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Experimental evaluation of ballistic hazards in imaging diagnostic center

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Summary

Background: Serious hazards for human health and life and devices in close proximity to the magnetic resonance scanners (MRI scanners) include the effects of being hit by ferromagnetic objects attracted by static magnetic field (SMF) produced by scanner magnet – the so-called ballistic hazards classified among indirect electromagnetic hazards. International safety guidelines and technical literature specify different SMF threshold values regarding ballistic hazards – e.g. 3 mT (directive 2004/40/EC, EN 60601-2-33), and 30 mT (BMAS 2009, directive proposal 2011). Investigations presented in this article were performed in order to experimentally verify SMF threshold for ballistic hazards near MRI scanners used in Poland.

Material/Methods: Investigations were performed with the use of a laboratory source of SMF (0–30 mT) and MRI scanners of various types. The levels of SMF in which metal objects of various shapes and 0.4–500 g mass are moved by the field influence were investigated. The distance from the MRI scanners (0.2–3T) where hazards may occur were also investigated.

Results: Objects investigated under laboratory conditions were moved by SMF of 2.2–15 mT magnetic flux density when they were freely suspended, but were moved by the SMF of 5.6–22 mT when they were placed on a smooth surface. Investigated objects were moved in fields of 3.5–40 mT by MRI scanners. Distances from scanner magnet cover, where ballistic hazards might occur are: up to 0.5 m for 0.2–0.3T scanners; up to 1.3 m for 0.5T scanners; up to 2.0 m for 1.5T scanners and up to 2.5 m for 3T scanners (at the front and back of the magnet).

Conclusions: It was shown that SMF of 3 mT magnetic flux density should be taken as the threshold for ballistic hazards. Such level is compatible with SMF limit value regarding occupational safety and health-protected areas/zones, where according to the Polish labor law the procedures of work environment inspection and prevention measures regarding indirect electromagnetic hazards should be applied. Presented results do not support the increase up to 30 mT of the SMF limit for protected area.

Key words: **magnetic resonance scanner • static magnetic field • flying objects • health and safety hazards • occupational safety**

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Background

Many imaging diagnostics facilities exploit both computed tomography scanners (CT) as well as magnetic resonance scanners (MRI). Only some specialist magnetic resonance labs use solely MRI scanners. Use of both types of scanners for medical diagnostics has many common features. Therefore, these appliances have many common design features, which may be difficult to distinguish for people who are not involved in magnetic resonance techniques professionally (Figure 1).

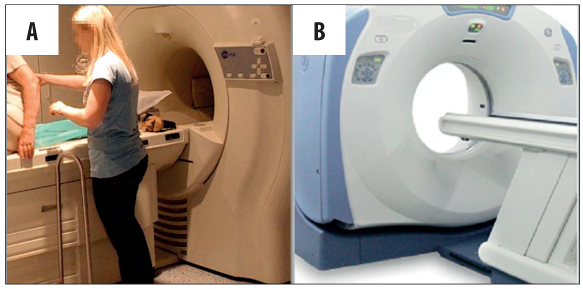

Figure 1. Devices for imaging diagnostic: (**A**) MRI scanner; (**B**) CT scanner.

Regarding safety of patients and personnel working around the scanners, these appliances have distinctly different characteristics.

CT scanners are sources of ionizing radiation only during patient scanning and during that time only it is necessary to comply with radiological safety requirements. There is no radiation risk between examinations.

On the other hand, MRI scanners produce non-ionizing radiation – static magnetic field (SMF), (i.e. magnetic field of magnetic flux density that is constant in time) – continuously from the time of turning the scanner magnet on. Moreover, similar to ionizing radiation in CT scanners, they produce electromagnetic fields (i.e. time-varying electric and magnetic fields) and related noise during patient scanning. Therefore, as in case of CT scanners, requirements regarding protection from undesirable effects of electromagnetic field should be complied with during the examination only. Such impacts include uncontrolled thermal effects or disruption of body's electrophysiological processes or electromagnetic interference with operation of electromagnetic devices. Prophylactic actions should also encompass protecting patients and personnel from noise.

The fact that threat caused by SMF of magnets is constant both during and in between patient examinations as well as after the end of work shift – i.e. 24 hours/day, 7 days a week is a unique characteristic of MRI scanners. They also require constant prophylactic actions involving all people who remain in the vicinity of MRI scanners, particularly: radiographers, anesthesiologists, nurses, as well as people accompanying patients, performing maintenance jobs on scanners and installations in the room, or cleaning.

Most important threats to the safety and health of patients and personnel, as well as to the integrity of the appliance itself, include the effects of pulling ferromagnetic objects into the MRI scanner (Table 1). Magnetic parameters of particular ferromagnetic objects that determine interaction with SMF depend on their chemical composition, production method and processing during construction as well as external physical conditions, e.g. temperature of the environment [1]. Therefore, their susceptibility to SMF may vary and requires individual assessment.

In strong SMF present directly near the magnet, even small objects made out of magnetic steel or nickel (such as tools, keys, oxygen tanks, chairs, patient beds, tables) may not only be moved toward the magnet due to the force it produce, but even levitate and behave as bullets flying toward the magnet (Figure 2). Therefore, they present a serious threat that striking by a moving object would cause not only damage to the scanner or other neighboring appliances, but may also lead to serious bodily harm or even death of patients and personnel [2–4]. Such hazards are called

Table 1. Examples of ferromagnetics, paramagnetics and diamagnetics [1].

Material	Relative magnetic permeability μ_r	Remarks
Pure iron (0.001% of admixtures)	100 000	Ferromagnetics
Technical iron (0.2% of admixtures)	6 000	
Nickel	600	
Air	1.00000036	Paramagnetics
Aluminium	1.000021	
Titanium	1.00005	
Vacuum	1	Diamagnetics
Gold	0.999964	
Silver	0.99998	
Copper	0.999968	
Water	0.999991	

Figure 2. An example of "flying objects" hazards – regular infusion pump (MR Unsafe), presenting a hazard while used in MRI chamber, was pulled by static magnetic field of MRI magnet [*http://www.MRIsafety.com* – with permission of Frank G. Shellock, Ph.D] [5].

ballistic hazards (*projectile hazards)* or "flying objects" hazards. Such problems do not concern objects made out of diamagnetic and paramagnetic materials (Table 1).

Mentioned hazards are present because non-uniform distributed magnetic field exerts translational force on all ferromagnetic objects and rotational force on elongated objects. If these forces exceed friction, depending on the shape and mass of an object as well as its surface and type of ground it stands on, the object is moved toward the magnet (magnet pulls the object as it moves toward it with increasing speed across the surface) or turned with long axis according to the polarity of SMF (similar to a compass needle). If gravitational forces are balanced, such object may levitate with rapidly increasing speed toward the magnet. Maxwell's equations describing phenomena occurring in electromagnetic fields show that translational force is proportional to the product of magnetic flux density (B) and its gradient in space (dB/dx) – $F_T \sim B\ (dB/dx)$, while rotational force is proportional to the square of magnetic flux density– $F_O \sim B^2$. Since SMF rapidly grows in proximity of a magnet, as it gets closer to its cover, attaining constant value within the magnet ($(dB/dx) \sim 0$), translational force also rapidly grows while approaching the magnet, but quickly disappears within the magnet. Rotational force also rapidly grows as it moves toward the magnet and attains maximal value inside.

Safety recommendations on prevention of hazards related to SMF contain conflicting information regarding thresholds of SMF level that could present ballistic hazards. Provisions of a EN 60601-2-33 standard [6] or requirements of European directive 2004/40/WE [7] report that threshold of SMF for ballistic hazards is 3 mT. However, a project of new European directive from 2011 [8] reports, according to German 2009 guidelines [9], threshold for ballistic hazards as ten times higher – 30 mT. Specialist literature also presents other thresholds for ballistic hazards caused by SMF, e.g. German guidelines from 2001 report that ballistic hazards may occur in SMF exceeding 67.9 mT [10]. On the other hand, ICNIRP'2009 guidelines report that ballistic hazards occur in fields SMF of several militeslas. Therefore, in order to simplify the rules of hazard prevention they suggest assuming level of SMF at 0.5 mT, which is used as a threshold for controlled access to the environment containing sources of strong SMFs due to hazards ensuing from the influence of such fields on electronic implants, also as a threshold for ballistic hazards [11]. Due to the scale of possible dangerous consequences of improper identification of conditions where ballistic hazards occur, laboratory and field studies were performed in order to experimentally verify the level of SMF associated with such hazards. There were also studies on spatial disrtibution of SMF around magnets of various MRI scanners in order to practically establish the area of potential ballistic hazards in imaging diagnostics facilities.

Material and Methods

Laboratory as well as field studies on susceptibility of metal objects of various sizes and mass to being set in motion by SMF.

Laboratory studies were performed using the source of SMF regulated in a range B=0–30 mT, produced by Helmholtz coils of 20-cm diameter (of our own construction, CIOP-PIB, Poland) and DC source (type 6554A, produced by Agilent, USA). Field source components are under meteorological control by a CIOP-PIB laboratory quality control system (certificate of accreditation of the Polish Centre for Accreditation AP061). Standard uncertainty of SMF produced at the source is 2.0%.

In our studies we tested susceptibility to being set in motion as a result of SMF force on such objects of size and shape typical for objects that may be accidentally carried in near magnets:

a. steel wire paper clip – mass: 0.4 g,
b. steel construction screw, 3 cm-long, 0.5-cm-wide – mass: 7.5 g,
c. steel paper clip, 5-cm-wide – mass: 20 g,
d. electrotechnical screwdriver, 16-cm-long, with a steel, 7.5-cm-long tip – mass: 36 g,
e. steel cap, 2.5-cm-long, thread diameter 3.5 cm – mass: 93 g,
f. steel cylinder, 5 cm in diameter and 2.5 cm in height – mass: 300 g,
g. steel, cylinder-shaped weight, 4-cm in diameter and 8 cm in height – mass 500 g.

Examined objects were placed on a smooth surface or freely suspended on a thread in the axis of Helmholtz coils. Object position was observed as the SMF level was gradually increased at a speed of 1 mT/second. The level of SMF that set the observed objects in motion as a result of a field effect was set as a threshold for ballistic hazards.

Field studies using selected objects were performed in SMF around MRI scanners. Objects placed on a smooth surface were set in uniform motion along the edge of patient table toward the magnet at a speed of 10 cm/second, i.e. at a speed 10 times less than adult walk. Threshold for ballistic

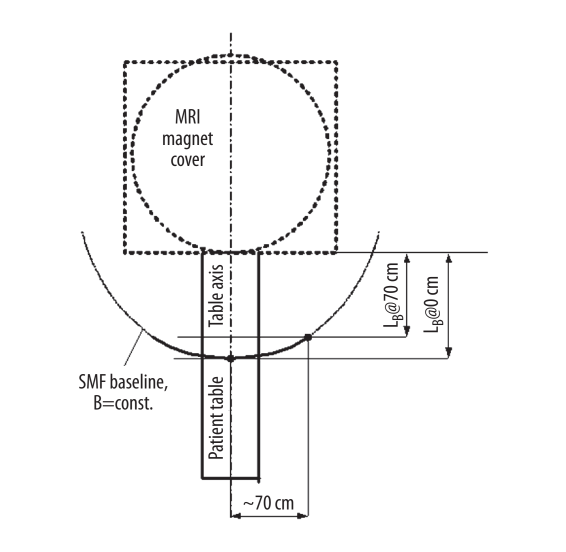

Figure 3. Static magnetic field in the vicinity of MRI scanners – magnetic flux density isolines which indicate the range of ballistic hazards.

hazards was determined at a level of SMF, while observed objects were set in motion as a result of force exerted on it by the field.

Moreover, in order to determine the distance from the magnet at which SMF threshold for ballistic hazards occurred, we performed studies on spatial SMF distribution around scanners most frequently exploited in diagnostic imaging facilities: open 0.2–0.3T (vertical SMF polarization) and with tunnel magnets 0.5T; 1.5T and 3T (horizontal field polarization). Due to the fact that entrance to the MRI chamber is located on the side of patient table, the range of ballistic hazards was set in places of routine staff activity as a range of distance from the MRI cover of magnetic flux density iso-line for SMF measured in the axis of patient table and at a distance of 70 cm from table axis (Figure 3).

Level of SMF, at which we observed movement of studied objects, as well as SMF distribution around magnets of MRI scanners were measured using RX-25 magnetometer with vector Hall effect sensor with measurement range B_0=0.01–3T (produced by Resonance Technology, Poland). The device is under meteorological control by the CIOP-PIB laboratory quality control system (certificate of accreditation of The Polish Centre for Accreditation AP061). Standard uncertainty of magnetic flux density measurement is 2.0%.

Results

Results of laboratory and field studies of threshold SMF level that might set studied objects in motion are presented in Table 2, while results of studies on the range of ballistic hazards around MRI scanners are shown in Table 3.

Studies performed under laboratory conditions demonstrated that studied metal objects, while hanging freely, are set in motion under the influence of horizontally polarized SMF of 2.2 mT to 15 mT. Objects placed on smooth surface are set in motion due to influence of a field of 5.6 mT to 22 mT. Studies performed in horizontally polarized fields that are present on patient table near MRI scanners revealed that studied metal objects may be set in motion in 3.5–40 mT SMF.

Conducted studies on SMF distribution demonstrated ballistic hazards for various objects at a distance of 0.35–0.5 m from the magnet for open 0.2–0.3T scanners, while near tunnel magnets this distance ranges between 1.0 and 1.3 m for 0.5T scanners, 1.75–2.0 m for 1.5T scanners and 2.35–2.5 m for 3T scanners.

Based on SMF distribution around scanners we also defined a coefficient $K=B(dB/dx)$ as a function of distance, which determined the value of translational SMF force around various types of scanners. Figure 4 presents a compilation of data regarding K coefficient for selected scanners, illustrating spatial distribution of relative ballistic hazard around various scanners.

Discussion

A "flying object" phenomenon occurs in strong SMFs. It is also called a ballistic hazard – setting ferromagnetic objects in motion and drawing them to the field source (magnet). Susceptibility of ferromagnetic objects to being moved by the force generated by the magnet depends on many factors such as: SMF level and its spatial distribution, mass and shape of the object, friction while moving the object on various types of surfaces. Object moved by the magnet may hit and harm a person standing near or inside the magnet or even lead to death. It may also cause damage to the scanner or nearby objects. Health hazard also depends on the place of impact, e.g. the head, eyes in particular, is exceptionally susceptible to mechanical damage.

The process of pulling ferromagnetic objects by a magnet is characterized by vigorous dynamics due to the dependence of translational force on the square of magnetic flux density, which is illustrated by K coefficient distribution presented on Figure 4. As a result, objects are brought toward the magnet with velocity increasing much more rapidly than when falling under gravitational force (constant near the surface of the earth), and thus rapidly gaining kinetic energy (proportional to the square of velocity and mass of the object).

For that reason, effects of the impact may be serious even in case of objects of small mass.

Discussed objects represent a wide range of various types of ferromagnetic objects that may be accidentally brought near MRI scanner and present threat to people and appliances as well as the scanner itself.

There were no studies on larger objects due to safety reasons. An object weighing several kilograms is pulled by a 1.5T or 3T magnet with a force that exceeds the ability to hold such object by an adult. Experimental studies on such objects could pose a threat of damaging scanners, while the source of SMF used in laboratory studies was too weak to move such objects.

Table 2. Static magnetic field in which movements of investigated objects due to the interaction with the field were observed.

Investigated object	Mass of the object	Magnetic flux density of the field in which movements of investigated objects were observed		
		In the vicinity of MRI scanner	In the Helmholtz coils	
	(g)	(mT)*	(mT)*	(mT)**
Paperclip	0.4	14	5.6	2.2
Screw	7.6	22	9.5	7
Office clip	20	11	5.9	2.5
Electrotechnical screwdriver	36	3.5	8.0	3.5
Nut	93	40	18	12
Cylinder	303	30	20	14
Weight	500	20/10***	22	15

* Objects placed on a smooth surface; ** objects freely suspended; *** vertical field polarisation.

Table 3. The range of ballistic hazards in the vicinity of magnetic resonance scanners.

Magnetic flux density B (mT)	Distance of particular isolines of magnetic flux density of SMF from the housing of scanner magnets; $L_{B@70\,cm} \div L_{B@0\,cm}$ (*) (cm)			
	Scanner 0.2–0.3T	Scanner 0.5T	Scanner 1.5T	Scanner 3T
3	32–50	100–130	175–200	240–250
10	5–34	50–85	120–145	160–175
20	–18(**)	30–62	92–118	120–145
30	–12(**)	15–50	75–105	100–125
40	–6(**)	8–42	65–93	90–112

* Marked according to Figure 1; ** the lack of $L_{B@70\,cm}$.

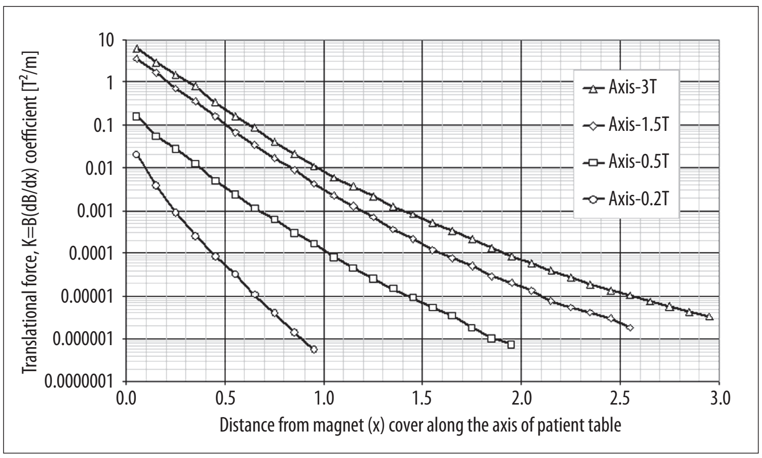

Figure 4. K=B(dB/d*x*) coefficient determining translational force values for SMF interaction with ferromagnetic objects in the vicinity of magnets of various type MRI scanners.

Removing objects that weight more than several kilograms from MRI scanner is not possible without turning the magnet off, which is associated not only with a break in its service, but also with costs that reach at least tens of thousands of Euros related to refilling the cooling system and turning the magnet on by specialist services. In case of damages to the appliances located near the scanner or the scanner itself, costs might be significantly higher. Likewise, the costs of compensations in case of harm to a patient or member of personnel may be equally high and indemnity paid in case of death of a person hit by a heavy object depends only on the decision of the court, in some countries reaching several million Euros. Therefore, issues such as precise determination where ballistic hazards may occur and effective training of people working around scanners regarding the nature and effects of such hazards as well as related prophylactic measures and absolute compliance with those rules are incredibly important.

"Flying object" incidents are usually not subject to reporting unless they caused harm to the body or instruments and there was no need to turn the magnet off. Therefore, reliable data on the number and types of such incidents is lacking. One of easily accessible sources of information in that regard is an internet webpage [5] posting numerous examples illustrating the diversity of undesirable incidents involving "flying objects" such as: metal instruments, trolleys, patient beds, tanks containing oxygen, anesthetic or welding gases, office chairs, vacuum cleaners, keys, etc. On the other hand, fatal accidents involving MRI scanners that occurred in many countries are usually discussed in popular media – e.g. reports on death of an employee performing repair works after being crushed by tanks containing welding gases or a patient who was hit with an oxygen tank [3,4].

Reports from facilities where "flying object" incidents occurred indicate that such accidents are mostly related to the presence around the scanner of people other than permanent staff at times when supervision over their presence and performed functions is difficult – e.g. during maintenance or repair works, but also to the presence of facility staff who are not permanently involved in MRI services. As previously mentioned, various common construction features of MRI and CT make it difficult for such people to distinguish which appliance is associated with ballistic hazards. Difficulties are also related to proper identification of objects susceptible to being pulled by a magnet. Also introducing a new scanner with a stronger magnet to the facility contributes to accidents when range of hazards around the magnet significantly increases, e.g. from 1.0–1.3 m for a 0.5T scanner to 2.35–2.5 m for a 3T scanner.

Due to the discussed hazards, it is important to properly identify places where they might occur. Clear marking of the area of ballistic hazards around scanners is exceptionally important in that regard, including use of standardized information and caution signs (Appendix).

Among prophylactic measures significant attention is also paid to proper organization of workspace and choice of materials, from which objects used in the vicinity of scanners as well as in nearby rooms are constructed. Prophylactic measures regarding ballistic hazards encompass both tight control of objects carried around the magnet as well as spatial organization of the workplace and organization of procedures in a manner that allow for supervision over people entering MRI chamber, including use of gate and hand held metal detectors.

Prophylactic measures should also involve patients, who are usually not aware of possible consequences of pulling ferromagnetic objects into the magnet of a scanner. It should be emphasized that discussed influence of SMF on ferromagnetic objects also involves objects located inside patient's body. Such hazards, presented in numerous reports [e.g. 5,6], were not discussed in this paper.

Conclusions

Conducted studies indicate that SMF of about 3 mT should be considered a threshold for occurrence of possible ballistic hazards. This threshold is consistent with the boundary of an intermediate zone where, according to Polish labor law, workplace control procedures should be implemented and appropriate protection from hazards related to working electromagnetic field should be ensured. Presented results of our studies argue against increasing the boundary of intermediate zone proposed by some recommendations. However, rules proposed by ICNIRP, which include use of unified threshold for identification of ballistic hazards and threats to electronic implants at a level of SMF at 0.5 mT, are worth considering. On one hand, such strategy results in setting a somewhat wider ballistic hazards zone around a scanner (SMF range with 0.5mT induction for various MRI scanners is greater by about 0.5–1.0 m than SMF with 3 mT induction), but from the other it is not necessary to establish two zones and complicate the rules of protection from indirect effects of SMF (0.5 mT for implant hazards and 3 mT for ballistic hazards). Moreover, in most facilities SMF zone exceeding the level of 0.5 mT is contained within Faraday's cage (i.e. electromagnetically shielded chamber) where the scanner is located and organization may come down to considering the entire inside of this cage as region susceptible to both types of hazards.

Regardless of adopted thresholds, clear labeling (well visible with both open and closed doors to scanner's chamber, best containing both vertical labeling on the doors and walls as well as horizontal labeling on the floor) constitutes a key to the safety of patients, staff and appliances located in the vicinity of MRI magnet.

In order to reduce the possibility of events related to "flying object" phenomenon and possible incidents there is a need for supervision over MRI chambers as well as training of all medical personnel, particularly the staff of imaging diagnostics facilities who work around MRI scanners. It is very important to train the cleaning staff, maintenance personnel, outsourced teams performing repairs and similar sporadic services, for whom it is not obvious that the magnet is still on even after the end of examinations and strong SMF around continues to pose lethal threat.

Appendix

Standardized warning and information labels regarding electromagnetic hazards (Figure 5).

According to general regulations on the occupational safety and health [Dz.U. nr 169, poz 1650, 2003) and regulations on the safety and health in electromagnetic fields [DzU nr 217, poz. 1833, 2002], electromagnetic field safety zones should be labeled with warning signs, the size and color of which were determined by the following standards: PN-T-06260: 1974, N-01256-03-1993, N-01256-03-1993/Az2:

Electromagnetic field source [PN-T-06260: 1974] | Strong magnetic field [PN-N-01256-03: 1993] | No ferromagnetic materials [PN-ISO 7010: 2006]

Figure 5. Labelling of electromagnetic hazards.

2001 and ISO 7010: 2008. According to PN-T-06580: 2002 standard, signs defined by the PN-74/T-06260 should be used around field sources with frequencies in the entire range covered by provisions of the mentioned regulation, i.e. 0–300 GHz.

Standardized labels can also be complemented or substituted by descriptive information on noticeable parts around sources of electromagnetic fields.

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