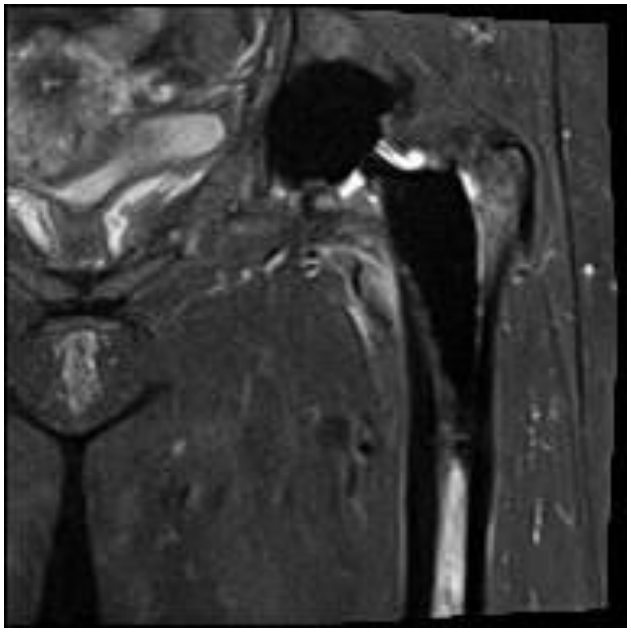
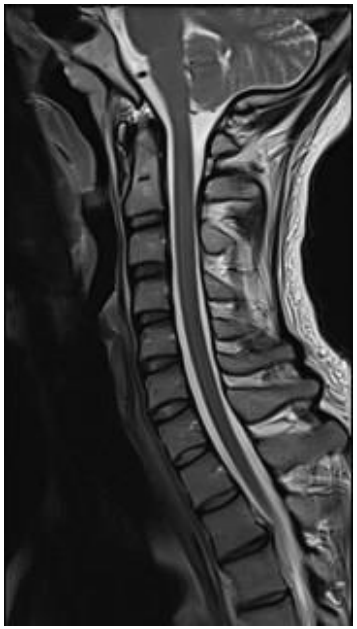
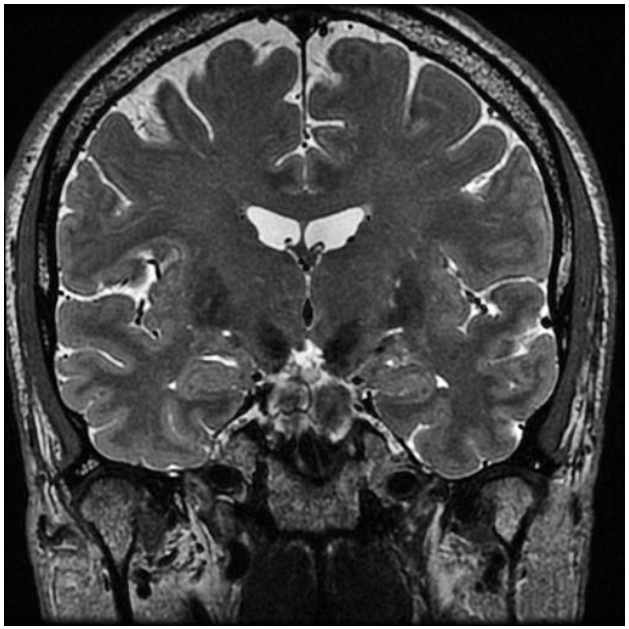
Magnetic Resonance Imaging

F.R.C.R. Physics Lectures

Lawrence Kenning PhD

7.10 MR safety (Part 1)

- MHRA guidelines as the primary safety reference for UK
- MR safety framework, definitions, roles & responsibilities
  - MR Responsible Person and MR Safety Expert
  - MR Authorised Persons
  - MR Environment and MR Controlled Access Area
  - MR Safe / MR Conditional / MR Unsafe / MR Unlabelled
- Safety issues, particularly with regards to implanted devices and emergency situations, including
  - Attraction, torque
  - RF heating: SAR and B_{1+} rms
  - Magnetic quench

7.10 MR safety (Part 2)

- Safety issues associated with gadolinium-based contrast agents
  - Linear versus macrocyclic-based agents
  - Nephrogenic systemic fibrosis (NSF)
  - Gadolinium deposition/retention
- Recommendations for scanning patients with implanted devices without the manufacturer's approval, e.g. 'off label'

7.11 Quality assurance

- Importance of quality assurance in MR to identify failing elements in phased array coils
- Quality assurance to help establish reproducibility of quantitative MR techniques

Introduction

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Man dies after being sucked into MRI scanner at Indian hospital

Man was carrying oxygen cylinder which was pulled by machine's magnetic force and then thought to have punctured

Boy, 6, Killed in Freak MRI Accident

By ABC NEWS July 31

A 6-year-old boy died after undergoing an MRI exam at a New York-area hospital when the machine's powerful magnetic field jerked a metal oxygen tank across the room, crushing the child's head.

The force of the device's 10-ton magnet is about 30,000 times as powerful as Earth's magnetic field, and 200 times stronger than a common refrigerator magnet.

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Safety Guidelines for Magnetic Resonance Imaging Equipment in Clinical Use, MHRA, February 2021

4.10.3 Responsibility for patients/volunteers whilst in the unit

While the patient is within the MR CONTROLLED ACCESS AREA, their health and well-being should be delegated to a clinician or supervising radiologist who is fully conversant with the current clinical aspects of the use of the particular MRI equipment and its effects on the safety, health and well-being of the patient.

The clinician or supervising radiologist will remain responsible for the safety, health and well-being of the patient throughout the period that the patient is within the MR CONTROLLED ACCESS AREA and any subsequent deleterious effects that are shown to be due to the scans.

4.16.1 Supervision

The administration of contrast media to patients must be under the supervision of a registered medical practitioner. The medically qualified professional will take the ultimate responsibility for the health of the patient during the scan and any subsequent deleterious effects that arise from the administration of the contrast medium.

MHRA (Medicines and Healthcare products Regulatory Agency)

- https://www.gov.uk/government/publications/safety-guidelines-for-magnetic-resonance-imaging-equipment-in-clinical-use

MR Responsible Person and MR Safety Expert

MR RESPONSIBLE PERSON

- It is recommended that the chief executive or the general manager delegate the day-to-day responsibility for MR safety to a specified MR RESPONSIBLE PERSON who might most effectively be the clinical director, head of the department, clinical scientist, medical physicist or MR superintendent radiographer of the institution where the equipment is located

MR SAFETY EXPERT

- The MR SAFETY EXPERT will have an advanced knowledge of MRI techniques and an appropriate understanding of the clinical applications of MRI. Ideally they will be a physicist with expertise in MRI. Clinical units should appoint an MR SAFETY EXPERT who acts according to recognised standards i.e. they should normally have Health and Care Professional Council (HCPC) registration or General Medical Council (GMC) specialist registration

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MR RESPONSIBLE PERSON

- **Jane Boddy** (MRI Speciality Manager), **Dr Paul Maliakal** (Clinical Director) and **Dr Hiten Joshi** (Lead for Neuroradiology) are the MRI RESPONSIBLE PERSON(S). Their role is to ensure there are adequate safety procedures, work instructions, emergency procedures and operating instructions issued to all concerned.

MR SAFETY EXPERT (MRSE)

- **Dr Lawrence Kenning** and **Dr Martin Pickles** are appointed as the MR Safety Experts. The MR Safety Expert is a professional with adequate knowledge and experience in MRI equipment, its uses and associated requirements.

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MR Authorised Persons

- MR AUTHORISED PERSON (**Non MR ENVIRONMENT**)

- An MR AUTHORISED PERSON is a suitably trained member of staff authorised to have access to the MR CONTROLLED ACCESS AREA but not the MR ENVIRONMENT

- People who need free access to the MR CONTROLLED ACCESS AREA, but do not have permission to enter the MR ENVIRONMENT without an AUTHORISED PERSON (SUPERVISOR) and are not permitted to let others into the MR CONTROLLED ACCESS AREA, e.g. management, clerical staff, radiologists without any formal safety training

MR Authorised Persons

- MR AUTHORISED PERSON (**MR ENVIRONMENT**)

- An MR AUTHORISED PERSON authorised to have free access to the MR ENVIRONMENT but not to supervise others

- People who additionally are given free access to the MR ENVIRONMENT and take responsibility for their own safety within the MR ENVIRONMENT, e.g. supporting clinical staff, basic researchers

MR Authorised Persons

- MR AUTHORISED PERSON (**SUPERVISOR**)

- An MR AUTHORISED PERSON who is authorised to have free access and to supervise others in the MR ENVIRONMENT

- People who need to perform safety screening of other people and take responsibility for the safety of others within the MR ENVIRONMENT, e.g. radiographers, clinical scientists

MR OPERATOR

- An MR OPERATOR is an MR AUTHORISED PERSON who is also entitled to operate the MRI equipment.

- MR OPERATORS are normally radiographers or radiologists but may include assistant practitioners, physicists, maintenance and research staff.

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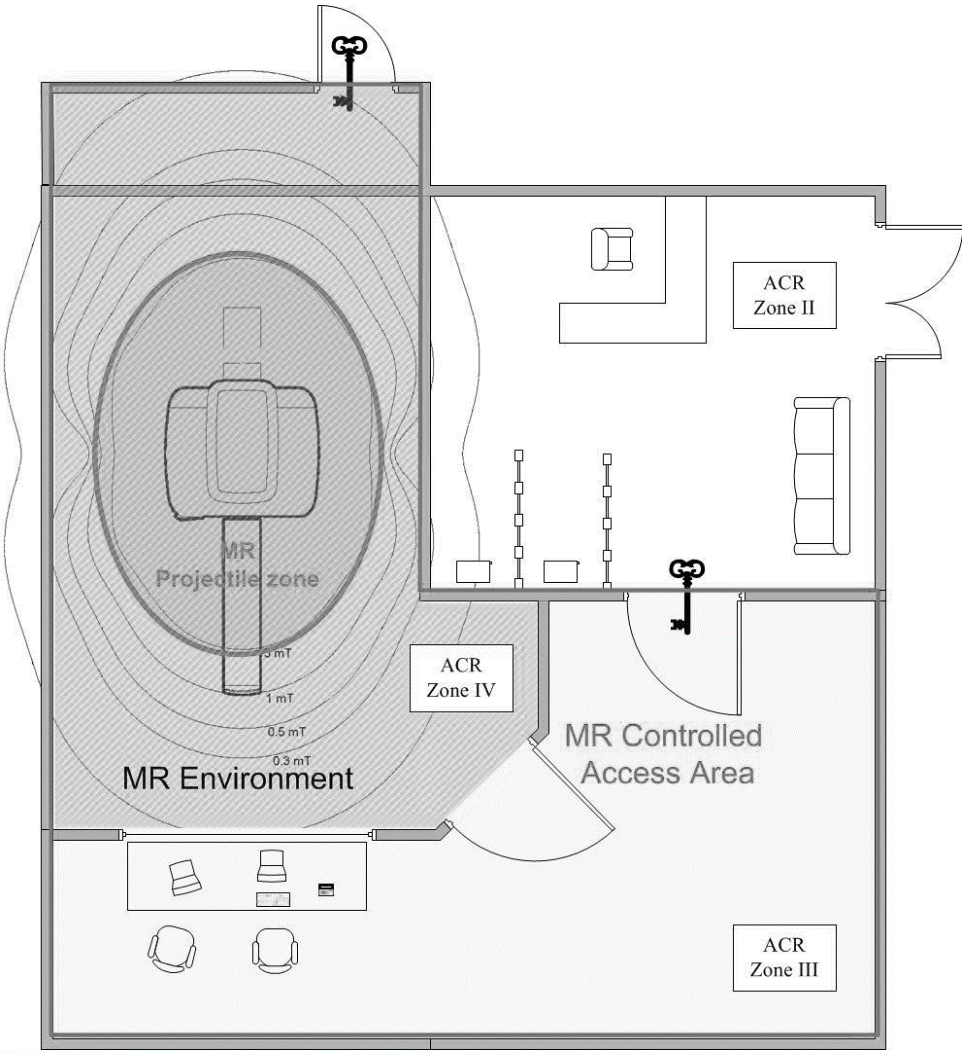
Access and supervision rights of MR AUTHORISED PERSONNEL

STAFF GROUP	MR ENVIRONMENT (scan room)	MR CONTROLLED ACCESS AREA (outside MR ENVIRONMENT)
AUTHORISED PERSON (NON-MR ENVIRONMENT)	May not enter without supervision	May enter and supervise
AUTHORISED PERSON (MR ENVIRONMENT)	May enter	May enter and supervise
AUTHORISED PERSON (SUPERVISOR)	May enter and supervise	May enter and supervise



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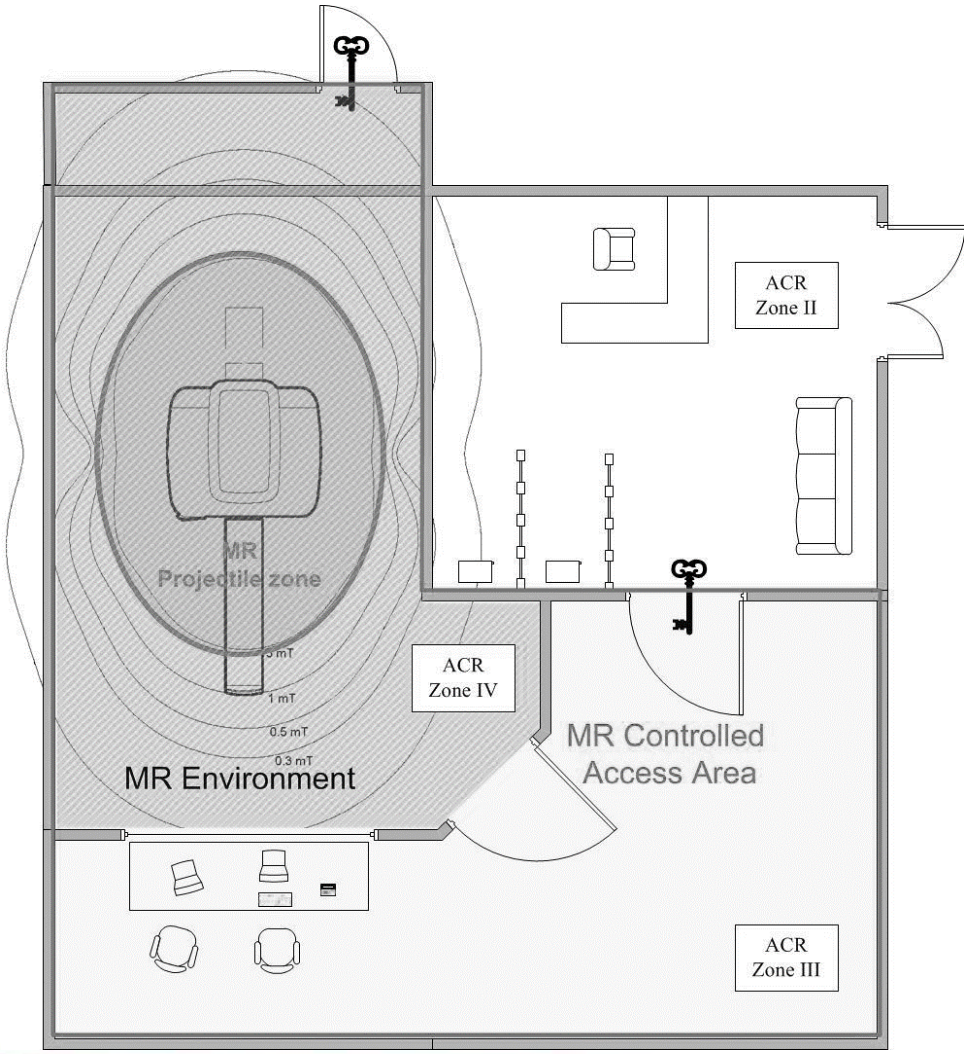
Designation of Areas

- MRI units are divided into 3 defined areas:
  - **MR CONTROLLED ACCESS AREA**
  - **MR ENVIRONMENT**
  - **MR Projectile Zone**



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MR CONTROLLED ACCESS AREA

- A locally defined area of such a size to contain the MR ENVIRONMENT. **Access shall be restricted and suitable warning signs should be displayed at all entrances**

- Free access to the MR CONTROLLED ACCESS AREA should be given only to MR AUTHORISED PERSONNEL

- **All other personnel**, including unauthorised staff and visitors must be appropriately screened and seek authority to enter the MR CONTROLLED ACCESS AREA

- A **CONTROLLED AREA** exists beyond each set of set of **CODED DOORS** in the MRI department. **ANY** equipment in this area without a **MR SAFE label** should be treated as **UNSAFE**

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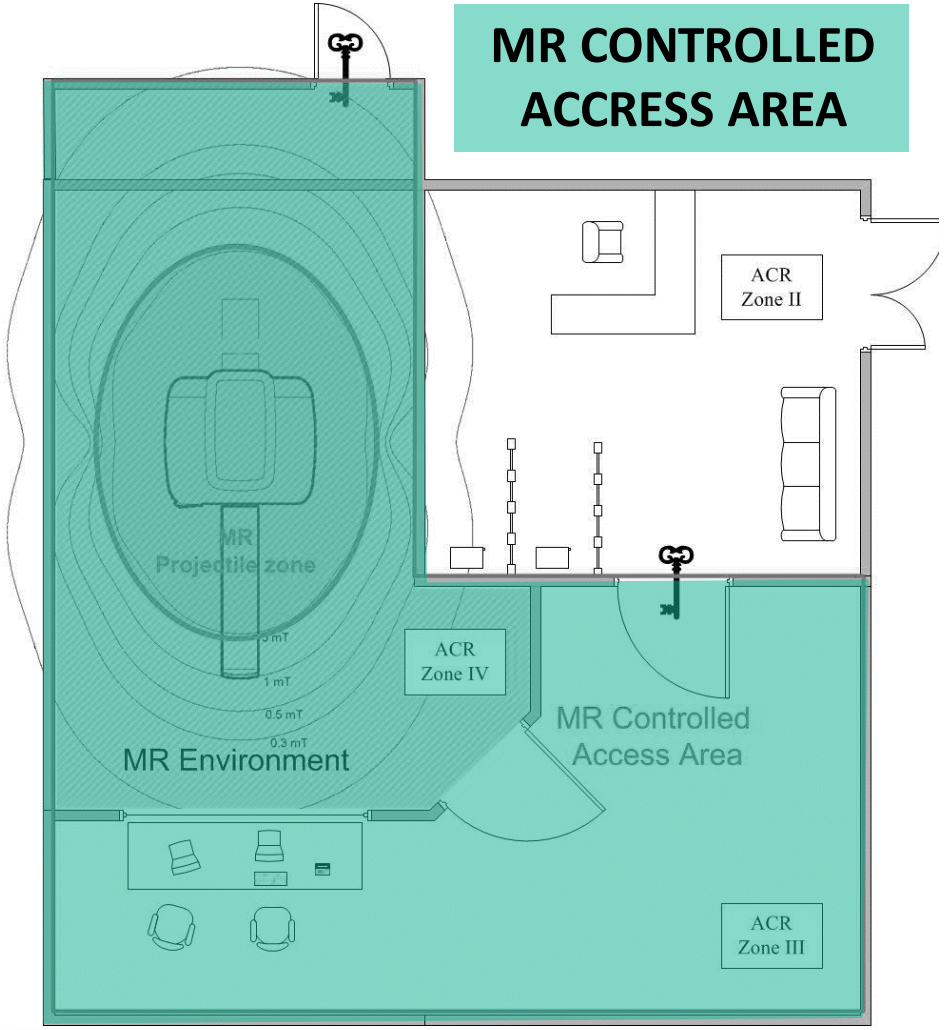
MR CONTROLLED ACCESS AREA



MR ENVIRONMENT

- ‘the **three dimensional volume** of space surrounding the MR magnet that **contains both the Faraday shielded volume and the 0.50 mT field contour (5 gauss (G) line).** This volume is the region in which an item might pose a hazard from exposure to the electromagnetic fields produced by the MR equipment and accessories.’

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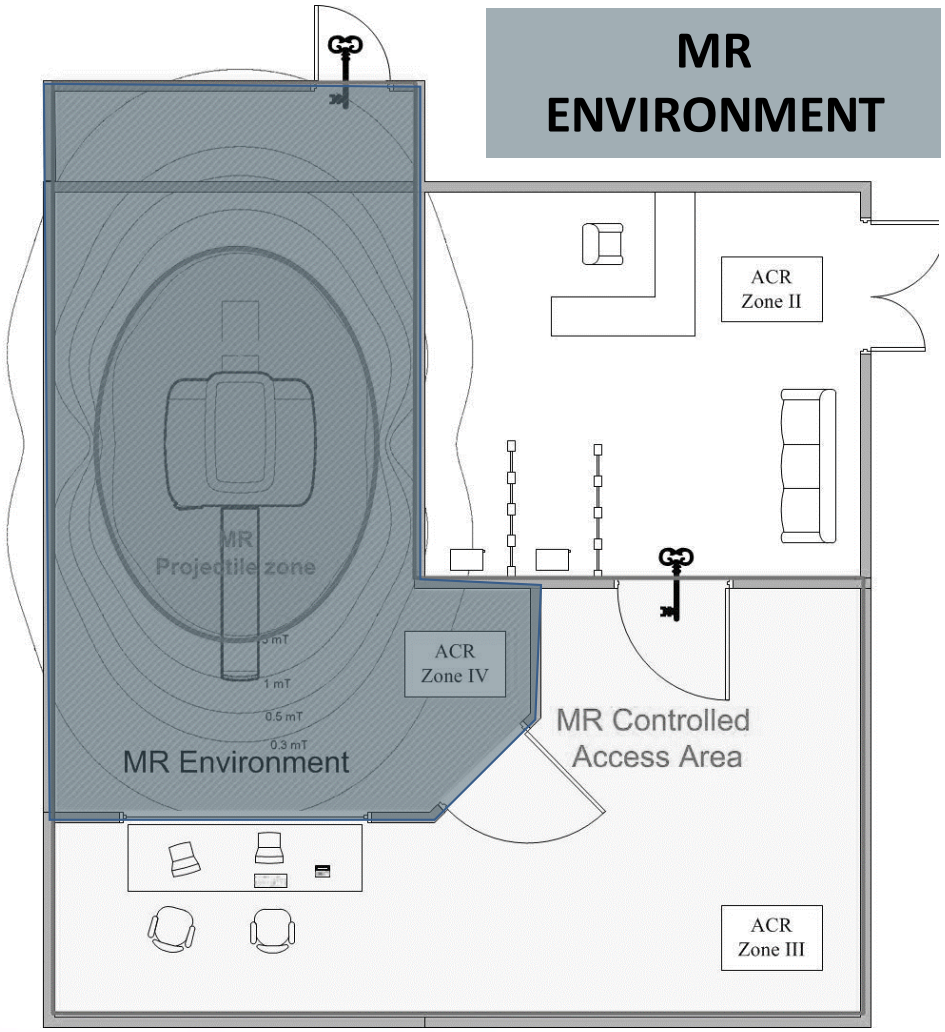
MR ENVIRONMENT



MR PROJECTILE ZONE

- A locally defined volume containing the full extent of the 3 mT (30G) magnetic field contour, or other appropriate measure, around the MRI scanner

- For the majority of MRI units, restrictions on the introduction of grossly ferromagnetic objects associated with the risk of projectiles are applied to the entire magnet room and consequently only 2 defined areas, MR CONTROLLED ACCESS AREA and MR ENVIRONMENT are sufficient

    - this is what we do at HUTH

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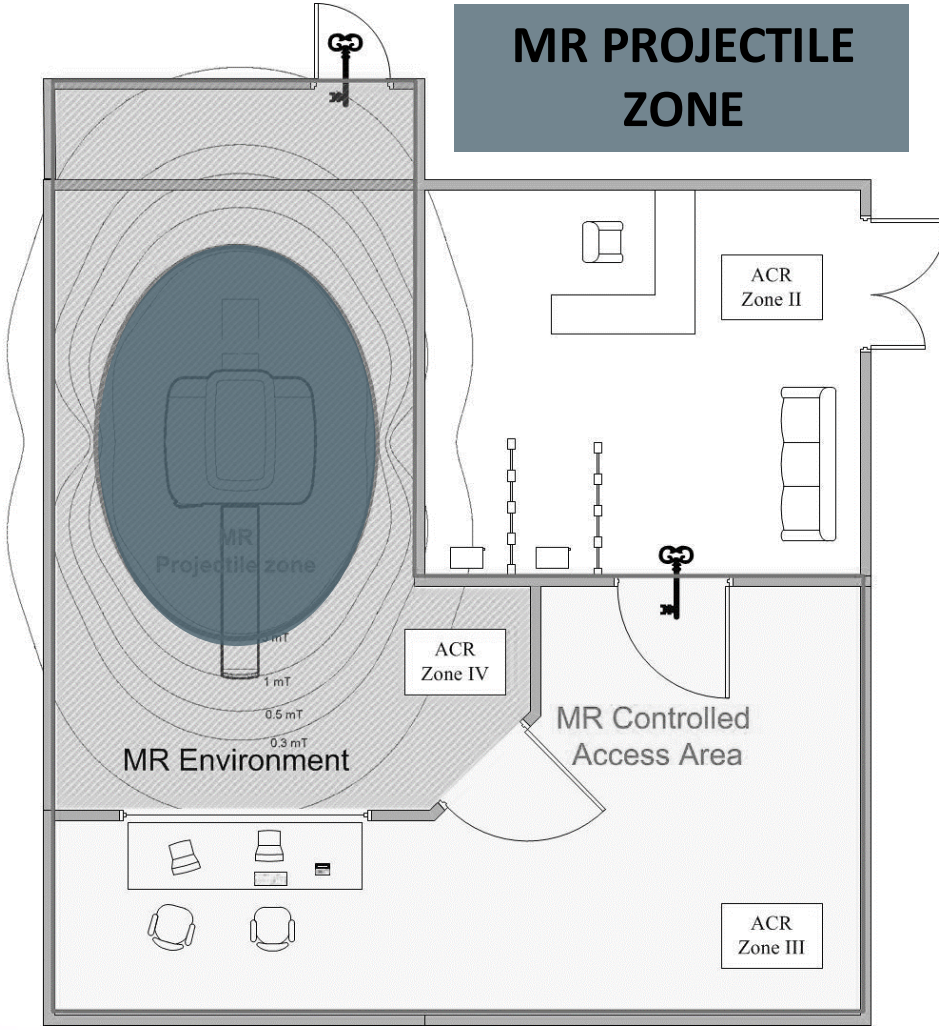
MR PROJECTILE ZONE



Screening

- Prior to entry into the MR CONTROLLED ACCESS and MR ENVIRONMENT areas patients/volunteers/staff must undergo screening
- Screening must take place every time the patient attends the MR unit
- Screening for entry into the MR CONTROLLED ACCESS AREA must include at least verbal questioning
- Screening for entry into the MR ENVIRONMENT must include a written questionnaire
- Additional information may be required about potential hazards before authorisation to enter the MR ENVIRONMENT can be given

Screening

- Safety questionnaires should be signed by the individual, verified, and then countersigned by an MR AUTHORISED PERSON
- The status of implanted devices should be known before entry into the MR ENVIRONMENT
- Additional information may be required about potential hazards before authorisation to enter the MR ENVIRONMENT can be given
- For patients who are unable to complete the safety questionnaire refer to 'Adequate safety screening of unresponsive/uncooperative patients prior to MRI scans' policy

Screening

Screening should reveal the following:

- **relevant patient conditions** (allergies, pregnancy, recent surgery, etc...)

- the presence of implantable medical devices (cardiac pacemakers, cochlear implants, aneurysm clips, etc...)

- **presence of potential ferrous objects**:
  - **in the body** such as bullets, shrapnel, etc...
  - **attached to the body** such as body piercing
  - **on the body** such as hairpins, jewellery, transdermal patches etc...

- It is important to identify the presence of metallic items on the patient and remove these items for safekeeping, together with magnetised bank, credit and library cards

MR safety framework, definitions, roles & responsibilities

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Have you ever had a **HEART PACEMAKER** or **DEFIBRILLATOR FITTED**?
Have you ever had any **HEART SURGERY** or **HEART VALVE REPLACEMENT**?
Have you had surgery to your **HEAD**, **EYES**, **EARS** or **SPINE**?
Have you ever had a **BRAIN HAEMORRHAGE**?
Do you have an **ANEURYSM CLIP**?
Have you had any **SURGERY** in the last 6 weeks?
Have you ever swallowed a **PILL CAM**? If **YES**, when was it excreted? *(capsule endoscopy procedure)*
Do you have any **STENTS**?
Do you have **INSULIN PUMP** or **MONITORING DEVICE**?
Do you have any other **IMPLANTED MEDICAL DEVICES**? *This includes but not limited to artificial joints, filters, bone plates or pins, hydrocephalus shunts, gastric bands, eye implants, neurostimulators, cochlear implants, drug infusion pumps, IV access ports & tissue expanders.*
Have you ever had an **EYE INJURY** involving **METAL FRAGMENTS**? *We need to know even if the fragment was removed or if it was many years ago.*
Have you ever had any **METAL FRAGMENTS** in your body? *This includes shrapnel injury, non-removable body piercings.*
Is there a possibility you are **PREGNANT**?
Are you currently **BREAST-FEEDING**?
Do you wear a **TRANSDERMAL SKIN PATCH** or **SILVER DRESSING**? *Bring a replacement if **YES**.*

Please tick **YES** or **NO** to the questions below and include details if possible	**NO**	**YES**	**DETAILS**
Are you allergic to anything? Do you suffer from hay fever?			
Do you have asthma that is not well controlled?			
Have you been diagnosed with glaucoma? *(increased pressure in the eyes)*			
Do you have any kidney problems?			
Are you waiting for a liver transplant?			
Do you have seizures, epilepsy, brain lesion(s) or a brain condition?			
Do you have diabetes?			
Have you had an MRI scan before?			
Have you had an injection during an X-ray, MRI or other type of scan?			
If "'YES" to the above question – did you have a reaction to the injection?			
Do you have any tattoos or body piercings?			
Do you have any false teeth, hearing aids, metal dental brace, wig, metallic hair extensions?			
What is your weight?	What is your height?		
I confirm all the above information I have given is correct **Patient's Signature:** **Date:**			

You will need to remove all metallic objects e.g. watches, jewellery (*excluding rings*), credit cards, coins, hairpins, metallic eyelashes, brassieres, spectacles, silver dressings and fully empty your pockets. Lockers will be provided to keep your property secure.

MR Safe / MR Conditional / MR Unsafe / MR Unlabelled

MR safety markings

- ASTM (American Society for Testing and Materials) International's standard F2503 for the marking of devices brought into the MR environment should be used. This has also been published by IEC as standard IEC 62570:2014

- Users should update all safety markings in line with the latest version of ASTM International standard F2503 and ensure that all relevant staff are made aware of them.

- The MHRA recommends that all equipment that may be taken into the MR ENVIRONMENT is clearly labelled using these markings and where possible, the appropriate descriptive text should be used

- Additional information may be required about potential hazards before authorisation to enter the MR ENVIRONMENT can be given

MR Safe / MR Conditional / MR Unsafe / MR Unlabelled

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MR SAFE

- 'an item that poses no known hazards resulting from exposure to any MR environment. MR Safe items are composed of materials that are electrically nonconductive, nonmetallic, and nonmagnetic' *

- * the updated definition now specifically prohibits items containing conductive, metallic and magnetic materials.

Patient Comfort Systems

MRI Protection Pad

Antimicrobial Positioner, MRI Patient Protection Pad • 29"W x 14"L x 0.625"D

MR Status: MR Safe

MR Safe / MR Conditional / MR Unsafe / MR Unlabelled

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MR CONDITIONAL

'an item with demonstrated safety in the MR environment within defined conditions. At a minimum, address the conditions of the static magnetic field, the switched gradient magnetic field and the radiofrequency fields. Additional conditions, including specific configurations of the item, may be required.'

MR5501

Adjustable Height Patient Trolley

MR Conditional

to 7 Tesla

MR Conditional

MR Safe / MR Conditional / MR Unsafe / MR Unlabelled

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MR UNSAFE

'an item which poses unacceptable risks to the patient, medical staff or other persons within the MR environment.'

MR103

Hand Held Metal Detector

MR Safe / MR Conditional / MR Unsafe / MR Unlabelled

MR UNLABELLED

'items which are not labelled (MR UNLABELLED) should be considered to be MR UNSAFE until determined to be otherwise'

4.11.4 Scanning patients with implants where MRI may be contraindicated

There may be a need to perform an MR examination in the following scenarios:

- the patient has a **MR CONDITIONAL** device but the manufacturer's guidance cannot be met,
- the patient has an implanted device whose compatibility is unknown, e.g. MR UNLABELLED,
- the patient is implanted with a device known to be **MR UNSAFE**.

If the **benefit to the patient outweighs the potential risk** of the procedure scanning should be undertaken provided the following are documented and available before the scan:

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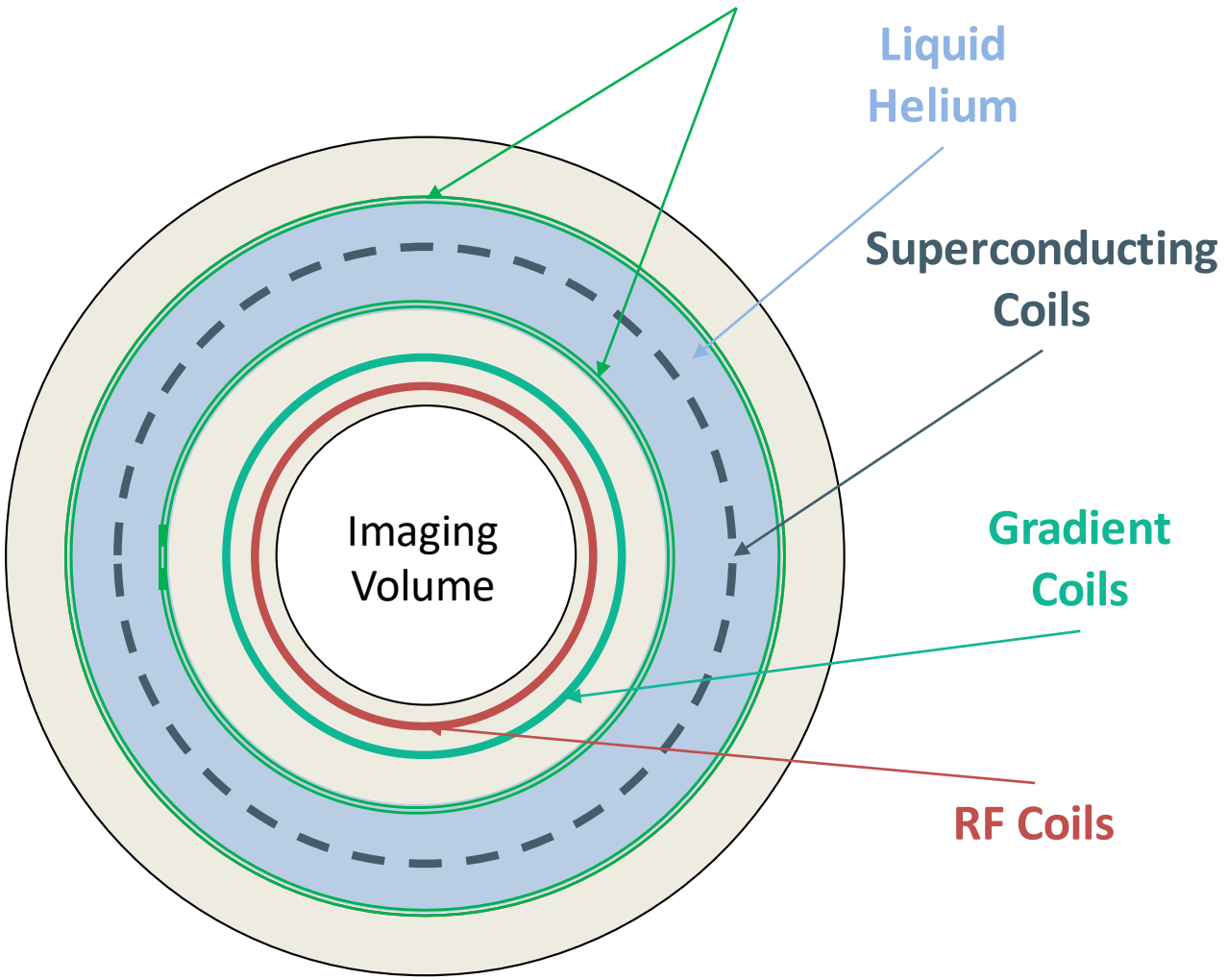
MR UNLABELLED

?

RISK

Magnet Cross-section



Static magnetic field **(B_0)** – projectiles, induced voltage, implants. Fringe field and controlled areas

Time-varying gradient fields **(dB/dt)** – eddy currents, stimulation, implanted devices, acoustic noise

Radiofrequency fields **(B_1)** – specific absorption rate, heating

Overview

Component	Mechanism	Adverse Effect
Static magnetic field (B_0)	Motion induced currents in tissues	Vertigo, metallic taste
	Attractive / torque forces	Projectile Tissue damage
	Interactions with implanted / peripheral devices	Device malfunction / damage
Time varying magnetic fields (dB/dt)	Induced currents in tissues	PNS
	Inducted currents and vibrations in implants	Device malfunction / damage
	Lorentz forces	Acoustic noise
Radiofrequency magnetic field (B_1)	RF induced currents in tissue	Heat
	RF induced currents in equipment	Burns
	RF interference	Device malfunction / damage

Static B_0 Magnetic Field - Biological effects

- The principal interactions of a static magnetic field, B_0 with the body are the **creation of electrical potentials** and resulting currents generated by body movements and the possible **displacement of naturally generated currents** within the body by B_0
- Electrical potentials and related effects during physical movements within static magnetic field gradients may induce sensations of **vertigo**, **nausea, phosphenes** and a **metallic taste** in the mouth.
- The **long-term biological effects of high magnetic field strengths are not well known**. At lower magnetic field strengths, there have not been any reports of harmful or non-reversable biologic effects, either acute or chronic.
- With very high field strength magnets (>4 T), there has been anecdotal mention of dizziness and disorientation of personnel and patients as they move through the field.

Static B_0 Magnetic Field - Biological effects

- **IEC/ICNIRP/HPA** all recommend that patients and volunteers are moved slowly into the magnet bore, to avoid the possibility of vertigo and nausea.

Table 5 Static field whole body limits

	Normal Mode	Controlled mode	Research / experimental mode	Movement dB/dt limit
HPA	≤ 4 T	4-8 T	> 8 T	1 Ts^{-1}
IEC 2002 †	< 2 T	2-4 T	> 4 T	-
IEC 2010 *	≤ 3 T	3-4 T	> 4 T	3 Ts^{-1}
ICNIRP 2009	≤ 4 T	4-8 T	> 8 T	1 Ts^{-1}

Fringe Field (B_0)

- The extent and intensity of the fringe field depends on:
  - Main magnetic field strength
  - Design of the magnetic (open vs. bore)
  - Shielding employed
- Staff should be aware of the fringe field
  - Refer to fringe field maps
- "Above 0.50 mT field contour (5 gauss (G) line) an item **might pose a hazard** from exposure to the electromagnetic fields produced by the MR equipment and accessories" - MHRA

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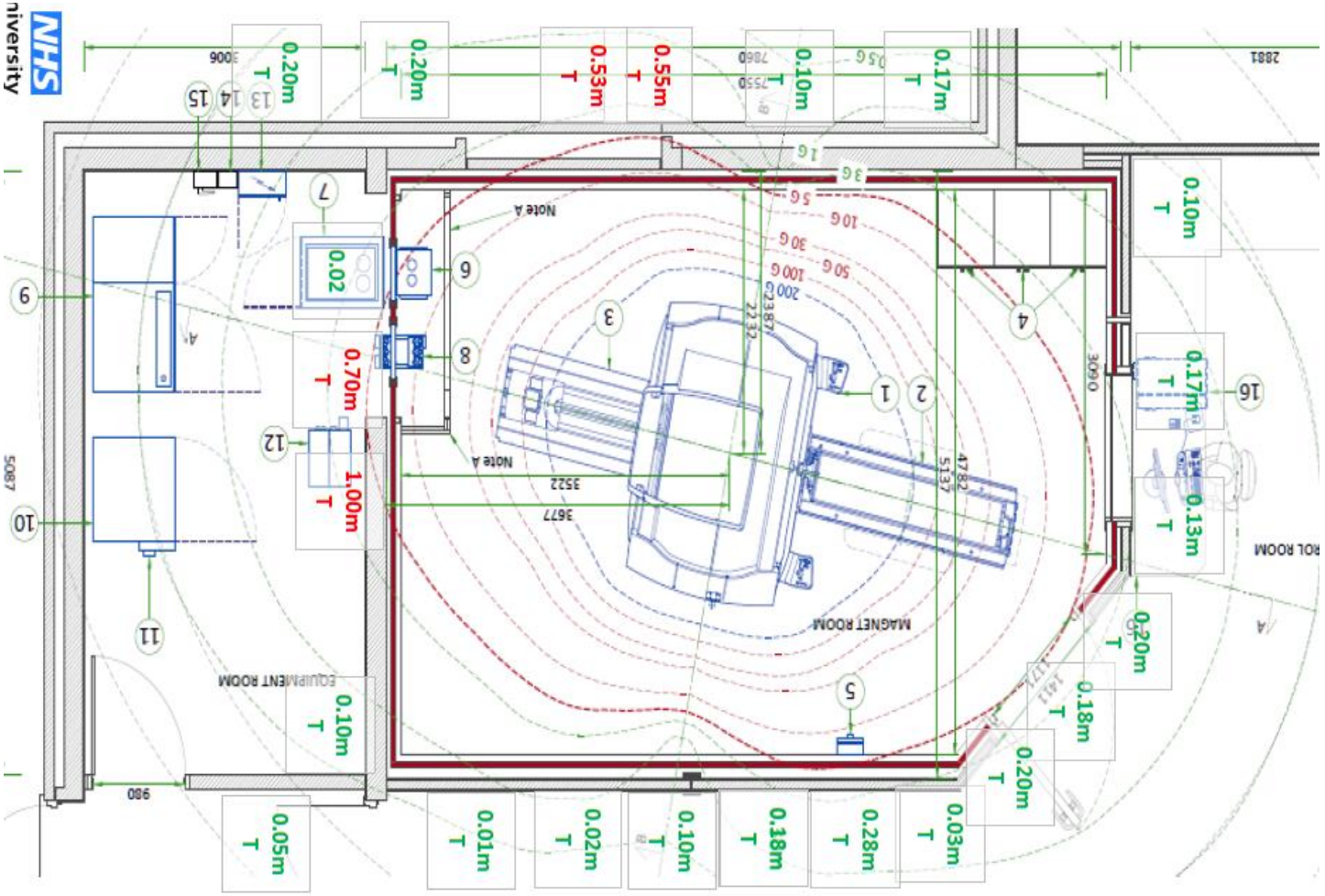
Fringe Field (B_0)



Fringe Field (B_0)

- Scanner 'footprint'
  - Credit card erased at 10 G
  - Safety limit is 'five Gauss line'
  - Pacemakers not allowed within **5 G (0.5mT)**

- Shielding (to reduce stray field)
  - Passive (metallic)
  - Active (outer superconducting coil whose field opposes that of the inner coil)

- May be measured with handheld Gaussmeter

> 30 G	Stainless steel, non-ferromagnetic objects
< 30 G	ECG monitors, unrestrained ferromagnetic objects
< 10 G	Credit cards, x-ray tubes
< 5 G	**Pacemakers, general public**
< 1 G	CT & PET scanners
< 0.5 G	Gamma cameras

1 G = 0.1 mT

B_0 - compatibility of peripheral equipment

- Most equipment brought into the scan room (wheelchairs, stretchers and emergency trolleys, cleaning equipment) should not contain significant amounts of ferromagnetic material in order to avoid the projectile effect from the static magnetic field

- It is recommended that appropriate **MR CONDITIONAL** monitoring and support equipment (eg ventilators, anaesthesia machines, pumps) is used.

- Staff should know any conditions (eg distance to magnet bore) which may affect the equipment's safety and these should be clearly marked on the equipment.

- Accessories to monitoring equipment should also be checked for compatibility eg ECG leads and electrodes.

Magnetic Materials

In the presence of an externally applied magnetic field:

- **Ferromagnetic** materials
  - Strongly attracted to magnetic fields
  - Induced magnetisation may persist after removal of field
  - E.g. iron, nickel, cobalt

- **Paramagnetic** materials
  - Weakly attracted to magnetic field,
  - No permanent magnetism persisting after field removal
  - E.g. magnesium, molybdenum, lithium, gadolinium contrast

- **Diamagnetic** materials
  - Repelled by magnetic field

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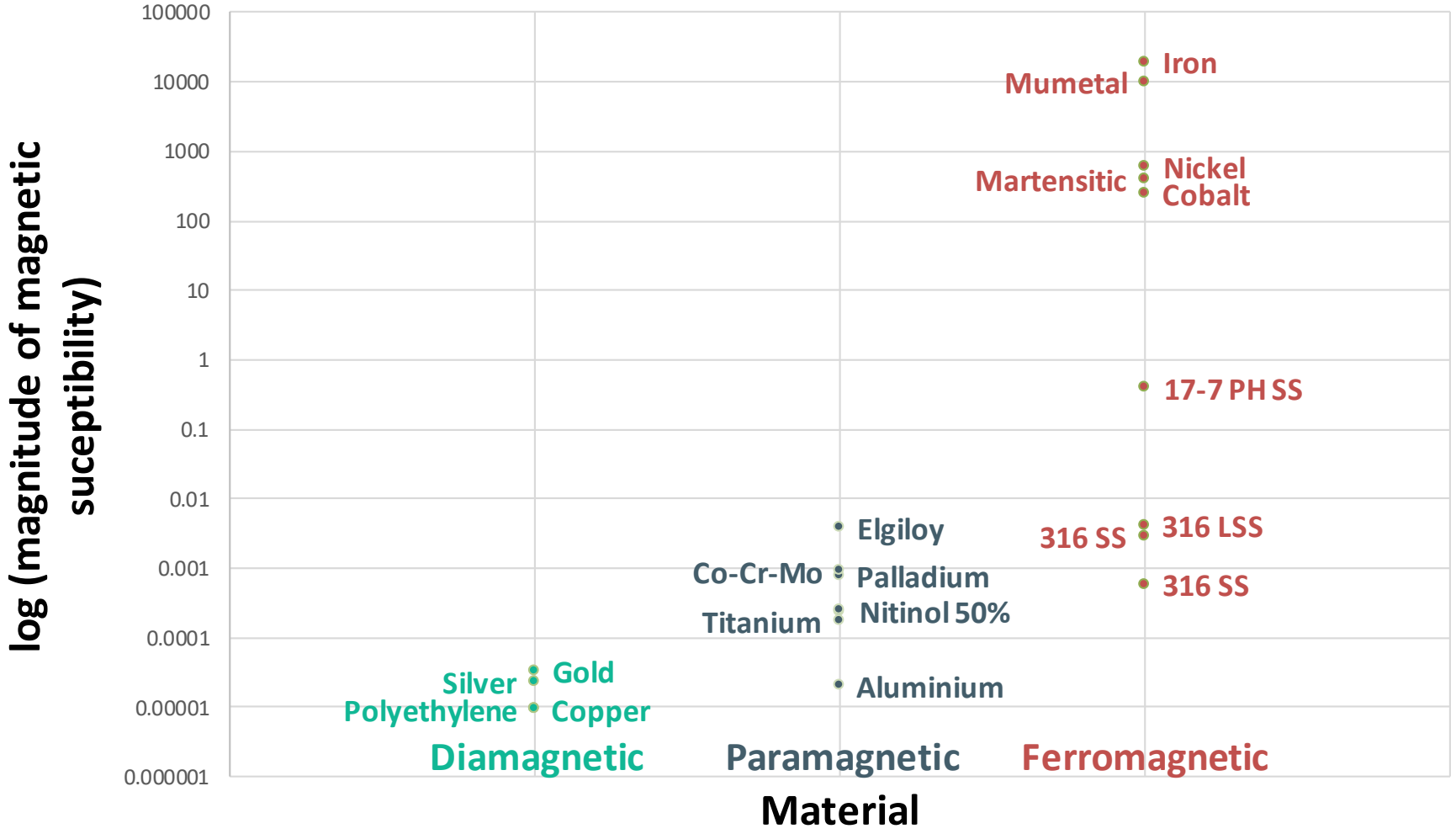
Magnetic Materials



Attractive (translational) forces

- Attractive force (Newtons) proportional to the magnetic field (B_0) and the spatial field gradient (dB/dz)

$$F = B_0 \times dB/dz$$

- Now add in information about the material:

$$F = \frac{\chi}{\mu_0} \times V \times B_0 \times dB/dz$$

- χ =magnetic susceptibility, μ_0 = magnetic permeability in a vacuum, V = volume of object

- $\mu_0 = 4\pi \times 10^{-7}$ H/m = 1.2566370614…$\times 10^{-6}$ N/A^2 (1 henry per metre = newton per square ampere)

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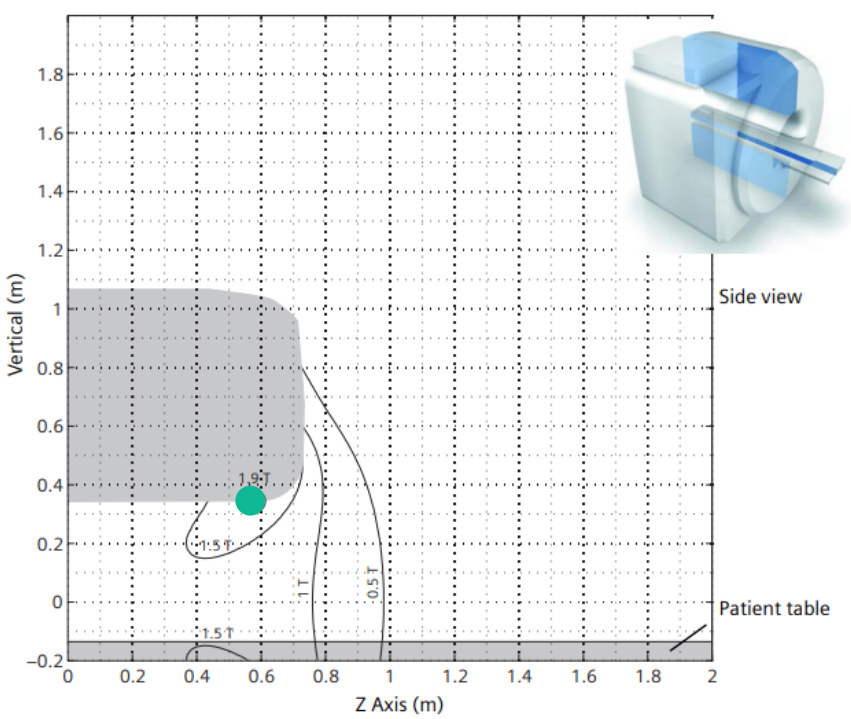
Static B_0 Magnetic Field - projectile hazard

- Translational force = magnetic field x spatial field gradient



Spatial Field Map
Siemens Aera 1.5T

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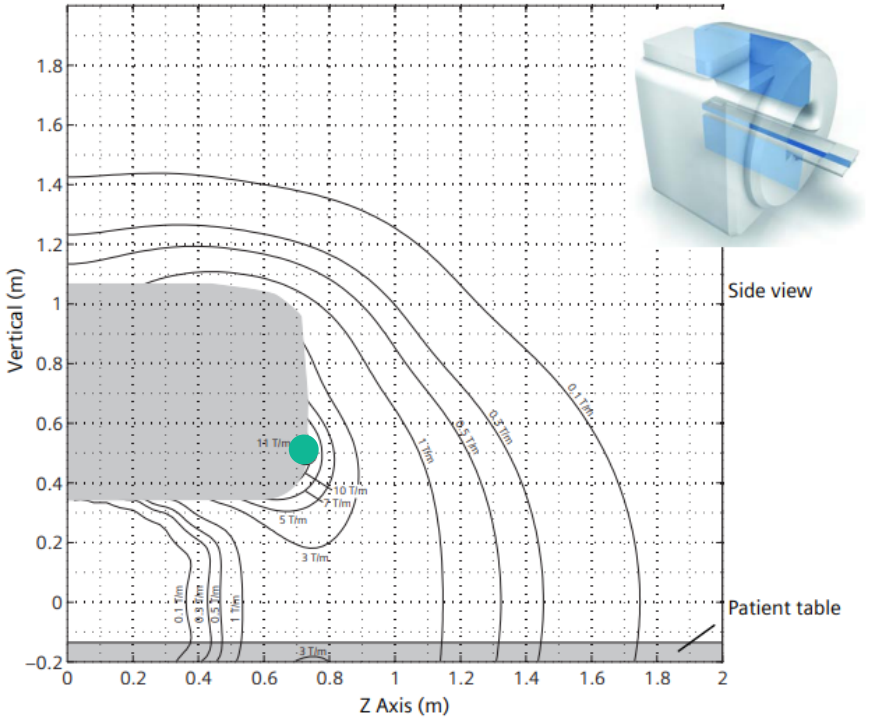
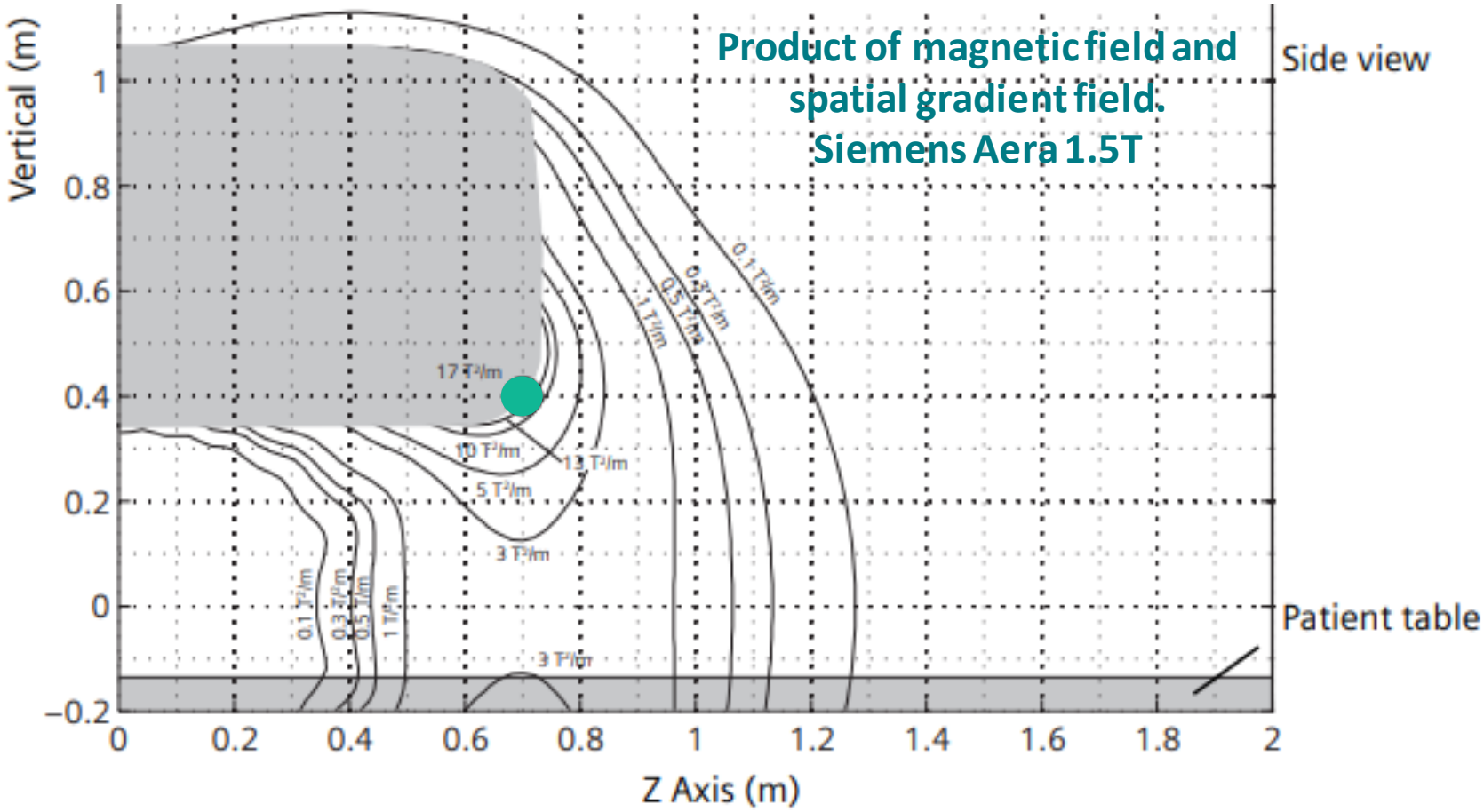


Spatial Field Gradient Map
Siemens Aera 1.5T

Static B_0 Magnetic Field - projectile hazard

- Translational force = magnetic field x spatial field gradient



Static B_0 Magnetic Field - projectile hazard

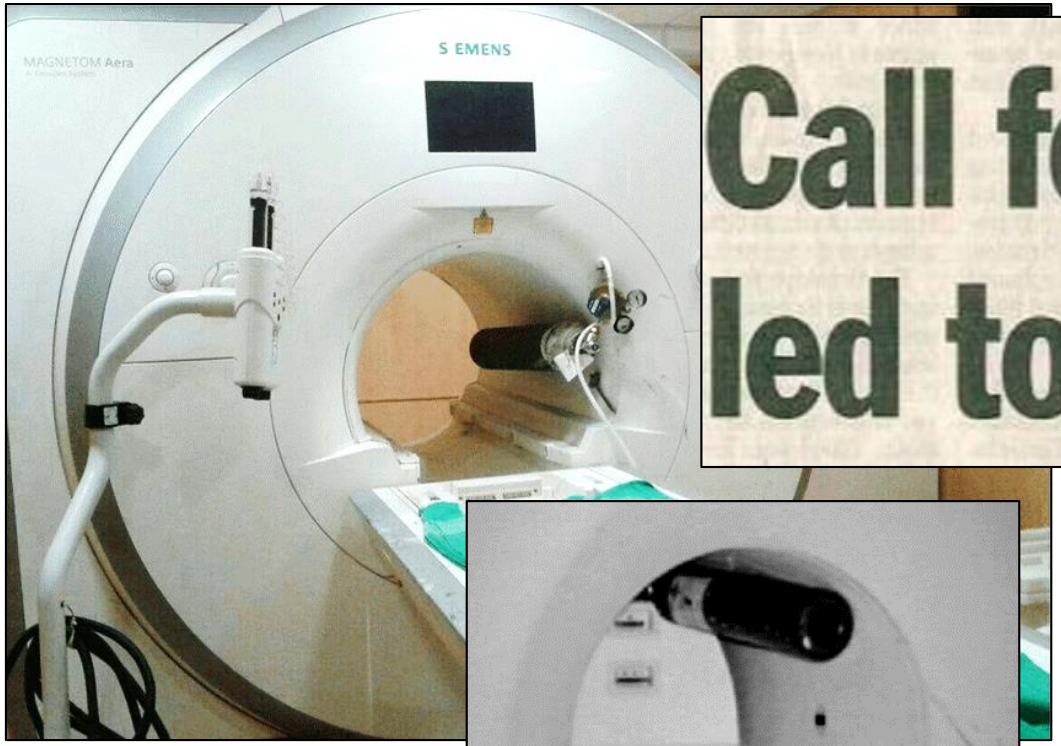
- July 31, 2001 New York: Death of 6 year-old boy due to oxygen tank pulled into bore
  - This is thought to be the first ever death due to projectiles

TUESDAY, July 31, 2001 (HealthDayNews) -- A 6-year-old cancer patient in New York was killed during a routine brain scan when the machine's massive magnet turned a nearby oxygen tank into a ballistic missile.

The boy died two days ago from head injuries and brain trauma after being struck June 27 by a oxygen canister that was sucked into a magnetic resonance imaging (MRI) machine by its 10-ton magnet. He was being treated at the Westchester Medical Center in Valhalla for a brain tumor and was undergoing the scanning procedure to measure his progress, according to officials who just released details of the incident.

B_0 - compatibility of peripheral equipment

Oxygen Cylinders are **MR UNSAFE**




Call for oxygen led to MRI death

B_0 - compatibility of peripheral equipment

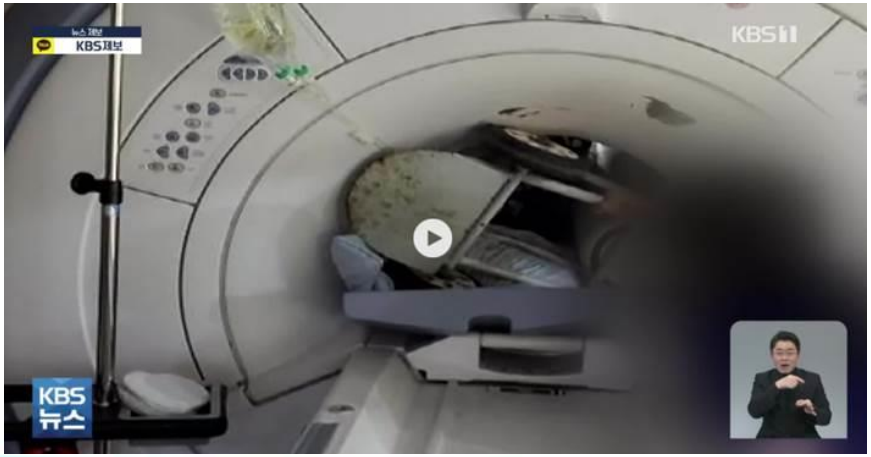
Oxygen Cylinders are **MR UNSAFE**

South Korean man dies after oxygen cylinder sucked into MRI machine

- The 60-year-old patient was hit in the head by a 60kg oxygen cylinder while undergoing a magnetic resonance imaging scan at a hospital in Gimhae
- Projectiles are one of the biggest dangers associated with MRI scanners, as the strong magnetic fields they generate cause metal objects to become airborne

Park Chan-kyong in Seoul + FOLLOW

Published: 12:03pm, 19 Oct, 2021



Safety issues, particularly with regards to implanted devices and emergency situations

- October 25, 2019 — A radiology nurse was seriously injured Oct. 23 at Sunderby Hospital in Luleå, located in northern Sweden, when caught in the strong magnetic field of the magnetic resonance imaging (MRI) scanner and pulled against it. The X-ray nurse is currently being treated at the intensive care unit at the hospital.
- A patient was in the MRI system undergoing an imaging exam when the accident happened. The hospital said the nurse went to the patient and was apparently wearing a weight vest containing ferris metal, according to a report on the incident by the Swedish news source Aftonbladet. Two security guards from the hospital came to the site to help and both suffered minor injuries.

Nurse Injured in MRI Accident at Swedish Hospital

Metal in weighted vest believed to have caused extensive injuries that landed nurse in intensive care

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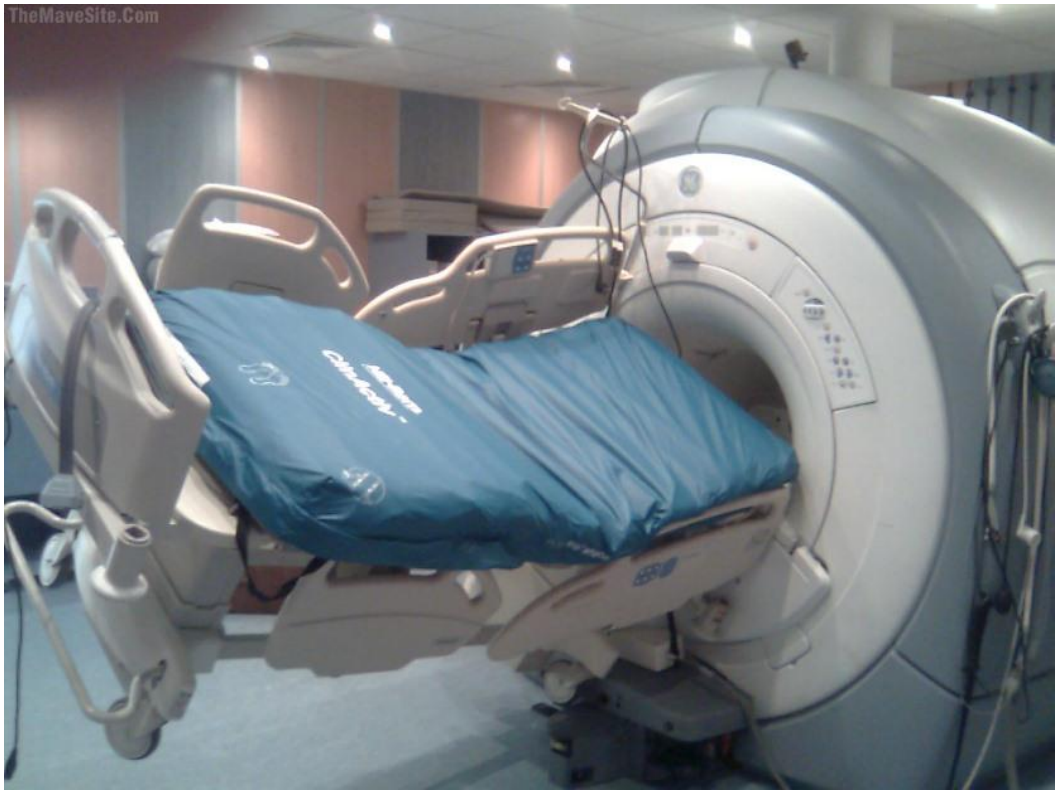
Static B_0 Magnetic Field - projectile hazard



Torque (rotational) forces

- Torque (Newtons) proportional to the square of the magnetic field (B_0)

$$T = {B_0}^2$$

- Now add in information about the material:

$$F = \frac{1}{\mu_0} \times \chi^2 \times V \times {B_0}^2 \times g_t$$

- χ =magnetic susceptibility, μ_0 = magnetic permeability in a vacuum, V = volume of object, g_t relates to the object's shape.

- $\mu_0 = 4\pi \times 10^{-7}$ H/m = $1.2566370614\ldots \times 10^{-6}$ N/A^2 (1 henry per metre = newton per square ampere)

- Torque is largely shape dependent and is proportional to the field strength, B_0, and to the angle the object is away from alignment with the field

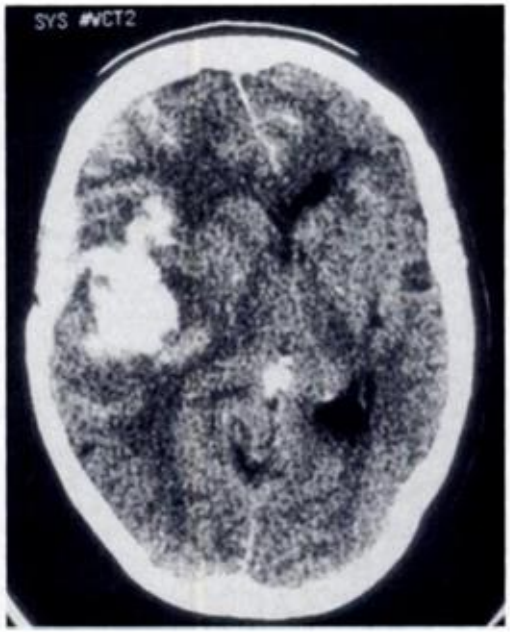
- Rod or cylinder shapes are more likely effected by torque

Richard P. Klucznik, MD • David A. Carrier, MD • Ron Pyka, MD • Regis W. Haid, MD

Placement of a Ferromagnetic Intracerebral Aneurysm Clip in a Magnetic Field with a Fatal Outcome[1]

Magnetic resonance (MR) imaging may be contraindicated in patients with biomedical devices, among the most dangerous of which are intracranial aneurysm clips, owing to the possibility of torque and dislodgment. A case is presented in which a patient with a reportedly nonferromagnetic clip was placed in a magnetic field. The patient developed an acute intracerebral hemorrhage in the MR unit, with a fatal outcome. Imaging studies strongly suggested a torqued clip as the cause. Autopsy revealed a torn middle cerebral artery from clip movement, and the clip was identified as a ferromagnetic type. This is the first reported case, to the authors' knowledge, of a fatal outcome due to an intracranial aneurysm clip placed in a magnetic field.

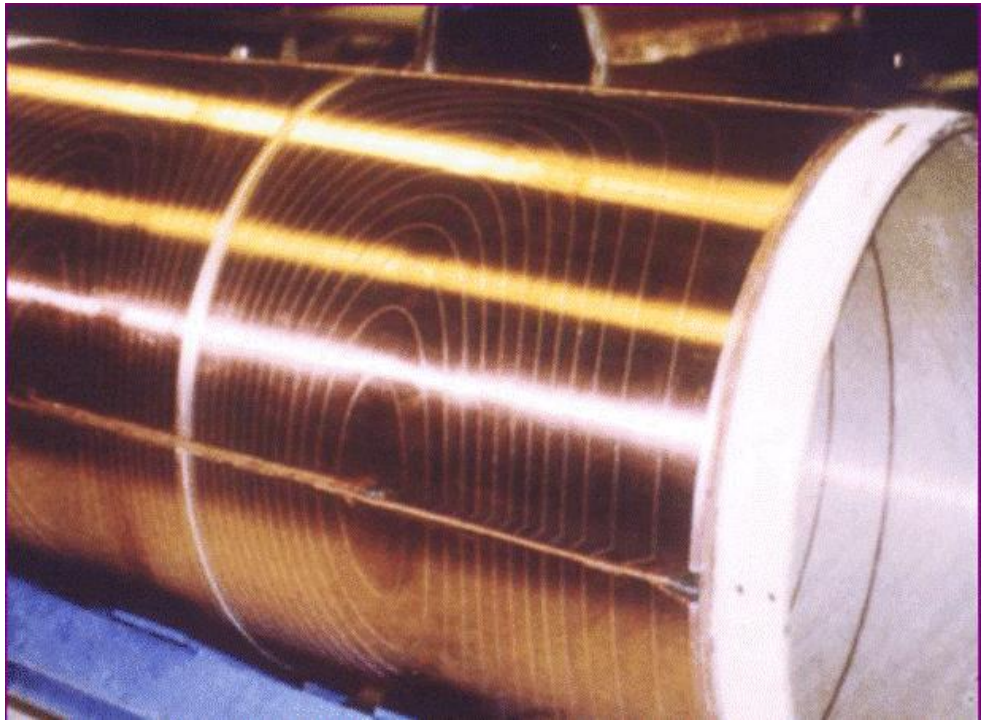
material may prevent possible catastrophic complications. Four patients with known intracranial aneurysm clips—one of which was ferromagnetic—have been imaged, without neurologic complications (2). MR imaging centers may image patients with biomedical devices safely by using published data on such implants (3–5). The data concerning intracranial aneurysm clips have been considered complete and are used at MR imaging centers as a reference for those patients who may benefit from an MR study but in whom there is a question of the safety of an aneurysm clip. We present a case in which death was caused by movement of an intracranial aneurysm clip that was misidentified and was believed to be nonferromagnetic. According to the U.S. Food and Drug Administration



June 1993

Time varying magnetic field gradients (dB/dt)

- Biological effects
- Acoustic noise
- Implant interactions



Time varying magnetic field gradients (dB/dt)

Biological effects

- Time varying electromagnetic fields (e.g. gradients) can lead to induced electric fields and circulating currents in conductive tissues
- The currents induced will be determined by the rate of change of the magnetic field and the local body impedance
- In MR, three orthogonal magnetic field gradients are switched on and off to select the region of diagnostic interest and to spatially encode the MR signals.
- Time varying magnetic fields induced currents that can interfere with the normal function of nerve cells and muscle fibres– Peripheral Nerve Stimulation (PNS)
- Main concern is possible cardiac fibrillation!!!

Time varying magnetic field gradients (dB/dt)

Biological effects

- Other biological effects with the time-varying magnetic field gradients are :
  - peripheral nerve stimulation (PNS)
  - muscle stimulation
  - acoustic noise
  - phosphenes (flashing lights)

- As a general guide, the faster the imaging or spectroscopy sequence, the greater the rate of change of the gradient fields used and the resultant current density induced in the tissue

Time varying magnetic field gradients (dB/dt)

Biological effects

- Electrical stimulation can occur (Peripheral Nerve Stimulation, muscular) at about 60 T/s
- Cardiac stimulation is theoretically above this
- Actual threshold depends on rise time
- Echo planar sequences are those most likely to cause this type of effect

Implant interaction

- The time-varying magnetic field gradients can interact with implants
- This may result in device heating and vibration

Time varying magnetic field gradients (dB/dt)

IEC/ICNIRP/HPA guidance:

- …the system must not have gradient output that exceeds the limit for peripheral nerve stimulation (PNS). This will also protect against cardiac fibrillation…

- **IEC/ICNIRP/HPA normal operating mode:**
  - The gradient system shall operate at a level that does not exceed 80% of the directly determined mean threshold for PNS, where the threshold for PNS is defined as the onset of sensation.

- **IEC/ICNIRP/HPA first level controlled operating mode**:
  - the gradient system shall operate at a level that does not exceed 100% of the directly determined mean threshold for PNS.

Time varying magnetic field gradients (dB/dt)

IEC/ICNIRP/HPA guidance:

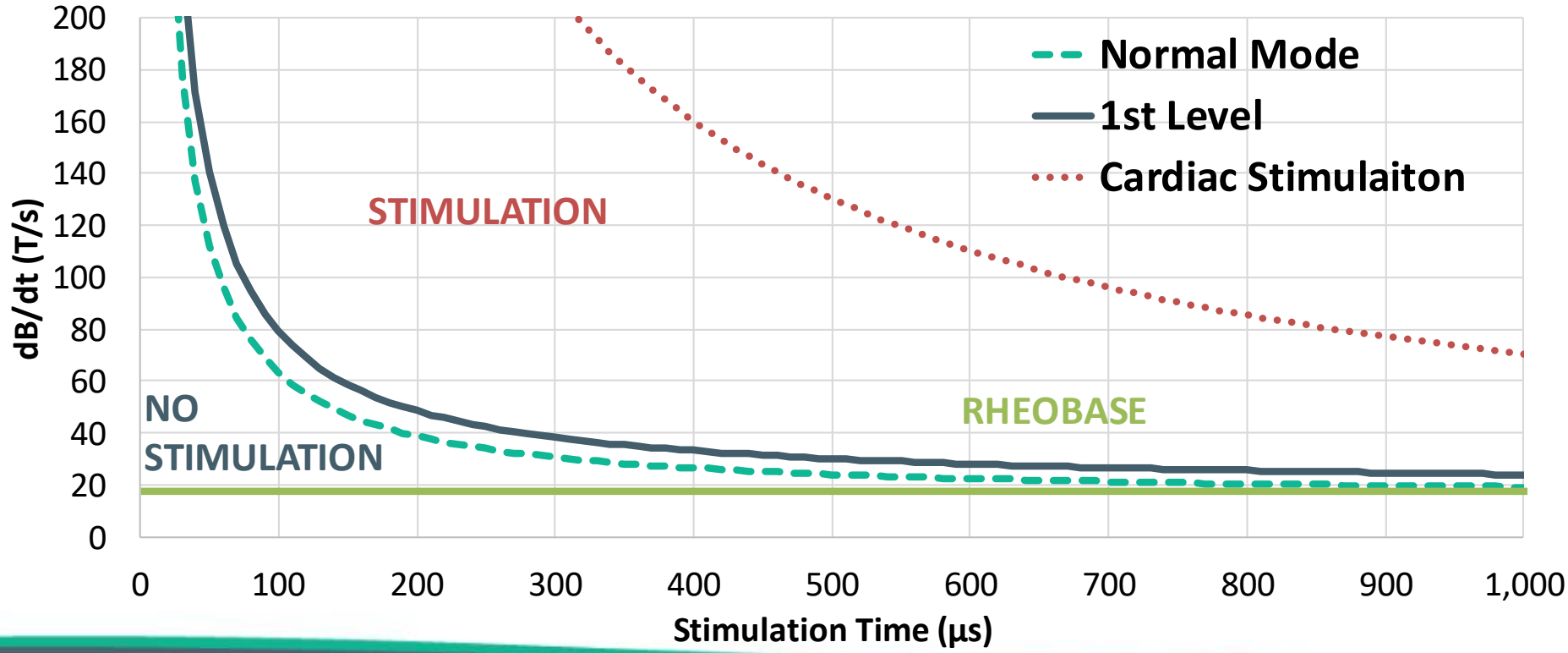
Table 6 IEC/ICNIRP/HPA patient and volunteer exposure limits to time-varying magnetic fields

	NORMAL MODE	CONTROLLED MODE	RESEARCH / EXPERIMENTAL MODE
Limits for gradient output: Expressed as a percentage of the median perception threshold, $dB/dt=20(1+0.36 / t_{s,eff})T\ s^{-1}$ (%) *	<80	80 - 100	100 – 120 ‡
IEC limit to prevent cardiac stimulation. For all modes of operation (Ts^{-1}).	$\frac{dB}{dt} < \frac{20}{\left\{1-\exp\left(-\frac{t_{s,eff}}{3}\right)\right.}$ *		

* - ($t_{s,eff}$ is the effective stimulus duration, in ms.)
‡ - No limit for IEC

Time varying magnetic field gradients (dB/dt)

- The curve flattens out with long stimulus durations, reaching the **RHEOBASE** (lowest threshold for long stimulus durations).
- Lowest thresholds occur for long stimulus durations (Ramp duration) so faster switching allows for greater changes in gradient amplitude without PNS



Derived strength–duration (SD) curves for the IEC 60601-2-33 limits for cardiac stimulation and the normal (L01) and first-level (L12) for a GE Signa Premier 3.0T

Time varying magnetic field gradients (dB/dt)

Acoustic Noise

- Time varying magnetic fields gradients result in the production of acoustic noise

- Lorentz forces are generated by the gradient coils when low frequency currents are pulsed through them in the presence of the static magnetic field (B_0)

- The Lorentz forces result in the movement of the gradient coil generating sound waves (loudspeaker coil)

Time varying magnetic field gradients (dB/dt)

Acoustic Noise

- Lorentz force on gradient coils

- Gradient coils vibrate and this is transmitted to other parts of scanner and patient

- Type of noise is 'stressful' (low frequency and periodic)

Noise Levels

- MRI recorded up to 115 dB
- Rock concerts 110-140 dB
- Jet takeoff 130 dB
- Acoustic trauma threshold is 140 dB

Time varying magnetic field gradients (dB/dt)

Acoustic Noise

MHRA Guidelines - Hearing protection

- Hearing protection shall always be provided for patients and volunteers unless it can be demonstrated that noise levels will not exceed 80 dB(A).

- When the noise level exceeds 80 dB(A) it is recommended that staff and others remaining in the scan room wear non-metallic earplugs and/or ear defenders

- The hearing protection should be chosen to match the noise frequency spectrum of the MR system in use and to reduce noise at the eardrum to **below 85 dB(A)**, the instructions for use should be consulted for the manufacturer's recommendations.

- For high noise sequences ear plugs and muffs can be used in combination, however the protection provided is less than the sum of the two

Magnetic Forces due to Motion

Lenz's Law

- The Faraday-Lenz Law of electromagnetism states that electrical currents are induced in nearby conductors by a changing magnetic field. Since MR uses rapidly changing magnetic fields (dB/dt, RF), swirling ('eddy') currents are always produced whenever imaging is performed

- Eddy currents induced by movement generate a magnetic field in the opposite direction to the change in magnetic flux

- The conductive material in which eddy currents are induced may be any metallic component of the MR scanner implants within the patient, and the patient as a whole.

- Materials such as gold, aluminium, copper and gold have high electrical conductivities and more prone

http://mriquestions.com/eddy-current-problems.html

Induction

- The movement of implants through dB/dt can result in large eddy currents (several amperes)

- Induced eddy current from magnetic field gradients can be two orders larger, resulting in:
  - Electrical excitation (shock)
  - Vibration
  - Heat generation

Radiofrequency magnetic field (B_1)

Safety issues concerning radiofrequency fields

- The main safety issues for radiofrequency (RF) fields in MR are:
  - thermal heating leading to heat stress induced current burns
  - contact burns

- At all frequencies, induced currents will lead to power dissipation within the body's tissues, which in turn lead to a rise in body temperature

- If heating occurs, dilation of blood vessels results in an increase in blood flow and the removal of excess heat

- A core temperature rise of 1.0°C is acceptable to a normal healthy person

- Ambient temperature, air flow, clothing and humidity all play a major role in the rate of dissipation. The lower the ambient temperature and the lower the humidity, the greater the transfer

IEC RF exposure limitation

Limits are set in terms of core and local tissues temperature (°C) to prevent heat stress and tissue damage

Temperature rises >1-2 °C can cause adverse effects such as heat exhaustion and heat stroke

Operating mode	Maximum core temperature (°C)	Maximum local tissue temperature (°C)	Rise of core temperature (°C)
Normal	39	39	0.5
First Level	40	40	1
Second Level Controlled	>40	>40	>1

Radiofrequency magnetic field (B_1)

- Heat stress is of particular concern for some patients, such as those suffering from hypertension, or pregnant women, or those on drugs such as diuretics or vasodilators that may compromise these responses.

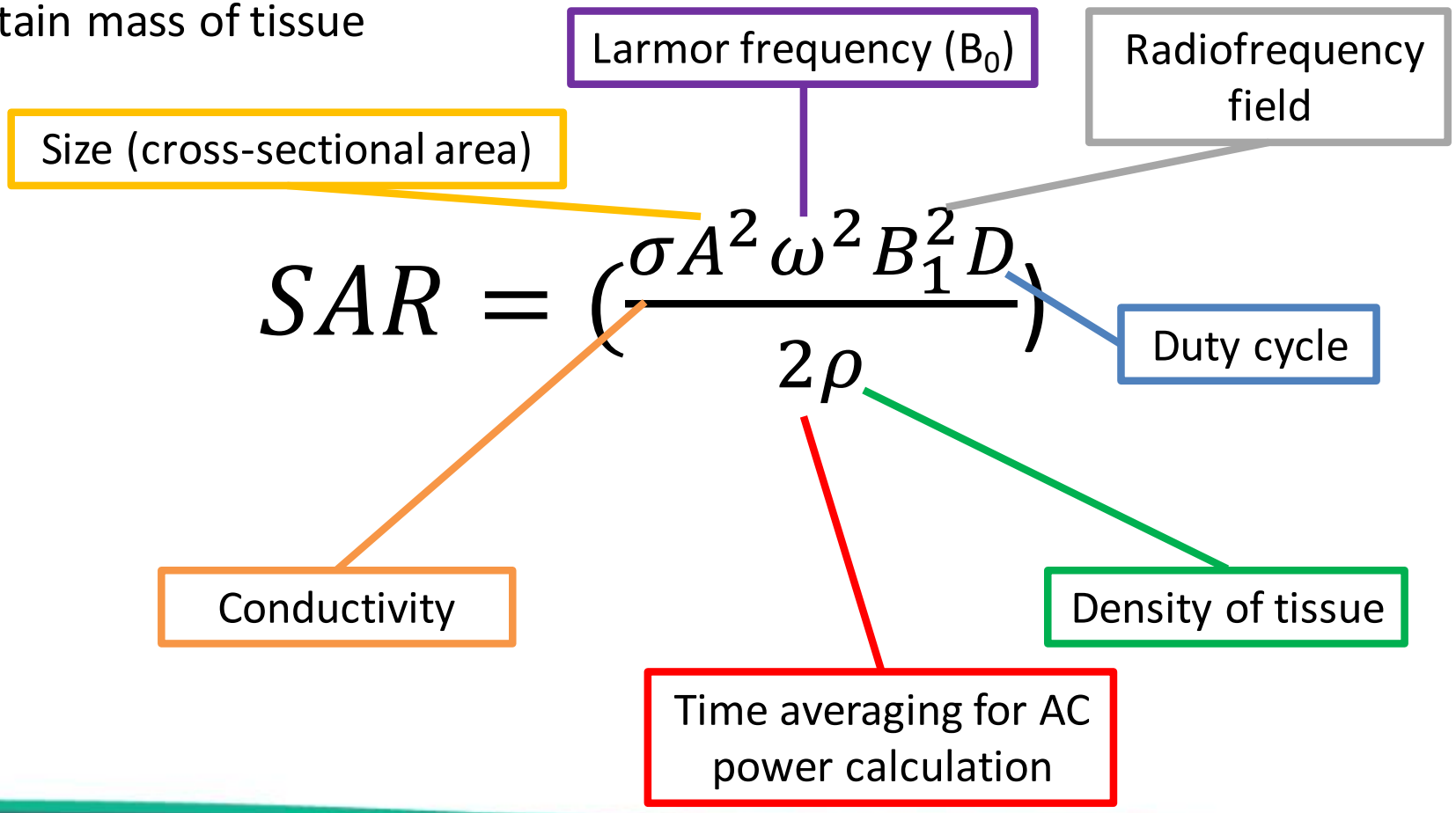
- One fundamental issue is excessive cardiovascular strain resulting from thermoregulatory responses to body temperatures raised over a short period of time by more than 0.5°C in vulnerable people. MR scanners limit temperature rise by limiting SAR (Specific Absorption Rate)

Mode	Head	Fetus	Trunk	Limbs
NORMAL MODE	38°C	38°C*	39°C	40°C
CONTROLLED MODE	38°C	38°C*	39°C	40°C
RESEARCH / EXPERIMENTAL MODE	>38°C	-	>39°C	>40°C
HPA upper limit	39°C		40°C	41°C

* only ICNIRP has a specific limit for the fetus

Radiofrequency magnetic field (B_1)

- RF power deposition expressed as Specific Absorption Rate (SAR in W/Kg) and is a measure of the amount of power deposited by a radiofrequency field in a certain mass of tissue



Radiofrequency magnetic field (B_1)

- SAR is proportional to the electrical conductivity of tissue (σ). Tissue conductivity varies by a factor of 10 across the body, being largest in high water content materials like blood and urine and lowest in tissues like bone, fat, and lung. Foreign metal objects in the body are frequently highly conductive and significant (even dangerous) heating levels around these may occur.

$$SAR = \left(\frac{\sigma A^2 \omega^2 B_1^2 D}{2\rho}\right)$$

Conductivity

Tissue	Density (ρ)	Conductivity (σ) @ 1.5T
Water	1000	1.55
Fat	911	0.066

Radiofrequency magnetic field (B_1)

- SAR increases significantly with body size. SAR tends to be concentrated more around the periphery (where the radius is larger). So larger and obese patients are more at risk. In a homogeneous sphere, 87% of the RF power dissipation occurs in its the outer third.

Size (cross-sectional area)

$$SAR = \left(\frac{\sigma A^2 \omega^2 B_1^2 D}{2\rho}\right)$$

- Fortunately heat deposited on the perimeter of the body can be more easily dissipated.

Radiofrequency magnetic field (B_1)

- SAR is proportional to the square of the RF frequency (ω). Typically, the RF frequency is chosen to closely match the Larmor frequency.

Larmor frequency (B_0)

$$SAR = \left(\frac{\sigma A^2 \omega^2 B_1^2 D}{2\rho}\right)$$

- Remember $\omega = \gamma B_0$ therefore SAR $\propto B_0^2$

- The same pulse sequence in the same patient imaged at 1.5T would therefore generate 4x the SAR if performed at 3.0T.

ω = angular frequency or Larmor frequency
For ^1H, γ = 42.58 MHz/T (gyromagnetic ratio)

Radiofrequency magnetic field (B_1)

- SAR is proportional to the square of the RF-flip angle (α). This follows from the fact that (α) is proportional to the mean amplitude of the RF-pulse (B_1).

Radiofrequency field

$$SAR = \left(\frac{\sigma A^2 \omega^2 B_1^2 D}{2\rho}\right)$$

- Remember $\alpha = \gamma B_1 t_p$ - where α is the flip angle, γ is the gyromagnetic ratio, B_1 is the strength of the RF pulse and t_p is the RF pulse duration

- Since SAR is proportional to B_1^2, it is also proportional to α^2. Thus a 180°-pulse would create 4x the SAR as a 90°-pulse.

Radiofrequency magnetic field (B_1)

- Duty cycle is the RF pulse length times the number of pulses per TR divided by the TR i.e. the percentage of time (TR) the RF is on

- If RF on throughout the TR the duty cycle would be 100%, if the RF was on for only a tenth of the TR the duty cycle would be 10%

$$SAR = \left(\frac{\sigma A^2 \omega^2 B_1^2 D}{2\rho}\right)$$

Duty cycle

Radiofrequency magnetic field (B_1)

- Density of tissues are fairly similar

$$SAR = \left(\frac{\sigma A^2 \omega^2 B_1^2 D}{2\rho}\right)$$

Tissue	Density (ρ)	Conductivity (σ) @ 1.5T
Water	1000	1.55
Fat	911	0.066

Density of tissue

Time averaging for AC power calculation

Radiofrequency magnetic field (B_1)

- SAR increases with:
  - The square of Larmor frequency (B_0)
  - The square of the flip angle
  - Patient size
  - Duty cycle

- Conductivity, density and size of conductors are not uniform within a body – *localised SAR hot spots*
  - At higher fields the body is more conductive and leads to weaker penetration - RF power needs to therefore be increased

- B_1 not uniform - *localised SAR hot spots*

- **SAR is patient DEPENDANT** (same protocol 2 different SAR values)

Radiofrequency magnetic field (B_1)

SAR Limits

Table 8 IEC 2010 patient and volunteer SAR limits (Wkg^{-1}) for RF field exposure

	Whole body	Partial body			Local	
		Head	Not head [a]	Head [b]	Trunk	Extremities
NORMAL MODE	2	3.2	2–10	10	10	20
CONTROLLED MODE	4	3.2	4–10	20	20	40
RESEARCH / EXPERIMENTAL MODE	>4	>3.2	>(4–10)	>20	>20	>40

a Partial-body SAR scales dynamically with the ratio r between the patient mass exposed and the total patient mass:
– normal operating mode: SAR = (10-8×r) Wkg^{-1}
– controlled operating mode: SAR = (10-6×r) Wkg^{-1}

b In cases where the eye is in the field of a small local coil used for RF transmission, care should be taken to ensure that the temperature rise is limited to 1°C.
Averaging time = 6 min.

Radiofrequency magnetic field (B_1)

- There are a number of practical steps that can be undertaken to manage the effects of SAR:
  - increase the TR
  - reduce excitation flip angles
  - reduce the number of slices in an acquisition
  - reduce the number of echoes in multiecho sequences
  - control the scanning room temperature
  - interleave high SAR and low SAR acquisitions to allow patient cooling
  - turning the patient bore ventilation system on
  - Change RF pulse duration (1 -> 2ms) will half SAR
  - Remove excess saturation bands
  - Reduce refocussing flip angle (SE/FSE). 180° -> 160 ° leads to 21% SAR drop

- see https://www.ajronline.org/doi/pdf/10.2214/AJR.14.14173 for more details

RF Heating

- Heating of metallic implants mainly occurs from dB_1/dt of the RF transmission pulses

- B_1 is a rapidly time-varying magnetic field and so will induce electric fields and current density in objects

- Complicated to predict due to:
  - Skin effect where current mainly flows on a materials surface
  - Effect of being imbedded in tissue leading to local B_1 variations
  - Antenna effect
  - Cooling mechanisms (perfusion and thermal conduction)

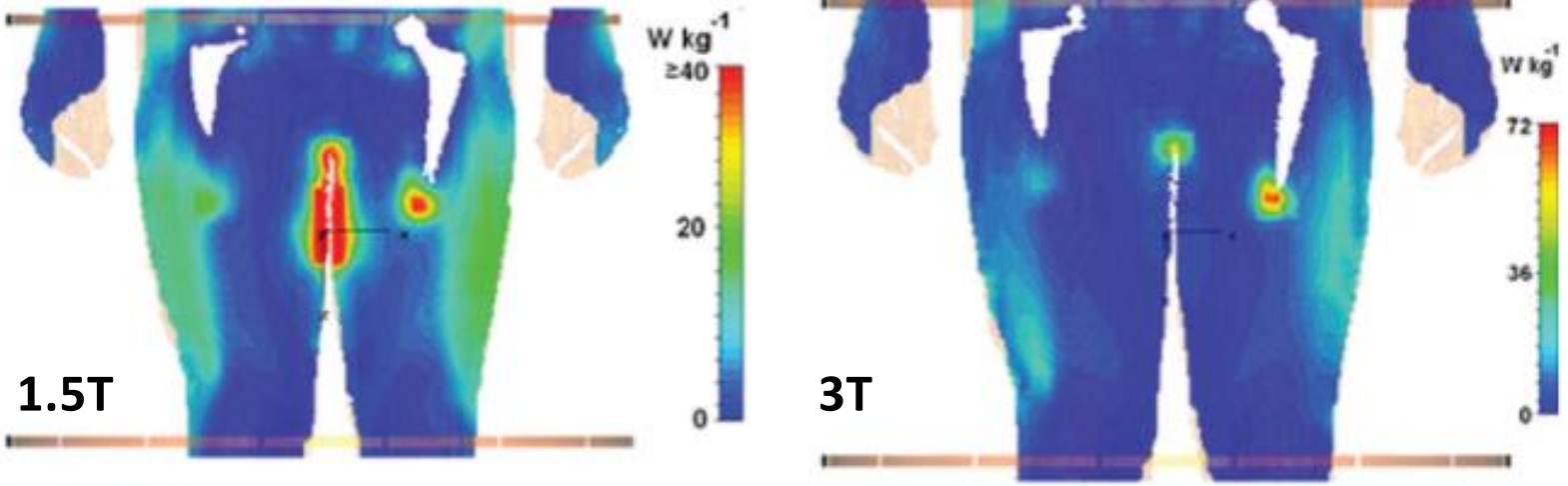
RF Heating

- A metallic implant will not necessarily exhibit more SAR and hence local heating at 3T when compared to 1.5T

› Magn Reson Med. 2012 Sep;68(3):960-8. doi: 10.1002/mrm.23304. Epub 2011 Dec 9.

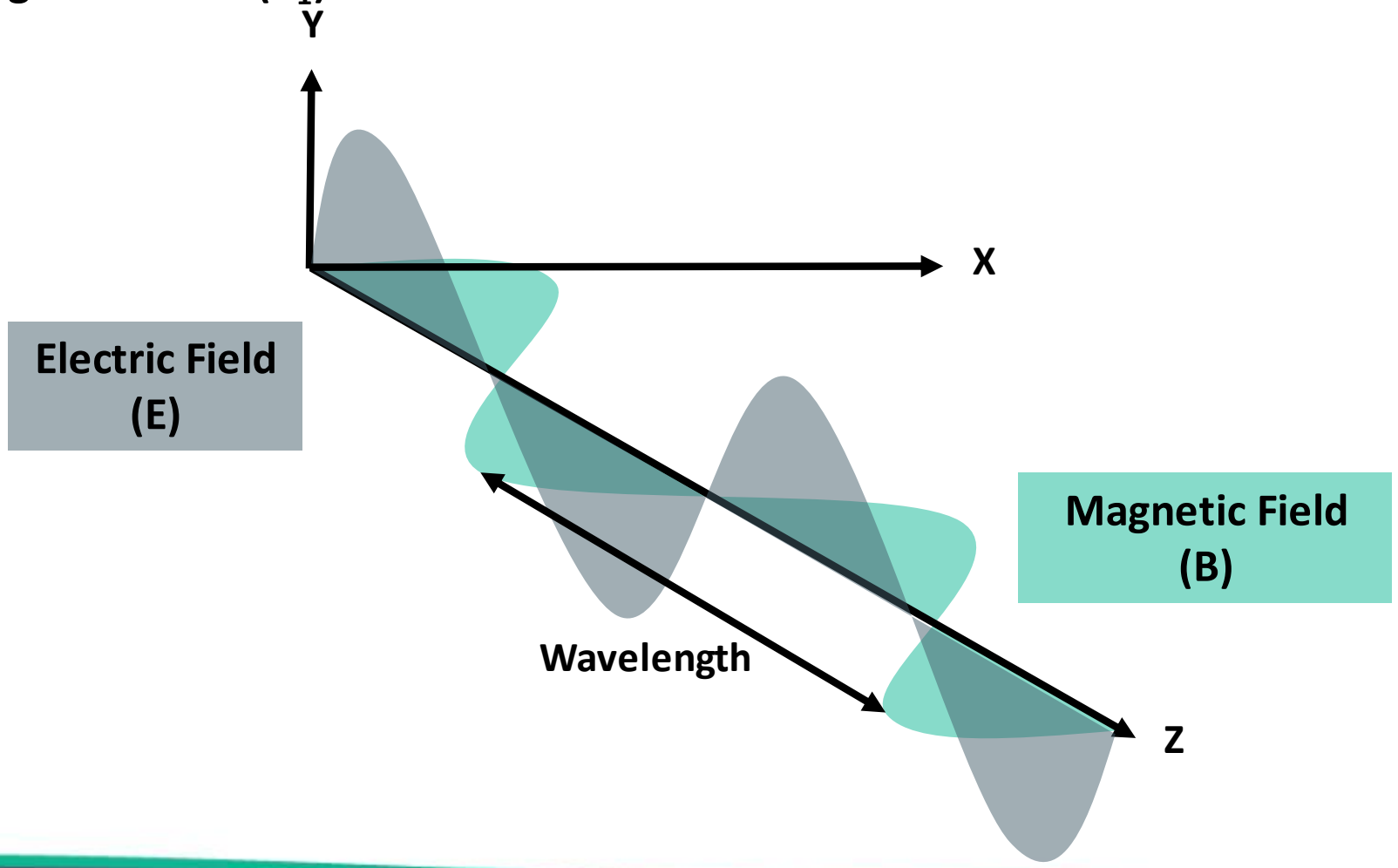
Numerical simulation of SAR induced around Co–Cr–Mo hip prostheses in situ exposed to RF fields associated with 1.5 and 3 T MRI body coils

John Powell [1], Annie Papadaki, Jeff Hand, Alister Hart, Donald McRobbie



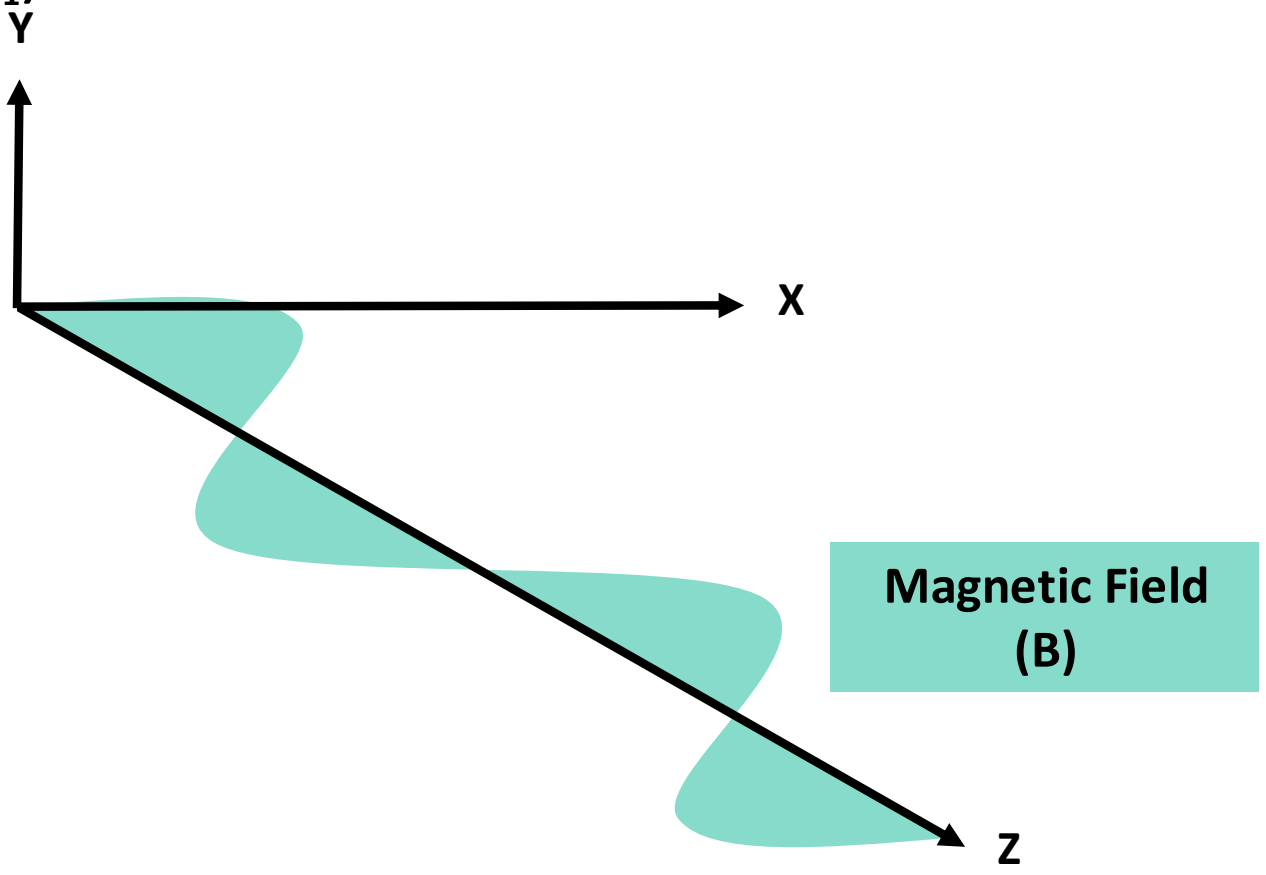
Radiofrequency magnetic field (B_1)

Electromagnetic Wave (B_1)



Radiofrequency magnetic field (B_1)

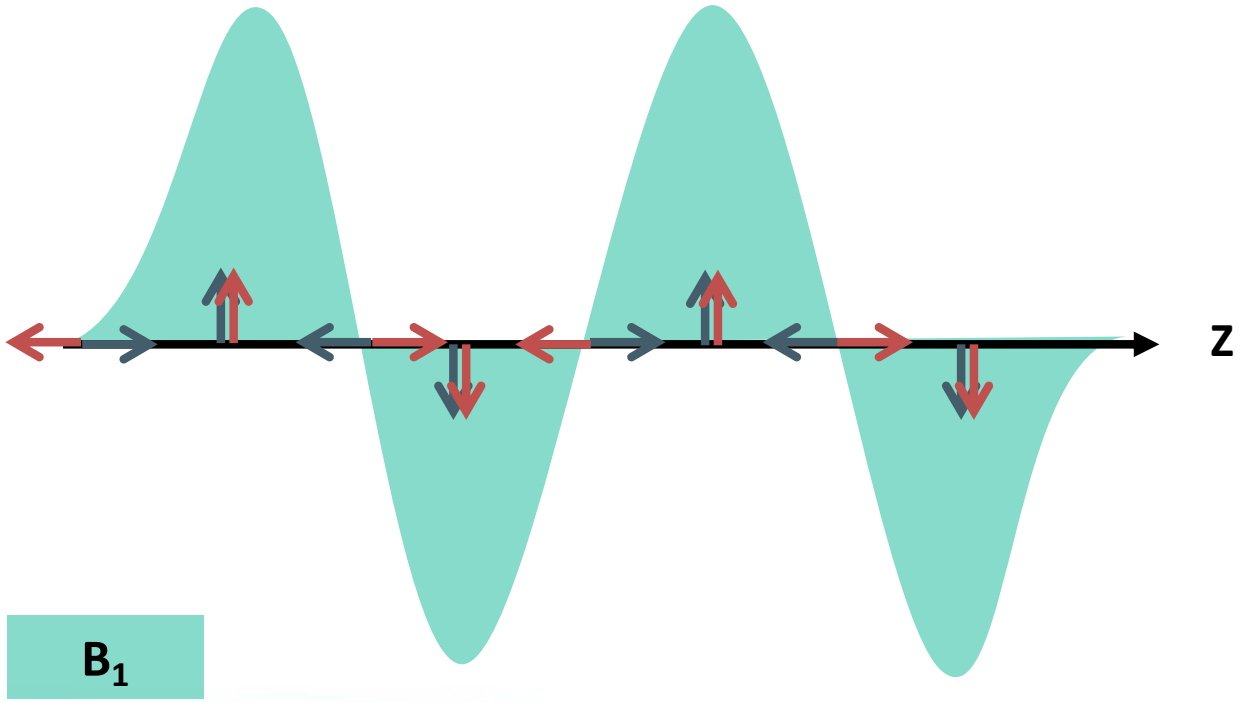
Electromagnetic Wave (B_1)



Radiofrequency magnetic field (B_1)

Electromagnetic Wave (B_1)

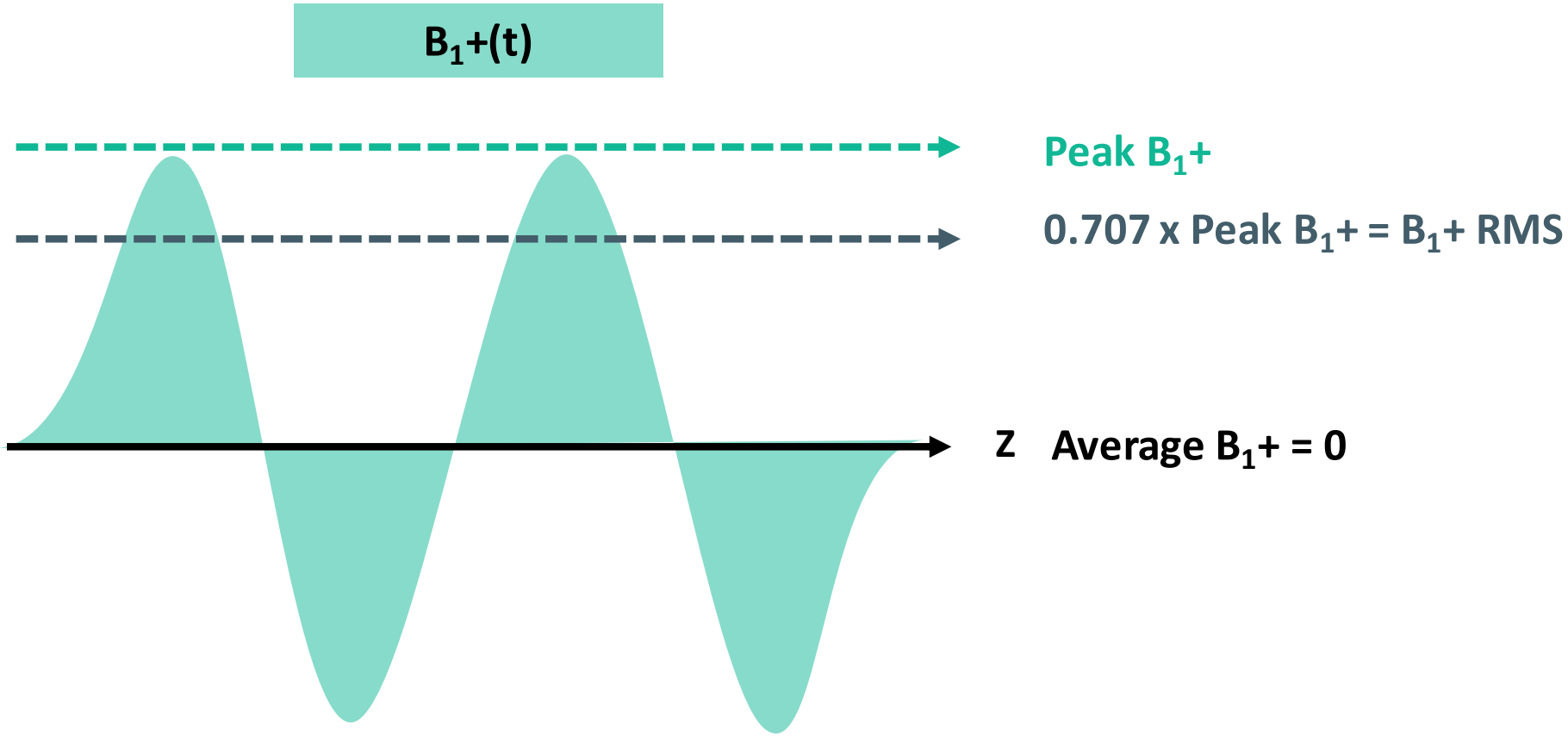
- B_1 can be decomposed into two components: a component rotating in the same direction as nuclear precession **(B_1+)** ↺ and a component rotating in the opposite direction **(B_1–)** ↻.



- The **B_1+ subfield** is responsible for tipping the nuclear magnetisation.
- The **B_1– subfield** and rotates opposite the spin system, generating heat via induced electrical currents but having no effect on nuclei.

Radiofrequency magnetic field (B_1)

Electromagnetic Wave (B_1)



Radiofrequency magnetic field (B_1)

B_1+ root mean square (RMS) is a newer alternative metric for measuring energy deposition. Units of **µT**

B_1+ RMS is patient **INDEPENDANT** (same protocol, same B_1+ RMS values)

- SAR is patient **DEPENDANT** (same protocol 2 different SAR values)

- B_1+RMS is the root mean square of the RF magnetic field (B_1) of a pulse sequence averaged over a pulse repetition period (TR)

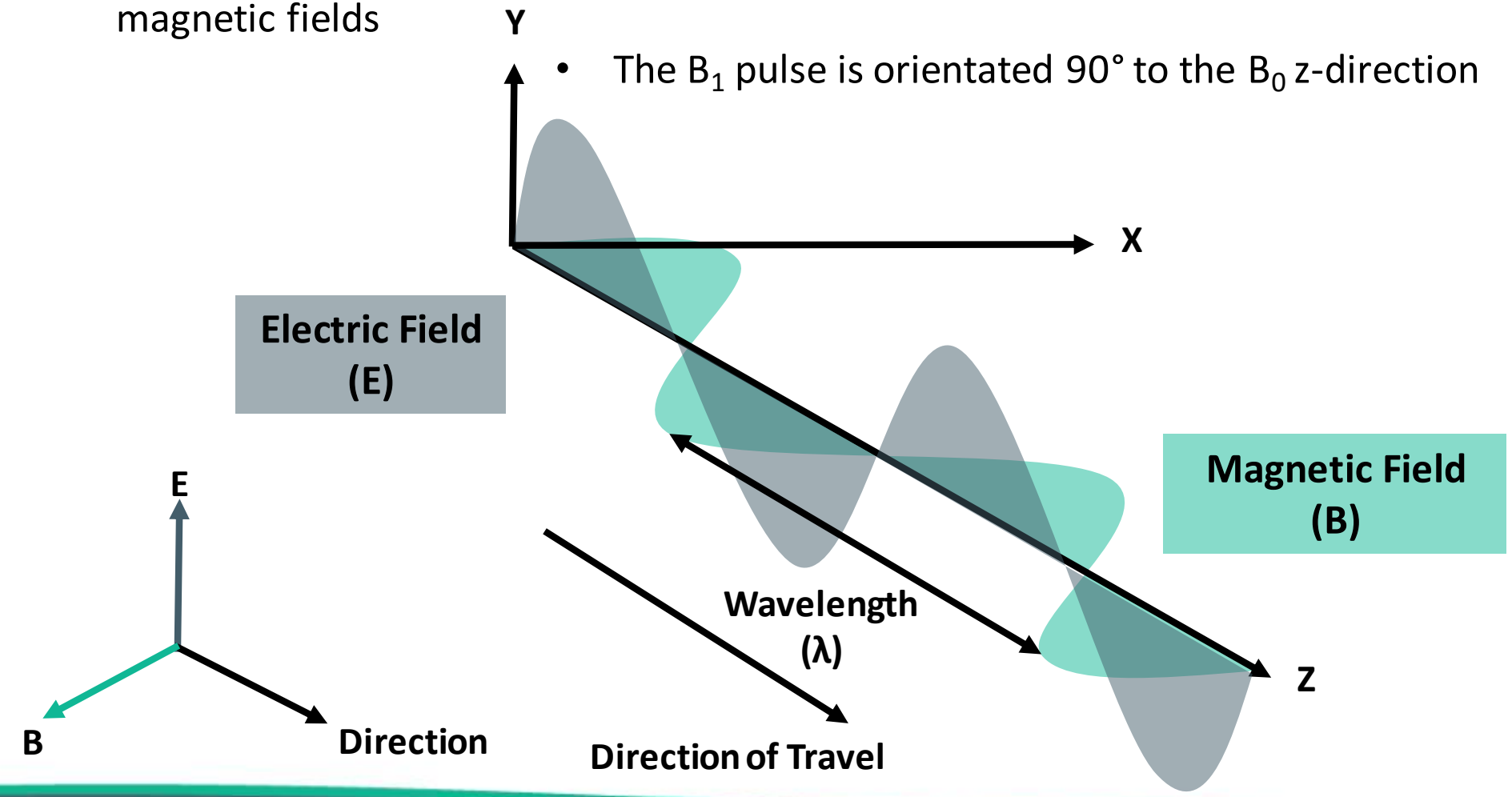
- B_1+RMS is estimated from the tip angle at the RF transmit coil centre for the B_1 component that precesses with the nucleus of interest (protons) at the start of a sequence using a standardised method

Implant Materials

- Concerning MRI safety, the “best” materials have:
  - Low magnetic susceptibility
  - Low Conductivity

Radiofrequency magnetic field (B_1)

- RF pulses in MRI refer to electromagnet waves with orthogonal eclectic and magnetic fields
  - The B_1 pulse is orientated 90° to the B_0 z-direction



Radiofrequency magnetic field (B_1)
Resonant Length ($\lambda/2$)

- Wavelength can be expressed as:

$$\lambda = c/f$$

- $c = 3x10^8$ m/s, $f = \gamma B_0$,

- This changes in a magnetic field to:

$$\lambda = c/(f\sqrt{\varepsilon_r})$$

- ε_r = relative permittivity of water/dielectric constant

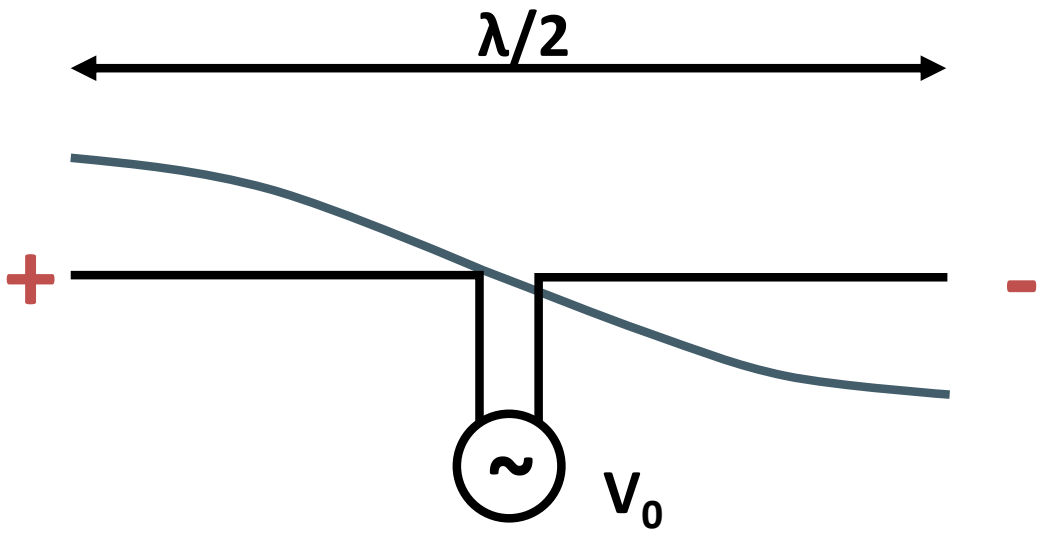
- The wavelength of B_1 changes from 4.7m in air at 1.5T to 0.51m in tissue

- Standing wave effects occur through superimposition of RF waves

- The half-wavelength of B_1 in tissue is 26cm @ 1.5T and 13cm @ 3.0T

Radiofrequency magnetic field (B_1)
RF Antenna Effect

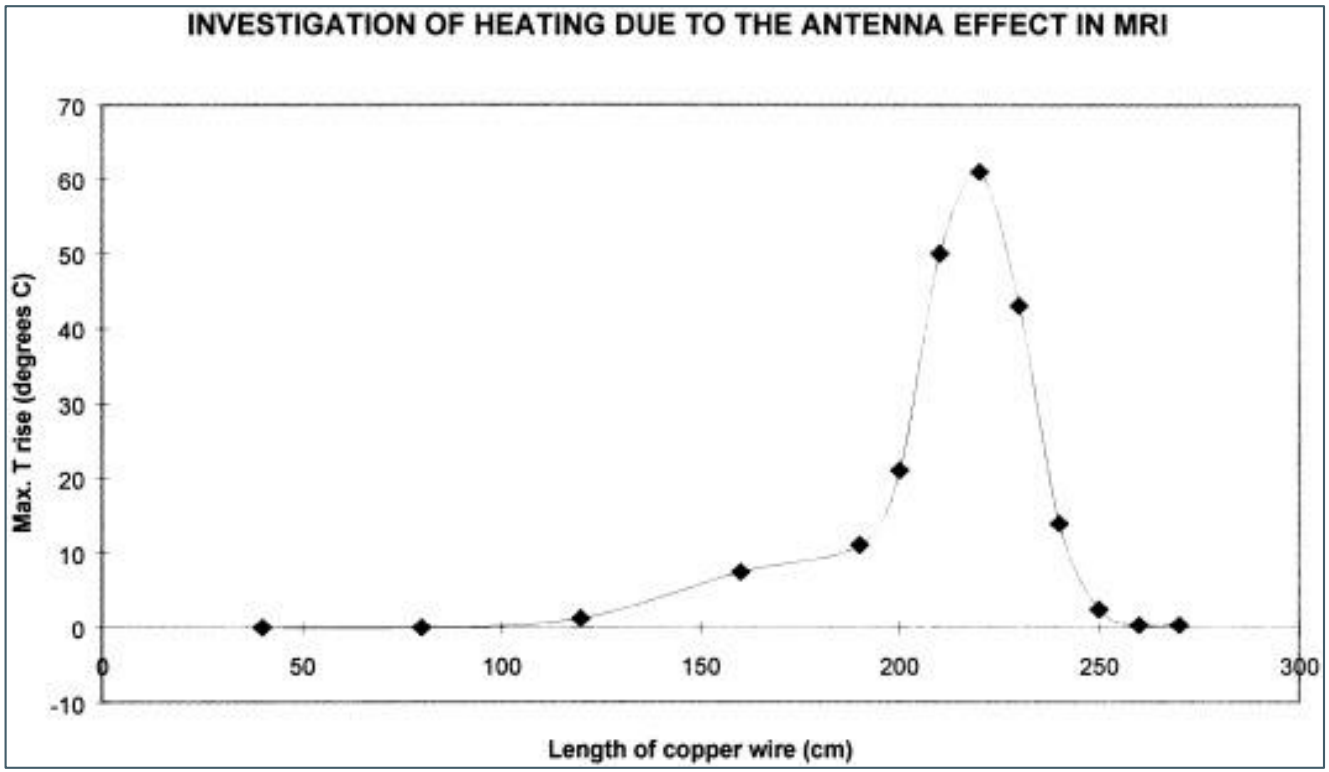
- Maximum temperature rise occurs at the end of conductors when the length of the wire/antenna is approximately equal to the half of the wavelength



Radiofrequency magnetic field (B_1)

RF Antenna Effect

Temperature at tip of wire vs. length of copper wire (1.5T)



- The largest temperature rise recorded was 63.5 ± 0.1°C at a length of 220 cm of copper wire.

https://doi.org/10.1002/jmri.1088

Implanted medical devices and other contraindications to scanning

Implantable medical devices fall into two main categories:

- **Non-active implantable medical devices (Passive).** These are passive in that they require no power source for their function. For example: hip/knee joint replacements, heart valves, aneurysm clips, coronary stents and breast implants.

- **Active implantable medical devices (Active).** These include: pacemakers, defibrillators, neurostimulators, cochlear implants and drug pumps, where functionality is dependent upon an energy source such as electrical, mechanical or pneumatic power.

- Both active and non-active implantable medical devices can contain metallic components, which may render the device incompatible with MR and therefore contraindicated by the implant manufacturer or may cause artefacts that can affect image quality.

Passive Implants

The potential sources of hazards from MRI for the patient with passive implants:

- **Movement** of the device from translation or rotation due to magnetic forces
- **Displacement** of the device arising from Lenz's Law forces
- **Heating** from the RF or imaging gradient exposures
- **Vibration** from the imaging gradient exposure
- **Induction** of electrical currents

Passive Implants

Effect on the Device	Static Magnetic Forces	Magnetic Forces due to Motion	Induction
Translation	Static field B_0 Spatial Gradient dB/dz	Lenz's Law: static field gradient dB/dz, velocity v	
Torque	Static field B_0	Lenz's Law: static field gradient dB/dz, velocity v	
Vibration	-		Gradient dB/dt
Electric Currents	-	Static field gradient dB/dz, velocity v	Gradient dB/dt RF dB/dt (frequency, B_1)
Localised Heating	-		RF dB/dt frequency amplitude duty cycle

Active Implants

The potential sources of hazards from MRI for the patient with active implants:

- Device malfunction
- Therapeutic inhibition
- Excess stimulation
- Damage to the device
- Excessive heating of lead or electrode tip
- Loss of data
- Battery depletion
- All of the hazards associated with passive implants

Active Implants

Static Magnetic Forces

- The major source of risk from B_0 is for devices which utilise “reed” switches as these are manufactured from soft ferromagnetic nickel-iron alloys which can become magnetised

- The manner in which reed switches behave in a magnetic field is dependant on direction meaning their behaviour is unpredictable in MRI

- For 162 different pacemaker models implanted prior to 1998, reed switch activation occurred between 0.7 and 6.0 mT

10.1016/j.eupc.2005.02.120

Active Implants

Induction from RF (B_1)

- B_1 is a rapidly time-varying magnetic field and so will induce electric fields and current density in objects

- A “wave-like” behaviour and **antenna effect** of conductors whose length is similar to the half-wavelength of tissue

- Pacemaker and ICD leads have shown increases between 3-63°C in animal models after 75 seconds of scanning at 1.5T leading to necrosis around the lead tip

10.1016/s0002-8703(97)70083-8

Summary

Component	Mechanism	Adverse Effect
Static magnetic field (B_0)	Motion induced currents in tissues	Vertigo, metallic taste
	Attractive / torque forces	Projectile Tissue damage
	Interactions with implanted / peripheral devices	Device malfunction / damage
Time varying magnetic fields (dB/dt)	Induced currents in tissues	PNS
	Inducted currents and vibrations in implants	Device malfunction / damage
	Lorentz forces	Acoustic noise
Radiofrequency magnetic field (B_1)	RF induced currents in tissue	Heat
	RF induced currents in equipment	Burns
	RF interference	Device malfunction / damage

Quench

- If any part of the windings ceases to be superconducting, electrical energy will be dissipated as heat in the surrounding regions of the magnet
- Quenches can be manually initiated (risk to life/serious harm) or spontaneous
- A quench will in general be accompanied by a loud bang and the emission of large quantities of cold gas
- In the event of a quench, low temperature liquefied gases, designed to keep the magnet close to **absolute zero (-273°C)** expand and boil off to the outside
- In order to detect any unplanned leakage of helium into the scanner room, suitable low oxygen warning alarms should be placed in the MR room and be regularly checked and maintained

Quench

- If the gases should enter the room instead of exiting to the outside, there will be the hazard of asphyxiation owing to the **displacement of oxygen**, **hypothermia** and **frostbite**.

- If there is inadequate venting, cold gas may spread through the patient area. It will form a white fog that eventually clings to the ceiling.

- There may also be over pressurisation in the room due to the rapid expansion of the liquid gas and this may make it difficult to enter the MR room.

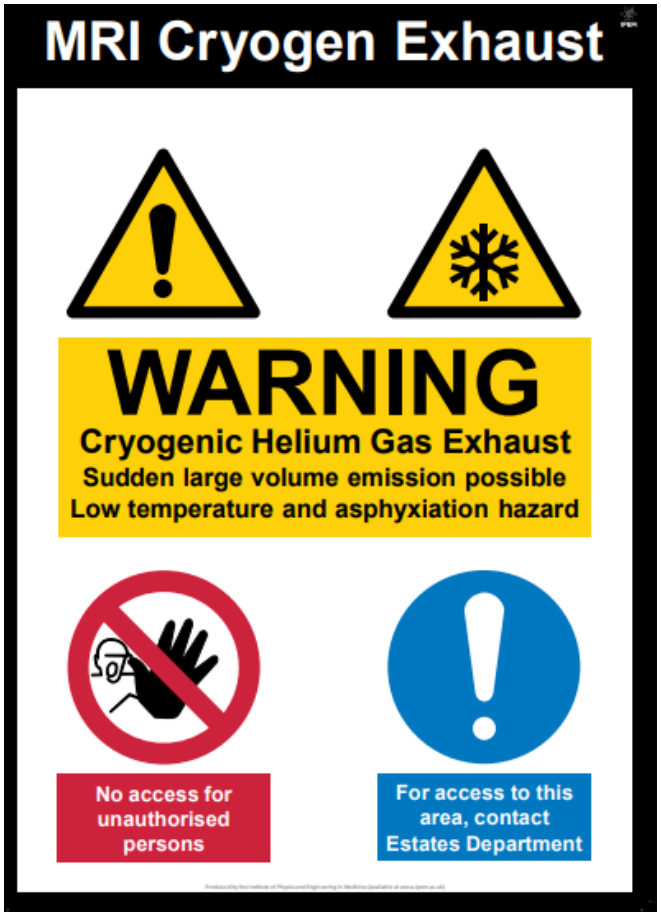
- A minimum three metre exclusion zone is recommended for the quench vent exhaust

Quench

- Controlled/deliberate quenches are necessary if patient is at risk
- 'Ramp Down' the magnet
- Controlled quench prevents damage to the magnet
- Quenching has the potential to be very costly!

Safety issues, particularly with regards to implanted devices and emergency situations

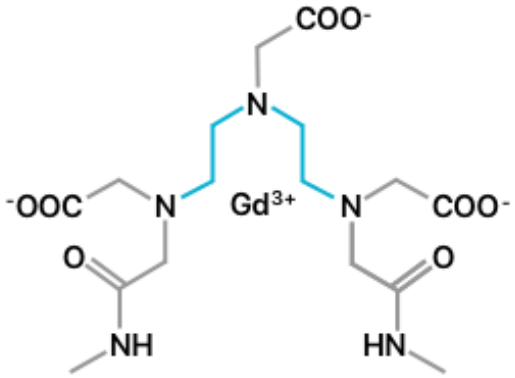
Hull University Teaching Hospitals NHS Trust

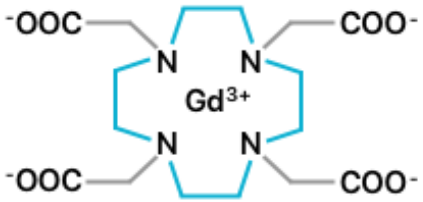


A minimum three metre exclusion zone is recommended for the quench vent exhaust [116]. Specific requirements should be obtained from the manufacturer.

Linear vs Macrocyclic

- There are 2 structurally distinct categories of commercially available GBCAs:
  - linear ("open chain")
  - macrocyclic
- In the macrocyclic structure, the gadolinium ion is "caged" in the preorganized cavity of the ligand
- The rates of dissociation of gadolinium from macrocyclic ligands are slower than dissociation from linear ligands and are thus considered to be the most "stable"





Linear Agents

Linear agents do not fully surround the gadolinium (Gd) ions.

Macrocyclic Agents

Macrocyclic molecules fully enclose gadolinium (Gd) ions with nitrogen (N).

https://www.drugwatch.com/gadolinium/side-effects/

Ionic vs Nonionic

- GBCAs are either **nonionic** (where the number of carboxyl groups is reduced to 3 and neutralizes the 3 positive charges of Gd^{3+}) or **ionic** (where the remaining carboxyl groups are salified with sodium or meglumine)

- The primary difference is that an ionic compound dissociates or dissolves into charged particles when it enters a solution such as blood

- Nonionic contrast media does not dissolve into charged particles when in a solution and have a lower viscosity and osmolality (a measure of the number of molecules and particles in a solution per kilogram of water)

- With nonionic agents, the absence of charged particles means there may be less potential to disrupt the electrical charges associated in brain and heart

- In practice, serious adverse events from extravasation or physiologic effects on the heart or brain with any GBCA are exceedingly rare

https://www.medscape.org/viewarticle/780675_4

Safety issues associated with gadolinium-based contrast agents

Type	Agent	Dissociation half-life
Linear non-ionic	Ominscan	<5s
	Optimark	<5s
Linear ionic	Magnevist	<5s
	Primovist	<5s
	MultiHance	<5s
Macrocyclic non-ionic	Prohance	3.9 hr
	Gadovist	4.3hr
Macrocyclic ionic	Dotarem	338 hr

Nephrogenic systemic fibrosis

- The 2015 MHRA risk classification is as follows:

- **High risk**—Omniscan (gadodiamide) *Linear nonionic*, OptiMARK (gadoversetamide) *Linear nonionic*, Magnevist (gadopentetic acid) *Linear ionic*

- **Medium risk**—MultiHance (gadobenic acid) *Linear ionic*, Primovist (gadoxetic acid) *Linear ionic*, Vasovist (gadofosveset) *Linear ionic*

- **Low risk**—Gadovist (gadobutrol) *Macrocyclic nonionic*, ProHance (gadoteridol) *Macrocyclic nonionic*, Dotarem (gadoteric acid) *Macrocyclic ionic*

- The rate of dissociation of gadolinium from macrocyclic ligands is slower than linear ligands and thus considered more stable

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European Medicines Agency 2017

Product	Type (formulation)	Recommendation
Artirem / Dotarem (*gadoteric acid*)	macrocyclic (i.v.)	maintain
Artirem / Dotarem (*gadoteric acid*)	macrocyclic (intra-articular)	maintain
Gadovist (*gadobutrol*)	macrocyclic (i.v.)	maintain
Magnevist (*gadopentetic acid*)	linear (intra-articular)	maintain
Magnevist (*gadopentetic acid*)	linear (i.v.)	suspend
Multihance (*gadobenic acid*)	linear (i.v.)	restrict use to liver scans
Omniscan (*gadodiamide*)	linear (i.v.)	suspend
Optimark (*gadoversetamide*)	linear (i.v.)	suspend
Primovist (*gadoxetic acid*)	linear (i.v.)	maintain
Prohance (*gadoteridol*)	macrocyclic (i.v.)	maintain

In Hull 3 gadolinium based contrast agents (GBCA) in use:

- Gadoteric acid 0.5mmol/ml (**Clariscan**) – New to market
  - Standard contrast agent
- Gadobutrol 1mmol/ml (**Gadovist**)
  - Vascular/Cardiac contrast agent
- Gadoxetic acid, disodium 0.5mmol/ml (**Primovist**)
  - Liver characterisation contrast agent
- Normally administered under Patient Group Directive (PGD) by an MR Radiographer
- Radiographers cannot administer GBCA to **paediatric patients**
  - Normally **Radiologist** or **Anaesthetist**

Gadoteric acid 0.5mmol/ml (Clariscan)

- A **macrocyclic** and **ionic** GBCA
- 1 mL solution for injection contains 279.3 mg gadoteric acid (as gadoterate meglumine) equivalent to 0.5 mmol
- **Gadoterate meglumine** has a cage-like structure which encloses the Gd^{3+} ion.
- *In vitro* data suggest that combining a macrocyclic structure for high kinetic stability, with ionicity for thermodynamic stability, may help to reduce the potential risk of gadolinium dissociation.
- The recommended dose is 0.1 mmol/kg BW, i.e. **0.2 mL/kg BW**

Gadobutrol 1.0 mmol/ml (Gadovist)

- A **macrocyclic** and **nonionic** GBCA
- 1 ml of solution for injection contains 604.72 mg gadobutrol (equivalent to 1.0 mmol gadobutrol containing 157.25 mg gadolinium).
- The recommended dose for adults is 0.1 mmol per kilogram body weight (mmol/kg BW). This is equivalent to **0.1 ml/kg BW** of the 1.0 M solution.
- If a strong clinical suspicion of a lesion persists despite an unremarkable MRI or when more accurate information might influence therapy of the patient, a further injection of up to 0.2 ml/kg BW within 30 minutes of the first injection

https://www.medicines.org.uk/emc/medicine/15927/SPC#gref

Gadoxetic acid, disodium 0.25 mmol/ml (Primovist)

- A **linear** and **ionic** GBCA
- Each ml contains 0.25 mmol gadoxetate disodium (Gd-EOB-DTPA disodium), equivalent to 181.43 mg gadoxetate disodium
- Primovist is indicated for the detection of focal liver lesions and provides information on the character of lesions in T1-weighted magnetic resonance imaging (MRI)
- Primovist should be used only when diagnostic information is essential and not available with unenhanced magnetic resonance imaging (MRI) and when delayed phase imaging is required
- The recommended dose is 0.25 mmol/kg BW, i.e. **0.1 mL/kg BW**

Safety issues associated with gadolinium-based contrast agents

Type	Agent	Molecular Weight (g/mol)	Osmolality (mosm /kg)	Viscosity (mPa/s)	Clearance $t_{1/2}$ (hr)
Linear non-ionic	Ominscan	591.7	789	1.4	1.3
	Optimark	661.8	1110	2.0	-
Linear ionic	Magnevist	938.0	1960	2.9	1.6
	Primovist	684.8	688	1.2	0.93
	MultiHance	1058.1	1970	5.3	1.6
Macrocyclic non-ionic	Prohance	558.7	630	1.3	1.57
	Gadovist	604.7	1603	5.0	1.81
Macrocyclic ionic	Dotarem	753.9	1350	2.0	1.6

Nephrogenic systemic fibrosis (NSF)

- NSF is a serious and life-threatening condition characterised by the formation of connective tissue in the skin which becomes thickened, coarse, and hard, sometimes leading to contractures and joint immobility.

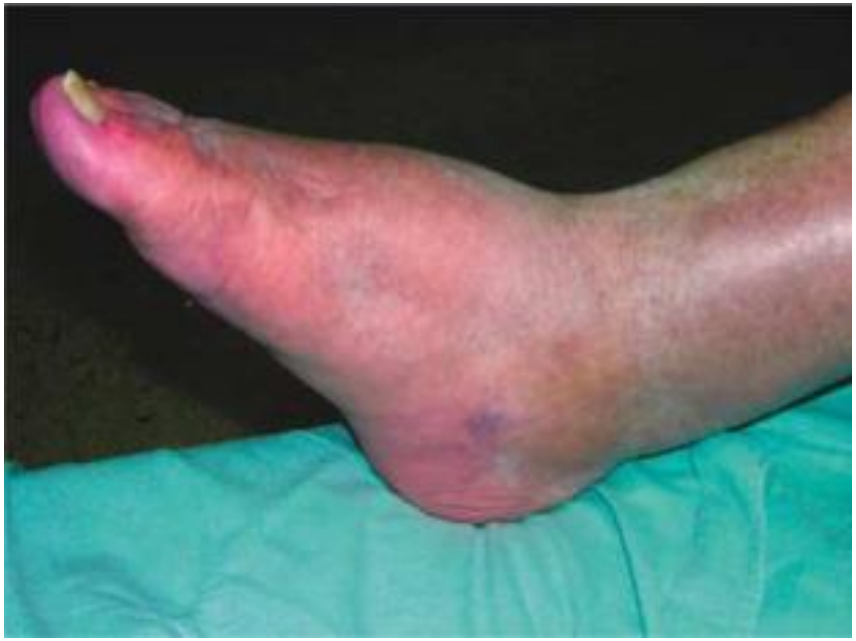
- Patients with NSF can have systemic involvement of other organs including the lungs, liver, muscles, and heart.

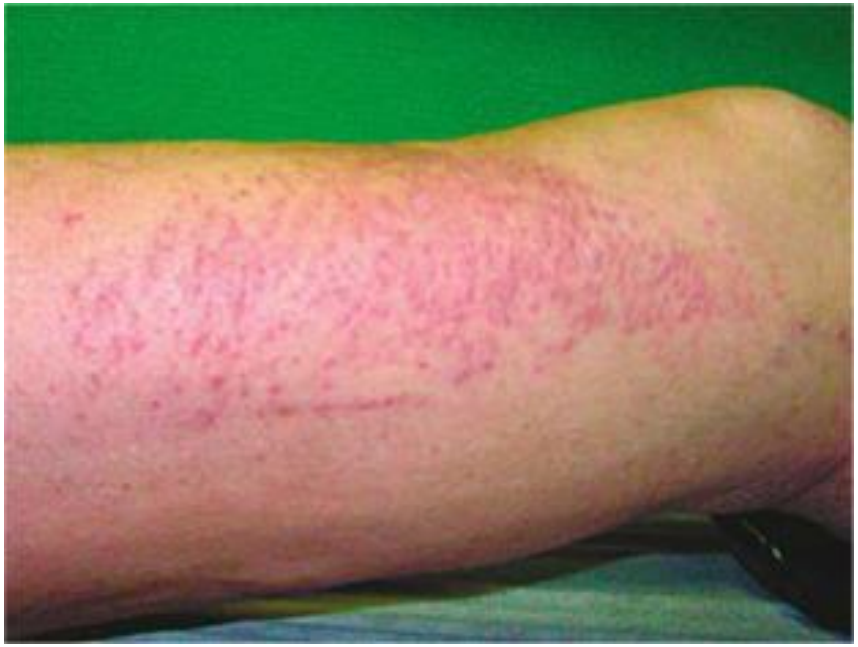
- Link to gadolinium based contrast agents discovered around year 2000
  - Gadodiamide (Omniscan®) *Linear non-ionic*

  - Today, NSF is unlikely to be seen due to safer GBCA

- Nine gadolinium-containing contrast agents are authorised in the EU to aid MRI of the body and of the blood vessels (magnetic resonance angiography, MRA)

Nephrogenic systemic fibrosis (NSF)





NHS
Hull University Teaching Hospitals
NHS Trust

Nephrogenic systemic fibrosis (NSF)

Forbes

FDA Requires New Warning On MRI 'Dyes' That Chuck Norris Says Poisoned His Wife

Last month, the couple filed a lawsuit in San Francisco Superior Court alleging that Gena Norris had been poisoned by GBCAs she had received ...

26 Dec 2017

Radiology Business

Chuck Norris voluntarily abandons poisoning lawsuit against ...

Actor Chuck Norris and his wife, Gena, have decided to vacate their lawsuit against gadolinium maker Bracco Imaging without any settlement, ...

17 Jan 2020

Gadolinium deposition disease

Original Research
Neuroradiology

Free Access

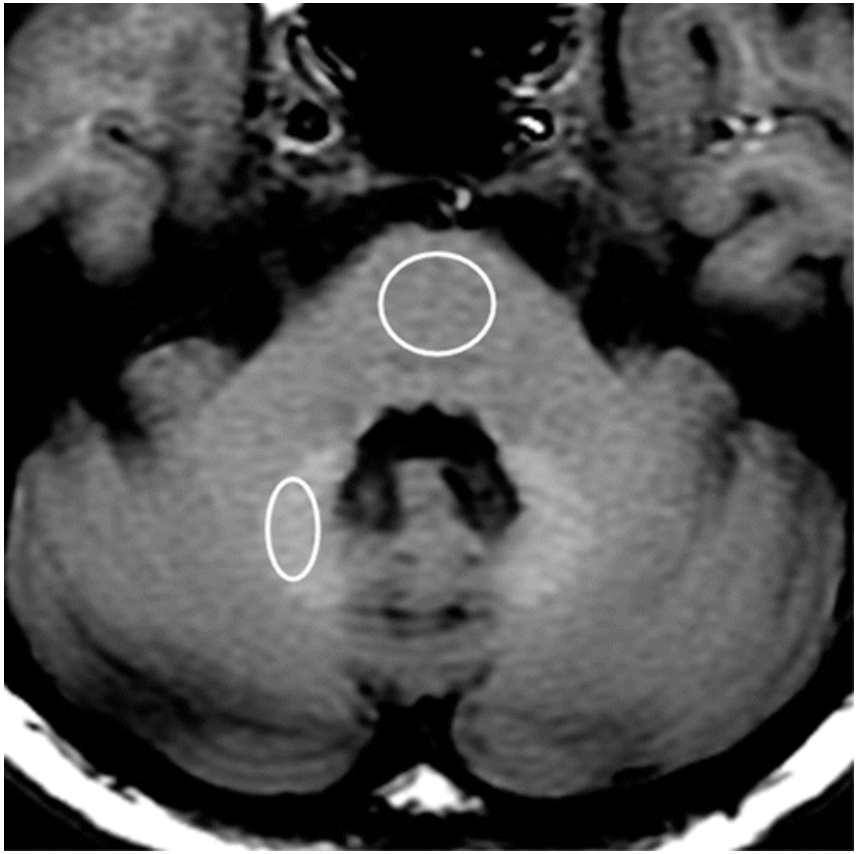
High Signal Intensity in the Dentate Nucleus and Globus Pallidus on Unenhanced T1-weighted MR Images: Relationship with Increasing Cumulative Dose of a Gadolinium-based Contrast Material

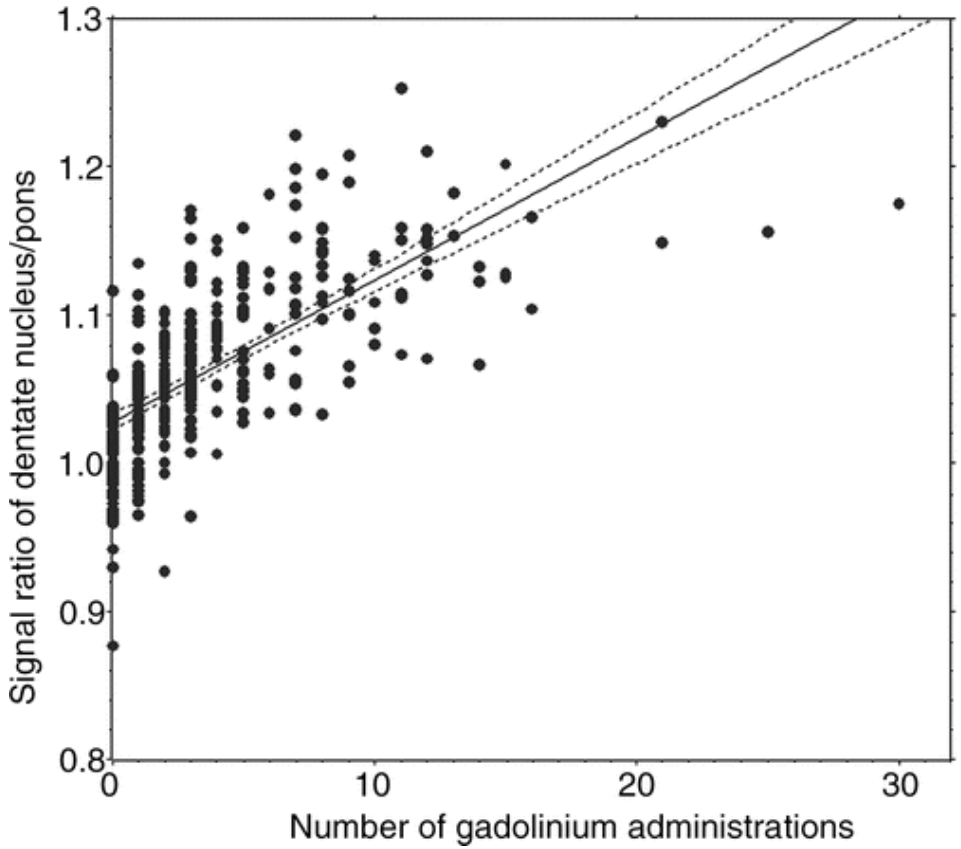
Tomonori Kanda, Kazunari Ishii, Hiroki Kawaguchi, Kazuhiro Kitajima, Daisuke Takenaka

Author Affiliations

Published Online: Dec 7 2013 | https://doi.org/10.1148/radiol.13131669

Gadolinium deposition disease





Gadolinium deposition disease

Magn Reson Imaging. 2016 Dec;34(10):1383-1390. doi: 10.1016/j.mri.2016.07.016. Epub 2016 Aug 13.

Gadolinium deposition disease: Initial description of a disease that has been around for a while

Richard C Semelka [1], Joana Ramalho [2], Ami Vakharia [3], Mamdoh AlObaidy [4], Lauren M Burke [3], Michael Jay [5], Miguel Ramalho [6]

Affiliations + expand

PMID: 27530966 DOI: 10.1016/j.mri.2016.07.016

Gadolinium deposition disease

ORIGINAL ARTICLE

Gadolinium-Based MRI Contrast Agents Induce Mitochondrial Toxicity and Cell Death in Human Neurons, and Toxicity Increases With Reduced Kinetic Stability of the Agent

Bower, Danielle V. MD, PhD[*,†]; Richter, Johannes K. MD[*]; von Tengg-Kobligk, Hendrik MD[*,†]; Heverhagen, Johannes T. MD, PhD[*,†]; Runge, Val M. MD[*,†]

Author Information

Investigative Radiology: August 2019 - Volume 54 - Issue 8 - p 453-463
doi: 10.1097/RLI.0000000000000567

Gadolinium deposition disease

Review > Clin Toxicol (Phila). 2020 Mar;58(3):151-160. doi: 10.1080/15563650.2019.1681442. Epub 2019 Oct 30.

Gadolinium-based contrast agents – what is the evidence for 'gadolinium deposition disease' and the use of chelation therapy?

Kerry A Layne [1 2 3], David M Wood [1 2 3], Paul I Dargan [1 2 3]

- "There is currently no published information from well-designed clinical studies that support a link between gadolinium deposition and the development of clinical sequelae in patients with normal renal function."

- "Clinicians should exercise caution when considering whether or not gadolinium is of relevance in patients reporting symptoms after administration of gadolinium-based contrast agents."

Gadolinium deposition disease

Gadolinium Tissue Distribution in a Large-Animal Model after a Single Dose of Gadolinium-based Contrast Agents

Henning Richter*, Patrick Bücker*, Louise Françoise Martin, Calvin Dunker, Stefanie Fingerhut, Anna Xia, Agnieszka Karol, Michael Sperling, Uwe Karst, ... Show all authors

* H.R. and P.B. contributed equally to this work.

Author Affiliations

Published Online: Sep 21 2021 | https://doi.org/10.1148/radiol.2021210553

At 10 weeks after injection, linear GBCAs resulted in highest mean gadolinium concentrations in the kidney (502 ng/g [95% CI: 270, 734]) and liver (445 ng/g [95% CI: 202, 687]), while low concentrations were found in the deep cerebellar nuclei (DCN) (30 ng/g [95% CI: 20, 41]). Tissue concentrations of linear GBCAs were three to 21 times higher compared with those of macrocyclic GBCAs. Administered macrocyclic

Ten weeks after one injection of a clinically relevant dose of gadolinium-based contrast agents, the liver and kidney appeared to be reservoirs of gadolinium; however, despite gadolinium presence, no tissue injury was detected.

Safety issues associated with gadolinium-based contrast agents

Hull University Teaching Hospitals NHS Trust

Screening

Are you allergic to anything? Do you suffer from hay fever?			
Do you have asthma that is not well controlled?			
Do you have any kidney problems?			
Are you waiting for a liver transplant?			

- All relate to the use of gadolinium based contrast agents (GBCA)

Advice for healthcare professionals

The following risk-minimisation measures should be used for gadolinium-containing contrast agents for:

- **Renal-function monitoring** - this should be tested in all patients receiving high-risk agents, and is advisable for patients receiving medium-risk or low-risk agents. Important to screen patients aged 65 years or older

- **Renal Impairment** - for patients with severe renal impairment (glomerular filtration rate [GFR] <30 mL/min/1·73m^2), use of a high-risk agent is contraindicated

- If use of a medium-risk agent cannot be avoided or if it is necessary to use a low-risk agent, a single lowest dose possible can be used and should not be repeated for at least 7 days. For patients with moderate renal impairment (GFR 30–59 mL/min/1·73 m^2), if it is necessary to use a high-risk agent a single lowest dose possible can be used and should not be repeated for at least 7 days

https://www.gov.uk/government/publications/safety-guidelines-for-magnetic-resonance-imaging-equipment-in-clinical-use

Advice for healthcare professionals

- **Perioperative Liver-Transplantation Period** - use of a high-risk agent is contraindicated. If use of a medium-risk agent cannot be avoided or if it is necessary to use a low-risk agent, a single lowest dose possible can be used and should not be repeated for at least 7 days neonates - use of a high-risk agent is contraindicated. For medium-risk or low-risk agents, use a single lowest possible dose and do not repeat for at least 7 days

- **Infants** - use a single lowest dose of agent possible and do not repeat for at least 7 days

- **Breastfeeding** - discontinue for at least 24 hours after use of a high-risk agent

- The decision of whether to continue or suspend breastfeeding for 24 hours after use of a medium-risk or low-risk agent should be at your discretion in consultation with the mother

https://www.gov.uk/government/publications/safety-guidelines-for-magnetic-resonance-imaging-equipment-in-clinical-use

Advice for healthcare professionals

- **Pregnancy** - use of any gadolinium-containing contrast agent is not recommended unless absolutely necessary

- **Haemodialysis** - there is no evidence to support the initiation of haemodialysis for prevention or treatment of NSF in patients not already undergoing haemodialysis

- **Recording of the Agent Used** - when they become available, peel-off tracking labels found on the vials, syringes, or bottles should be stuck onto the patient record to accurately record the name of the gadolinium contrast agent used. The dose used should also be recorded reporting of suspected adverse reactions - on a Yellow Card for any suspected adverse reactions, including NSF, to gadolinium-containing contrast agents

https://www.gov.uk/government/publications/safety-guidelines-for-magnetic-resonance-imaging-equipment-in-clinical-use

2019 ESUR Guidelines V10.0

B.8. HOW LONG SHOULD THERE BE BETWEEN TWO GADOLINIUM-BASED CONTRAST AGENT INJECTIONS FOR ROUTINE EXAMINATIONS?

1. **Patients with normal or moderately reduced renal function (GFR > 30 ml/min/1.73 m²).**
   75 % of extracellular gadolinium-based contrast agents are excreted by 4 hours after administration.
   There should be 4 hours between injections of gadolinium-based contrast agent.
2. **Patients with severely reduced renal function (GFR < 30 ml/min/1.73 m²) or on dialysis.**
   There should be 7 days between injections of gadolinium-based contrast agent

B.6. CAN IODINE- AND GADOLINIUM-BASED CONTRAST AGENTS SAFELY BE GIVEN ON THE SAME DAY FOR ROUTINE EXAMINATIONS?

Efficient practice may involve giving iodine- and gadolinium-based contrast agents for enhanced CT and MR on the same day.
To reduce any potential for nephrotoxicity the following are recommended:

1. **Patients with normal renal function or moderately reduced (GFR > 30 ml/min/1.73 m²).**
   75 % of both gadolinium- and iodine-based contrast agents are excreted by 4 hours after administration. There should be 4 hours between injections of iodine- and gadolinium-based contrast agents.
2. **Patients with severely reduced renal function (GFR < 30 ml/min/1.73 m² or on dialysis).**
   There should be 7 days between injections of iodine- and gadolinium-based contrast agents.

Note: *Gadolinium-based contrast agents attenuate X-rays well and may be misinterpreted on CT when they have been excreted into the urinary tract. For abdominal examinations, enhanced CT should be done before enhanced MR. For chest and brain examinations, either CT or MR may be done first.*

Recommendations for scanning patients with implanted devices without the manufacturer's approval, e.g. 'off label'

4.11.4 Scanning patients with implants where MRI may be contraindicated

There may be a need to perform an MR examination in the following scenarios:

- the patient has a **MR CONDITIONAL** device but the manufacturer's guidance cannot be met,
- the patient has an implanted device whose compatibility is unknown, e.g. MR UNLABELLED,
- the patient is implanted with a device known to be **MR UNSAFE**.

If the **benefit to the patient outweighs the potential risk** of the procedure scanning should be undertaken provided the following are documented and available before the scan:

- A risk assessment, undertaken with the full involvement of a multidisciplinary team, including the MR RESPONSIBLE PERSON, MR SAFETY EXPERT, a radiologist (where available), a relevant specialist clinician and the referring clinician. The following should be considered:
  - Consideration of alternative imaging modalities
  - Consideration of scanning on a MRI scanner with a lower static and/or gradient fields, which may require referral to other centres if not available locally.
  - Advice from the implant manufacturer.
  - Available Professional Body recommendations
  - Published evidence of scanning the device
  - Available data about the device
  - Assessment of possible artefacts
  - MRI device parameters.

Recommendations for scanning patients with implanted devices without the manufacturer's approval, e.g. 'off label'

- Identification and implementation of appropriate precautions to minimize the risk.
  - Appropriate programming of the device
  - Suitable monitoring (e.g. SAR levels, physiological signals) during the scan. Physiological monitoring may require additional suitably trained personnel to operate and/or interpret the results.
  - SAR exposure including consideration of methods to reduce it, e.g. reduced flip angles, longer TRs, use of transmit/receive coils.
- Provision of procedures to ensure that a suitable clinician is available and in the department at the time of the scan, e.g. for cardiac devices, a cardiologist or cardiac physiologist.
- Procedures for post scan evaluation of the patient.

Patient consent should be obtained for this procedure.

An MR unit should not feel pressured into adopting the above procedure if they do not feel confident in the skills and experience available to them (e.g. mobile or stand alone units). It may be appropriate for such units to refer a particular patient to another MR facility with experience in either scanning the particular device/implant or in the general application of the above procedure.

Static fields (B_0)

- "very little is known about the effects of static magnetic fields in excess of 4 T on the growth and development of foetuses and infants, and therefore some caution may be warranted regarding their imaging **above 4 T**"

Time-varying magnetic field gradients (dB/dt)

- "There is no clear evidence that exposure to static or low frequency magnetic fields can adversely affect pregnancy outcome"

RF fields (B_1)

- "There are uncertainties concerning the effects of increased heat loads on infants and pregnant women and on people with impaired thermoregulatory ability as a result of age, disease or the use of medications. These people should be **imaged with caution**"

RF fields (continued)

- "Excessive heating is a potential teratogen; because of uncertainties in the RF dosimetry during pregnancy, it is recommended that **exposure duration should be reduced** to the minimum and that only the **normal operation level** is used"

- The 2004 ICNIRP report recommendation regarding exposure to pregnant patients is: 'There is at present insufficient knowledge to establish unequivocal guidance for the use of MRI procedures on pregnant patients. In these circumstances, it is advised that **MR procedures may be used for pregnant patients only after critical risk/benefit analysis, in particular in the first trimester**, to investigate important clinical problems or to manage potential complications for the patient or foetus.''

RF fields (continued)

- "The instructions for use shall describe that scanning of pregnant PATIENTS with the **WHOLE BODY RF TRANSMIT COIL** should be limited to the **NORMAL OPERATING MODE** with respect to the SAR level"

Table 10 Basic restrictions of maximum temperature for the body

Mode	Head	Fetus	Trunk	Limbs
NORMAL MODE	38°C	38°C*	39°C	40°C
CONTROLLED MODE	38°C	38°C*	39°C	40°C
RESEARCH / EXPERIMENTAL MODE	>38°C	-	>39°C	>40°C
HPA upper limit	39°C		40°C	41°C

* only ICNIRP has a specific limit for the fetus

The foetus and noise exposure

- "Reeves *et al* looked at this issue in 2010 found 'no significant excess risk of neonatal hearing impairment after exposure of the foetus to 1.5 T MR imaging during the second and third trimesters of pregnancy"

Pregnant patients conclusion

- The MHRA recommends that pregnant patients be scanned in **NORMAL MODE** whenever possible.

- If there is a need to scan in CONTROLLED MODE the decision to do so should be based on the information above about **risks weighed against the clinical benefit** to the patient and made at the time by the referring clinician, an MR radiologist and the patient

- Whenever the decision to proceed with the examination is taken, the scan should be carried out using a sequence that finds an optimal solution of minimising the RF and noise exposure.

Pregnant staff conclusion

- The MHRA recommends that throughout their pregnancy it is advisable that **staff do not remain in the scan room whilst scanning** is underway due to the concerns of acoustic noise exposure and risks to the foetus

- There is a requirement to undertake a risk assessment relating to the hazards caused by physical agents. In general, it is expected that the level of the time-varying electromagnetic fields, switched gradients and the radio frequency radiation will be relatively low except in the immediate vicinity of the scanning aperture. This may be of concern in the interventional situation

- The level of the static magnetic field exposure is dependent on the field strength and shielding incorporated into the design of the magnet

Reducing Heat Effects

- Fetal and/or abdominal imaging normally utilises high SAR sequences (single-shot FSE or balanced steady state gradient echo)
- Limit SAR by staying in normal controlled level (2 W/kg)
- Minimal sequences
- Maximise mother's heat loss – no blanket, high fans
- Distribute high SAR sequences throughout study
- If foetus is away from the isocentre, heating is *probably* decrease

Gadolinium based contrast agents (GBCA)

Breastfeeding

• Discontinue for at least 24 hours after use of a high-risk agent. The decision of whether to continue or suspend breastfeeding for 24 hours after use of a medium-risk or low-risk agent should be at your discretion in consultation with the mother

Pregnancy

• Use of any gadolinium-containing contrast agent is not recommended unless absolutely necessary

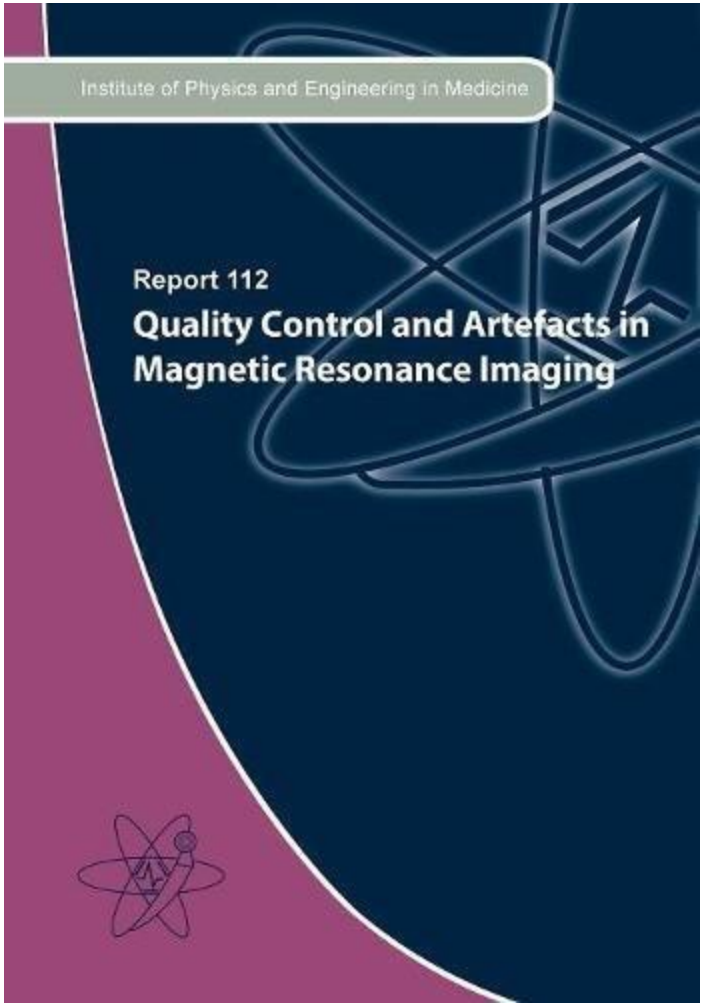
- Patient specific risk assessment must be performed
- Can an alternative MR technique or modality be performed?
- Risk of stillbirth or miscarriage appears to increase using GBCA

Why Test?

- Acceptance Testing
- Sequence Evaluation
- Scanner Evaluation
- Preventative Actions

Quality Assurance (QA) is the overarching system or process to ensure the ongoing delivery, maintenance and improvement in the quality of a service or produce

Quality Control (QC) details the technical procedures and measurements required to demonstrate compliance with standards or specifications.



Acceptance Testing

Opportunity to confirm that the equipment installed is operating in a clinically acceptable manner and to provide a baseline for QA programmes.

Typical tests could include:

- Signal to Noise Ratio (SNR)
- Image uniformity
- Spatial resolution
- Geometric distortion
- Slice thickness and position
- Artefacts (ghosting, RF, tissue-suppression)
- Tissue relaxation measurements
- Specialist QC testing (fMRI, spectroscopy, diffusion, radiotherapy planning)

Non-imaging tests should include confirmatory fringe field measurements.

5.3.3 Quality assurance programme

The hospital or clinical institution should have a written policy for MRI equipment image quality testing as part of its broader quality assurance programme. This should include the monitoring of both signal and geometric parameters. MR units should not rely solely on the manufacturer's daily quality assurance (QA) programme unless they are fully aware of the tolerance levels. For more information on MR QA and training, please contact your MR SAFETY EXPERT.

An audit of all the policies and procedures used in relation to the MR service should be a regular part of the broader QA programme.

5.3.4 Test objects

All QA measurements whether at acceptance test levels or on a regular basis should be undertaken using good quality test objects. If using the manufacturer's own test objects, MR units should ensure that these are testing to a known level and that the results will allow trends to identify levels for action before image quality is compromised.

MRI Quality Assurance

NHSBSP - MRI

Hull University Teaching Hospitals NHS Trust

MRIQA - Weekly Breast Coil QA tests

RadQA MRI NHSBSP

NHS Hull University Teaching Hospitals NHS Trust

HRI - GE Premier 3T

Date of test: 2023-01-17 User Initials: HR

QA protocol

1) Select the folder containing the images and run the calculations:

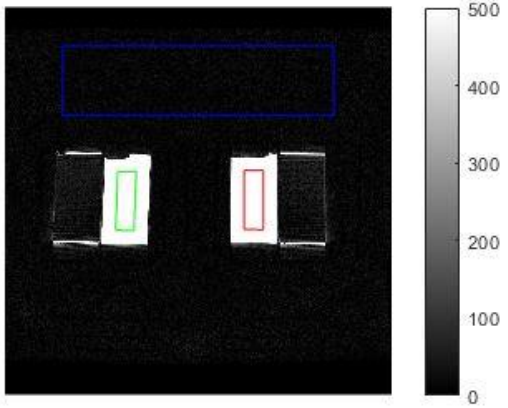
Load image datasets and run calcs...

Res...

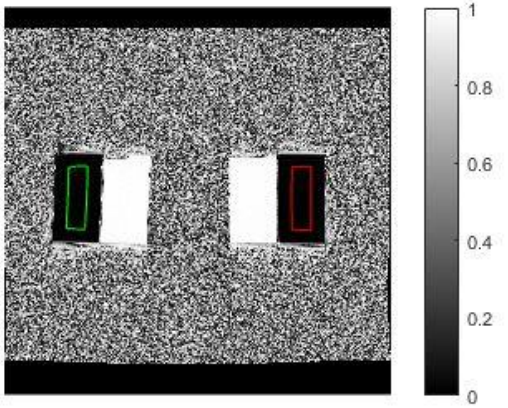
All tests PASS.

OK

Water Image - SNR Region



Water Fraction Map - Regions



Comments:

Trend analysis SNR

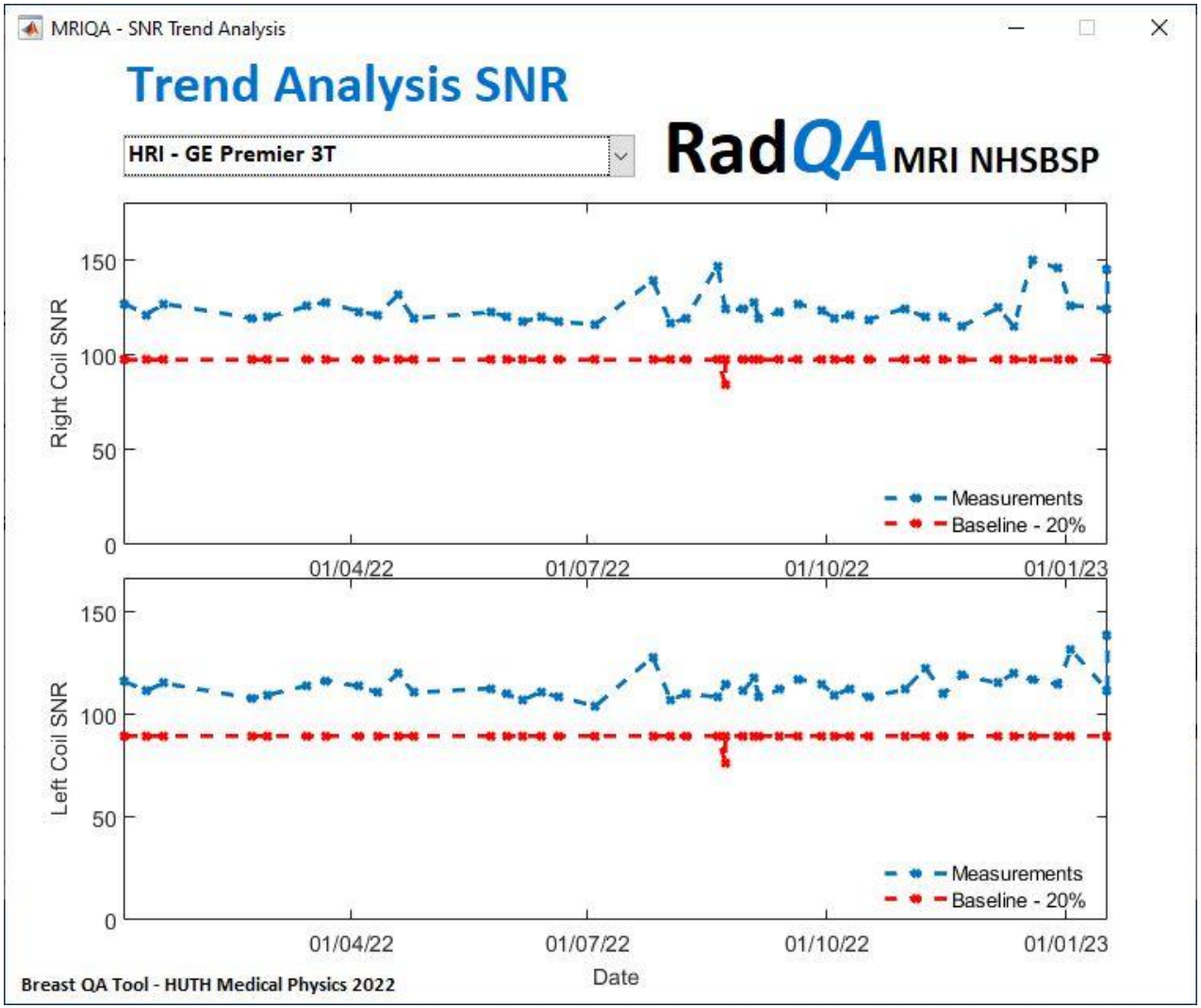
Trend analysis FATSAT

Left Phantom SNR	Right Phantom SNR	Left Phantom Fat Supression (%)	Right Phantom Fat Supression (%)
138.903	144.995	98.6081	98.7846

Pixel info: (X, Y) Pixel Value

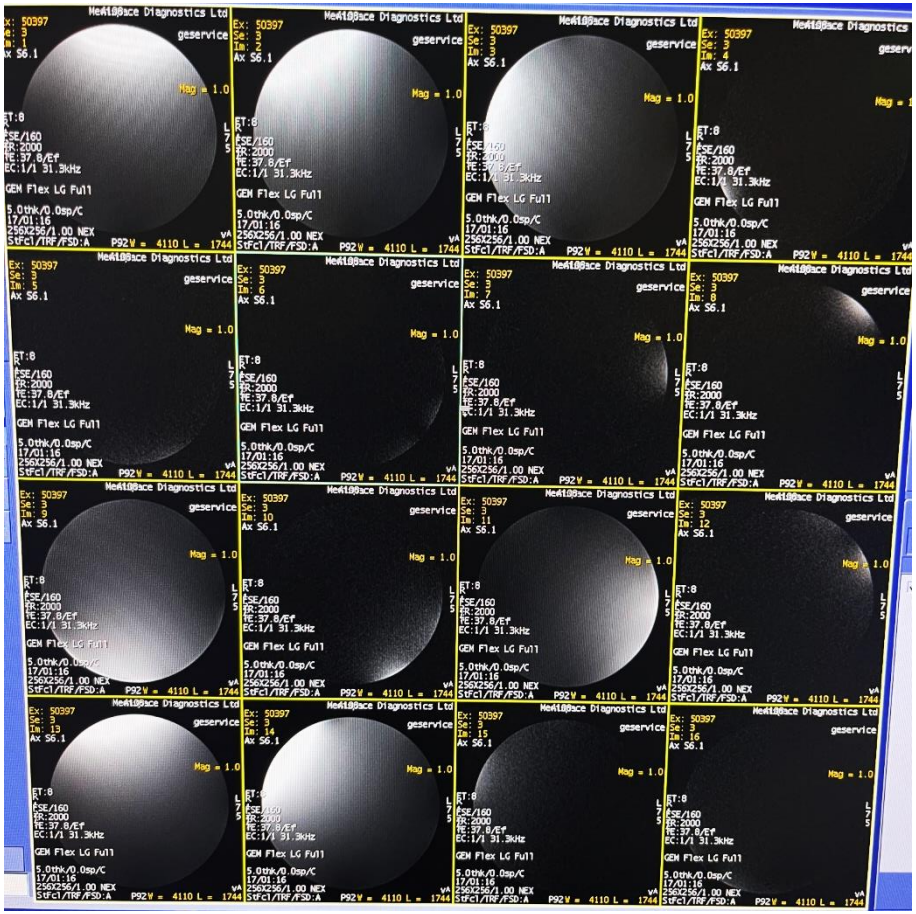
MRI Quality Assurance

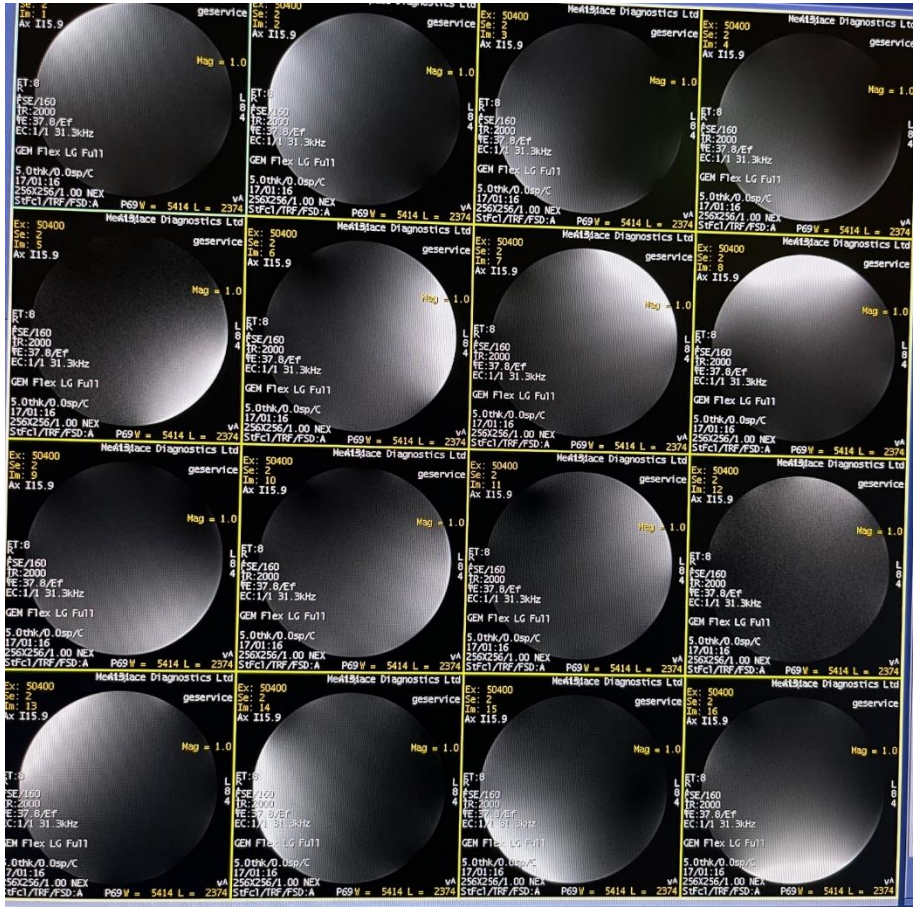
NHSBSP - MRI



MRI Quality Assurance

Coil Failure & Repair





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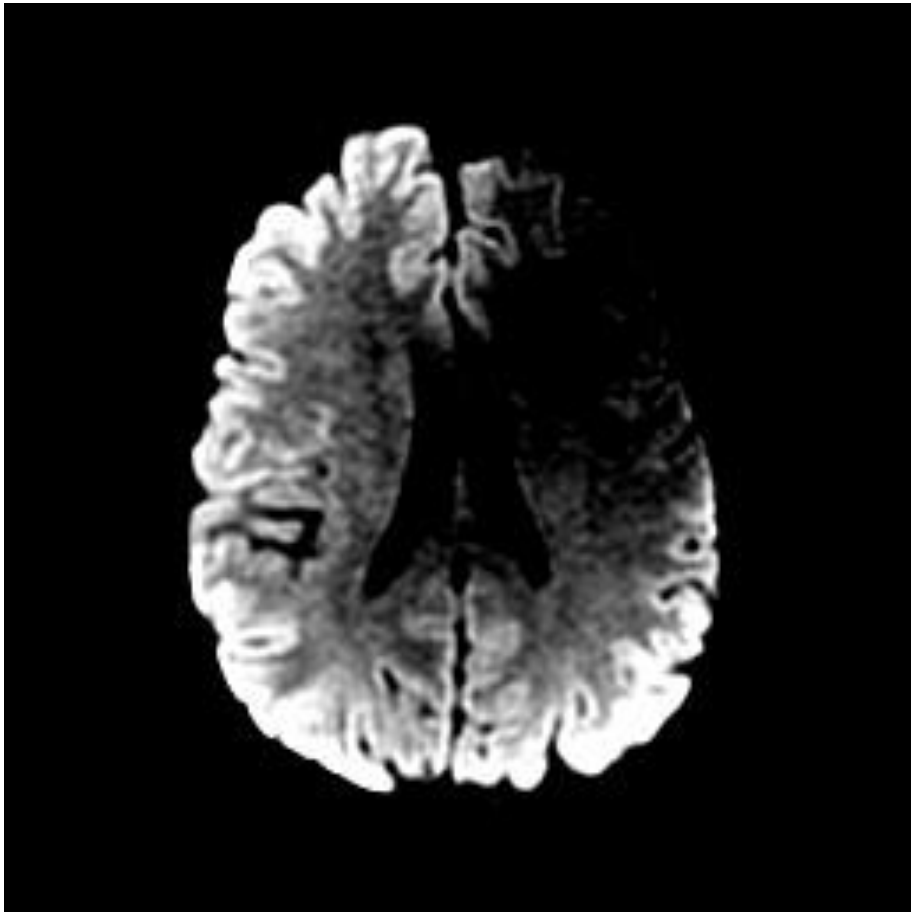
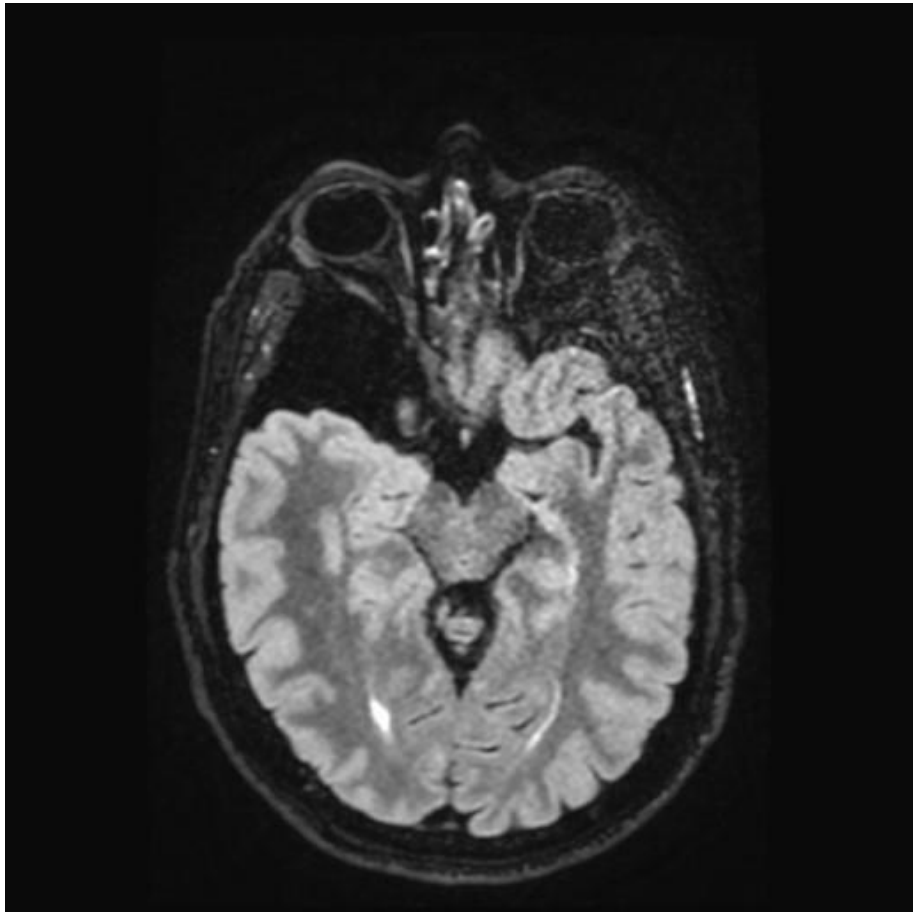
Coil Failure





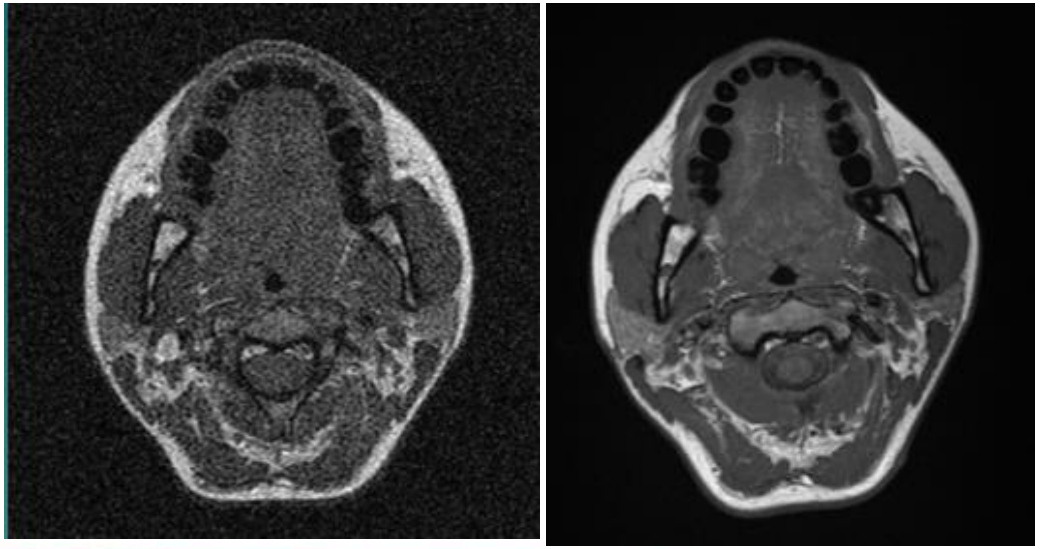
Signal to Noise Ratio (SNR)

The choice of sequence and parameters can have a major effect on the measured SNR, therefore it is necessary to use a standardised protocol for SNR measurements.

SNR measurements provide an overview of the overall system in combination with the designated RF coil (if a separate coil is used)

SNR represent a good signal measure of image quality that can be easily monitored over time.

Is a clinically relatable parameter (visual!)



Signal to Noise Ratio (SNR)

Ideal scenario is to acquire multiple datasets to minimise errors. (Method 1)

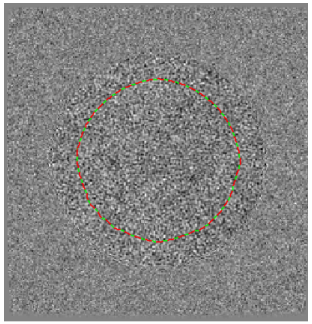
$$SNR(x,y) = \frac{\mu(x,y)}{\sigma(x,y)}$$

- μ = mean signal measured across all acquisitions
- σ = standard deviation of signal measured across all acquisitions

More pragmatic solution is to acquire two identical datasets (Method 2)

$$SNR_{subtraction} = \frac{\sqrt{2}\mu_{phantom}}{\sigma_{subtracted\ image}}$$

- μ = mean signal measured from 1 acquisition
- σ = standard deviation of the subtracted image

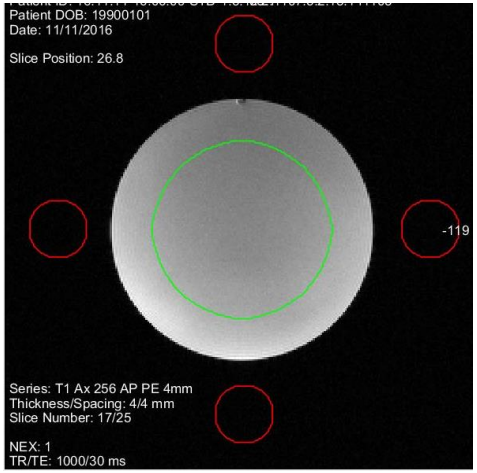


The noise in the subtracted image will be Gaussian with variation twice that of the source data (magnitude data)

Signal to Noise Ratio (SNR)

Even more pragmatic method for 1 image. (Method 3)

$$SNR_{background} = \frac{f \times \mu_{phantom}}{\sigma_{background}}$$



- μ = mean signal measured from 1 acquisition
- σ = standard deviation of the background noise
- f = correction factor for non-Gaussian nature of the noise distribution (0.66)

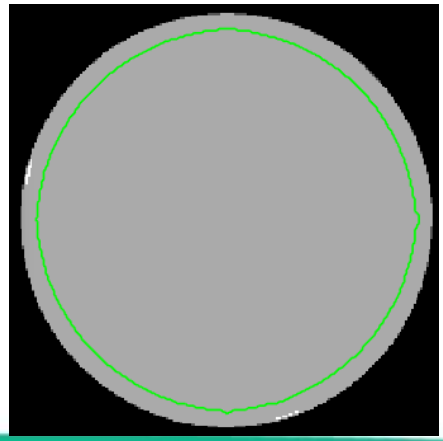
Uniformity

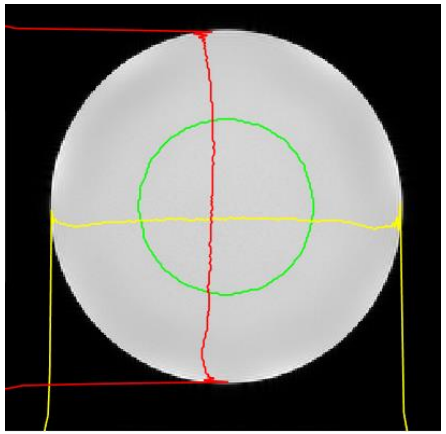
Is a measure of MRI system's ability to produce a contrast signal response over the image volume.

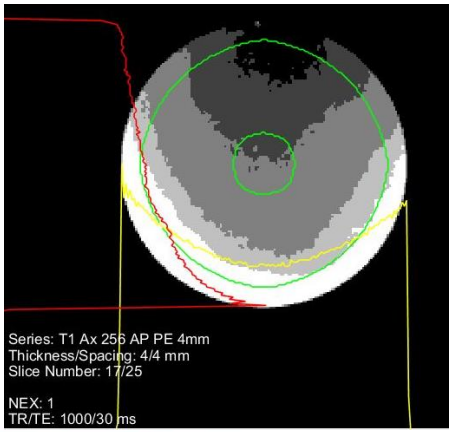
$$(\%)\ Uniformity_{Integral} = 100 \times (1 - \frac{S_{max} - S_{min}}{S_{max} + S_{min}})$$

- Integral Uniformity is calculated on smoothed data
- S_{max} / S_{min} = maximum and minimum signal intensities

A perfect uniformity would be 100%





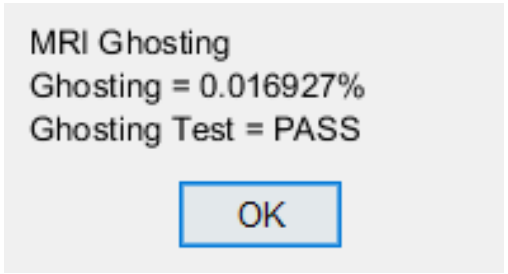


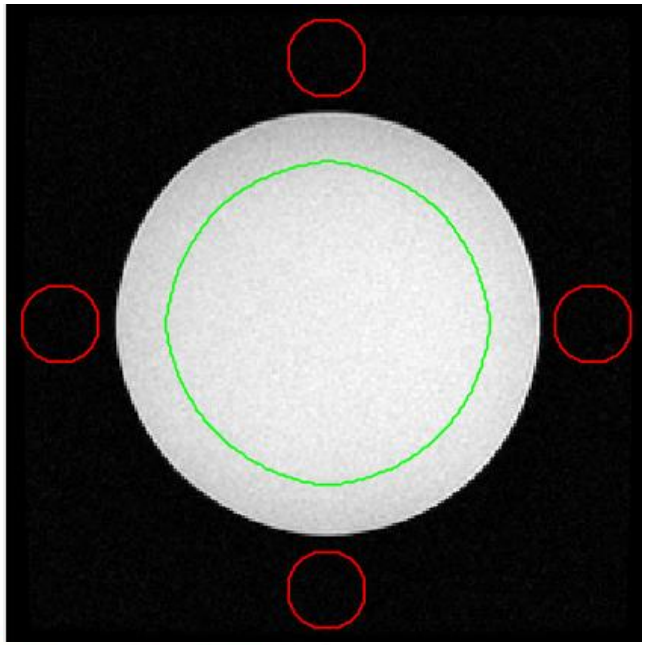
Ghosting

Normally associated with motion arising from patients, can be a sign of RF or gradient instability if observed on phantom studies.

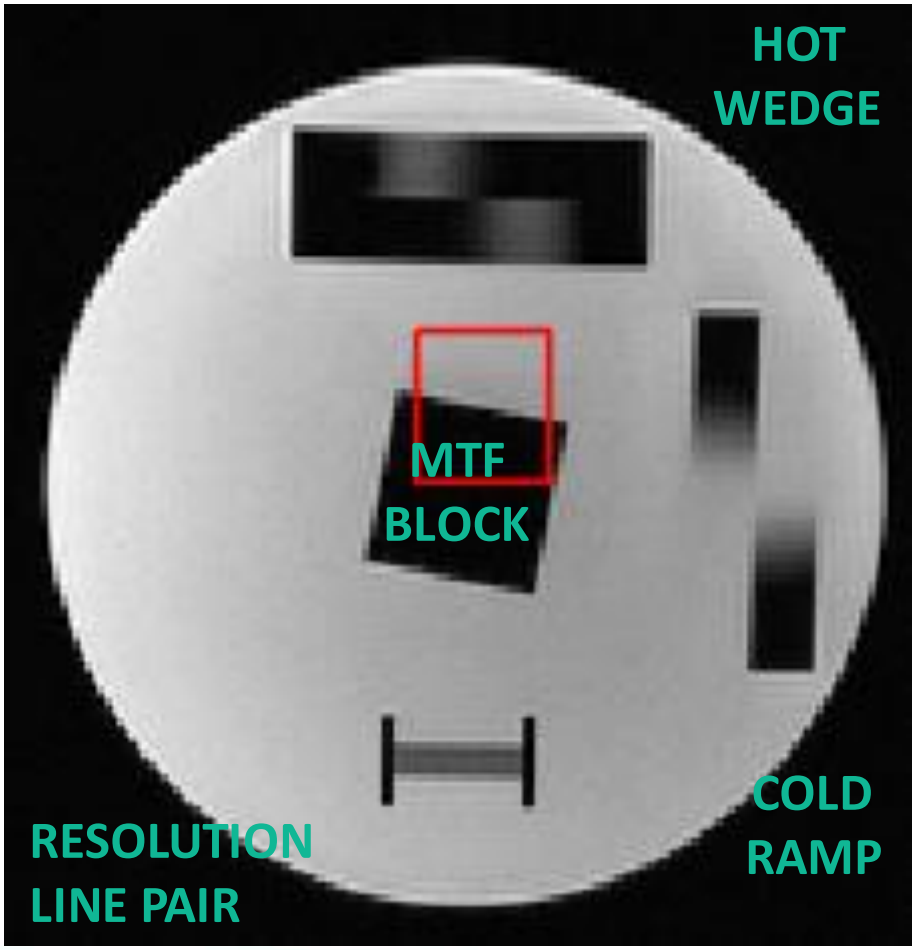
$$(\%)\ \text{Ghosting Ratio} = 100 \times \left(\frac{(top+bottom)-(left+right)}{2\times signal}\right)$$

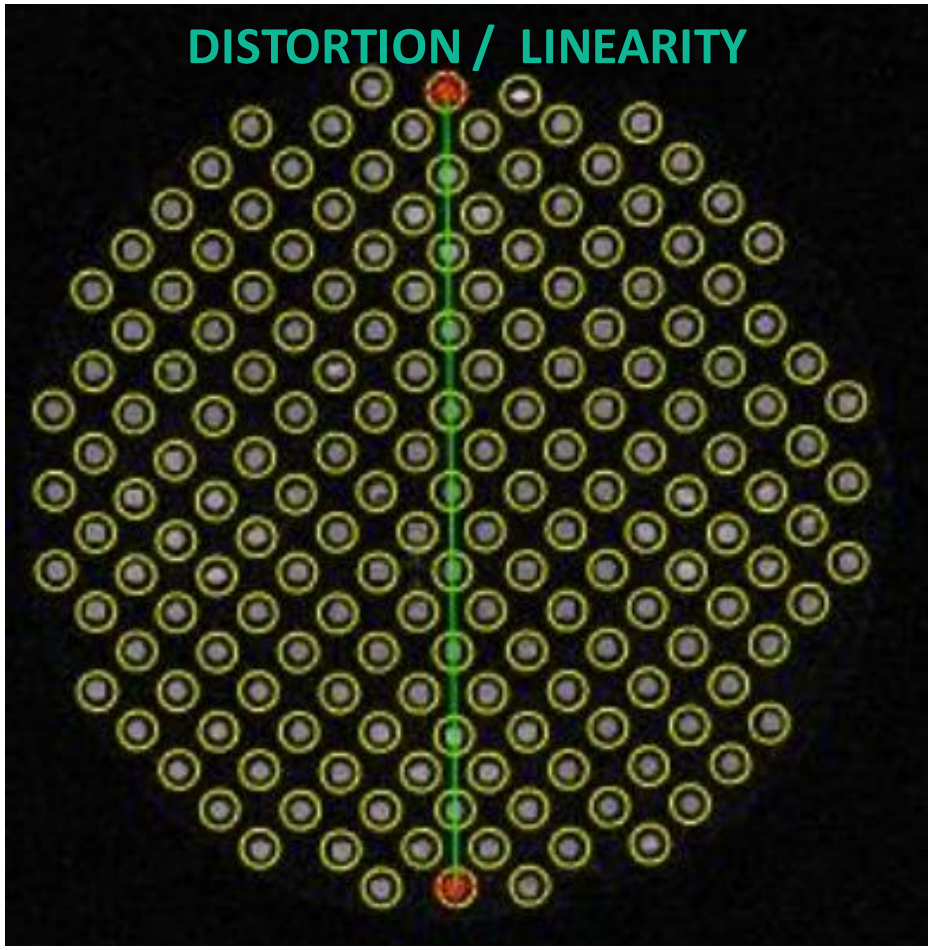
- A ghosting ratio close to zero indicates that's ghosting is not significantly above background





Spatial Resolution and Linearity





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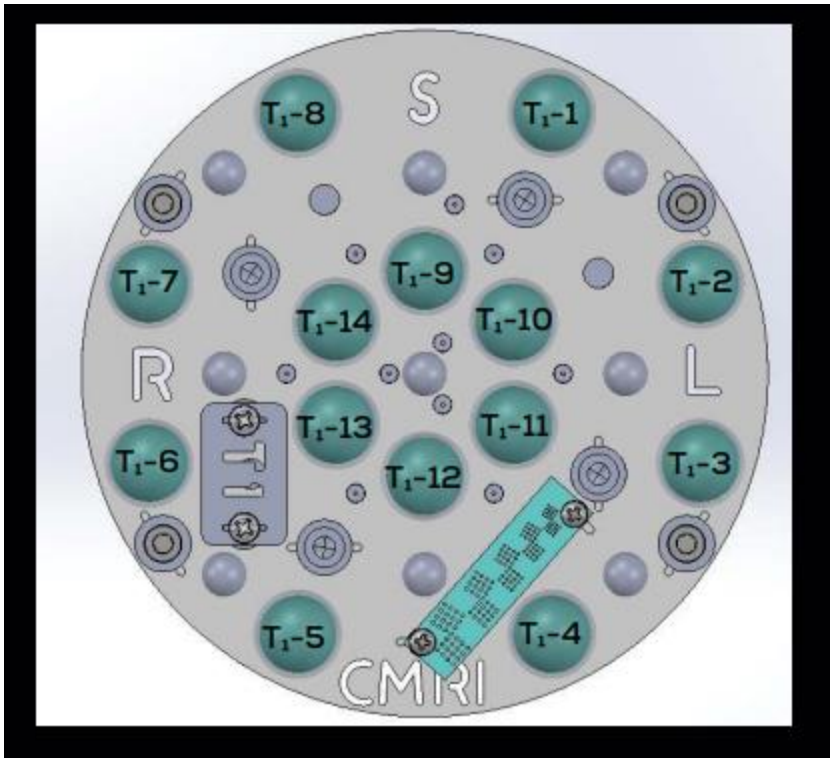
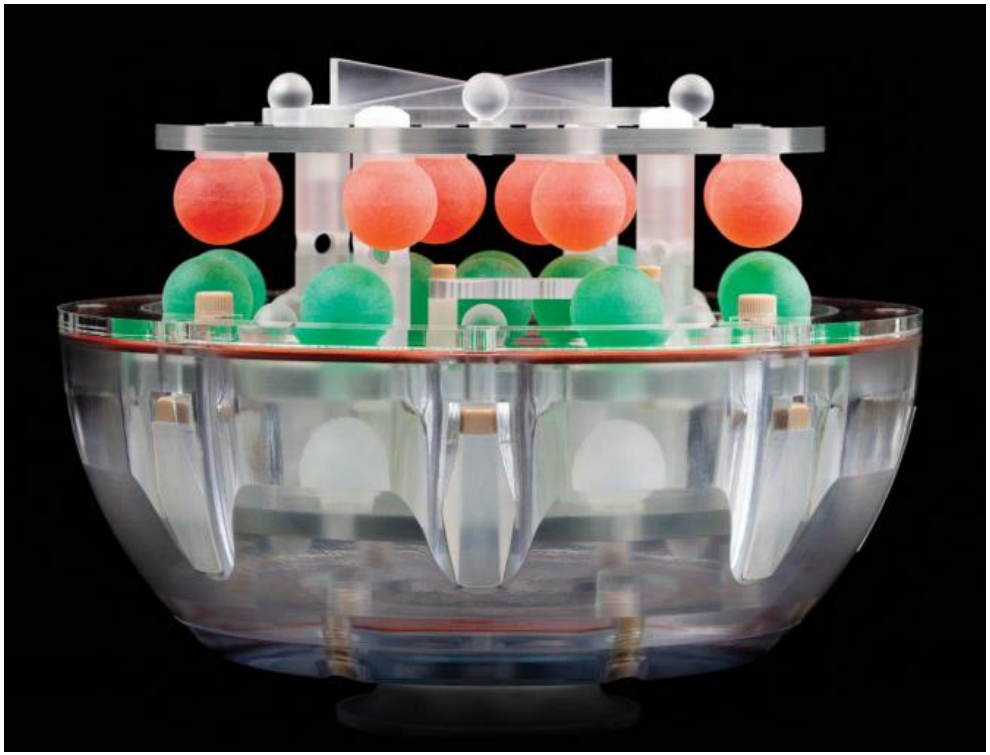
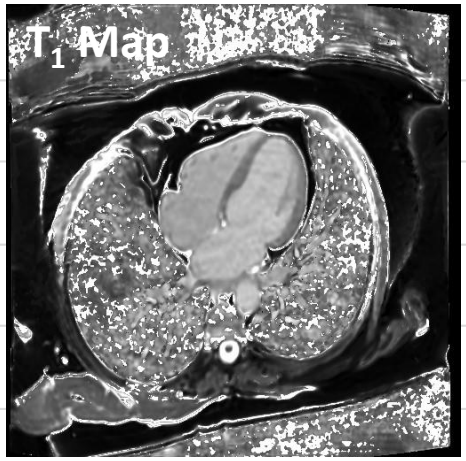
MR Relaxometry





MR Relaxometry



7.10 MR safety (Part 1)

- MHRA guidelines as the primary safety reference for UK
- MR safety framework, definitions, roles & responsibilities
  - *MRRP & MRSE*
  - *MR Authorised Persons*
  - *MR Environment and MR Controlled Access Area*
  - *MR Safe / MR Conditional / MR Unsafe / MR Unlabelled*

- Safety issues, particularly with regards to implanted devices and emergency situations, including
  - *Risks from B_0, dB/dt, B_1*
  - *B_0 - Attraction, torque*
  - *RF heating: SAR and B_{1+} rms*
  - *Magnetic quench*
  - *Pregnancy*

7.10 MR safety (Part 2)

- Safety issues associated with gadolinium-based contrast agents
  - *Linear versus macrocyclic-based agents*
  - *Nephrogenic systemic fibrosis (NSF)*
  - *Gadolinium deposition/retention*

- Recommendations for scanning patients with implanted devices without the manufacturer's approval, e.g. 'off label'

7.11 Quality assurance

- Importance of quality assurance in MR to identify failing elements in phased array coils

- Quality assurance to help establish reproducibility of quantitative MR techniques


Thank You