To Magnetic Attraction Study

This study investigates the behaviour of objects commonly encountered in healthcare settings in a magnetic resonance imaging (MRI) scanner. The researchers examined the objects' acceleration towards the scanner bore and the potential for tissue penetration, simulated using a block of ballistic gel.

Materials & methods

MRI Magnetic resonance imaging scanner
A 3 tesla 12 year old clinical Siemens Magnetom Skyra Tim Dot system MRI scanner was used

ELF Electromagnetic launch funnel
The researchers built this test rig to guide objects safely into the centre of the magnet bore and estimate the force of impact at the isocentre (centre of the front end of the magnet)

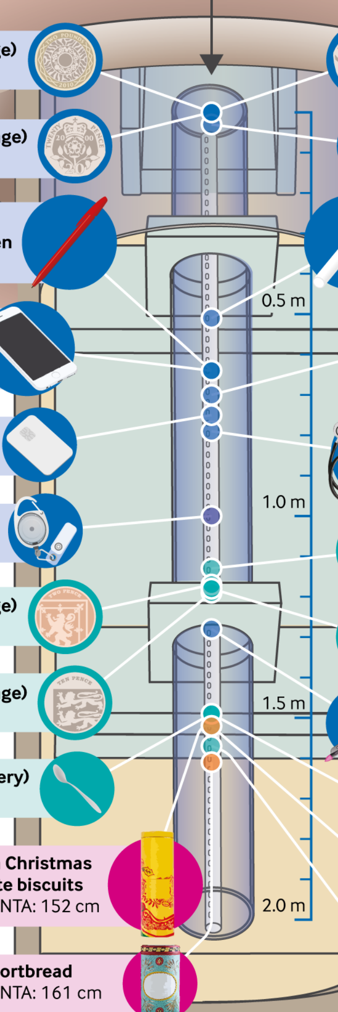
SANTA Site where applied newtonian mechanics triggers acceleration
The distance at which the attraction of the magnetic field overcomes the object's static friction, resulting in acceleration towards the magnet

Biscuit tin impact statement
High acceleration and impact against the ballistic gel block resulted in movement of the ELF deeper into the MRI scanner as well as breakage of a 2 mm thick acrylic shield

Ballistic gel penetration/deformation

5.5 cm Knife (NHS cutlery)
5.0 cm Teaspoon (NHS cutlery)
4.0 cm Fork (NHS cutlery)
3.5 cm Spoon (NHS cutlery)
0.5 cm 10p coin (2014 vintage)

5p, 2p, and 1p coins
These coins were adherent to the ballistic gel after the experiment and appeared to be indenting/deforming the ballistic gel



£2 coin (2010 vintage) SANTA: 0 cm
50p coin (2014 vintage) SANTA: 0 cm
20p coin (1982 vintage) SANTA: 0 cm
£1 coin (2006 vintage) SANTA: 3 cm
BIC Cristal Clic 0.8 mm ball point pen SANTA: 64 cm
BMA branded pen torch (including batteries) SANTA: 51 cm
Apple iPhone 6 Model A1586 SANTA: 64 cm
Thermometer (digital, sublingual) SANTA: 70 cm
Metallic credit card SANTA: 75 cm
Stethoscope (generic unbranded) SANTA: 79 cm
Badge pulley holder SANTA: 100 cm
5p coin (2014 vintage) SANTA: 113 cm
2p coin (2011 vintage) SANTA: 117 cm
1p coin (1993 vintage) SANTA: 118 cm
10p coin (2014 vintage) SANTA: 119 cm
Nursing safety scissors SANTA: 128 cm
Teaspoon (NHS cutlery) SANTA: 149 cm
Spoon (NHS cutlery) SANTA: 149 cm
Fortnum and Mason Christmas orange and chocolate biscuits 125 g tin (empty) SANTA: 152 cm
Fork (NHS cutlery) SANTA: 152 cm
Betty's Yorkshire Shortbread 220 g tin (empty) SANTA: 161 cm
Knife (NHS cutlery) SANTA: 157 cm

Experiment highlights

Apple iPhone 6 Model A1586
Retained both calling and smart phone functionality despite more than three passes to the front of the MRI scanner

BMA branded pen torch
Remained functional with no qualitative change in the brightness of the light

Metallic credit card
Successful purchase of ice creams post experiment by contactless payment at a self service terminal

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