Exposure and risk assessment for MR workers

Penny Gowland
Magnetic Resonance Centre
University of Nottingham

Summary

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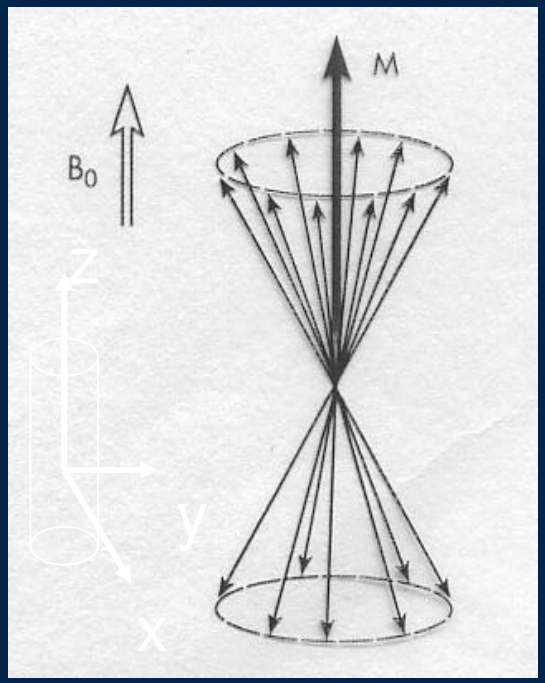
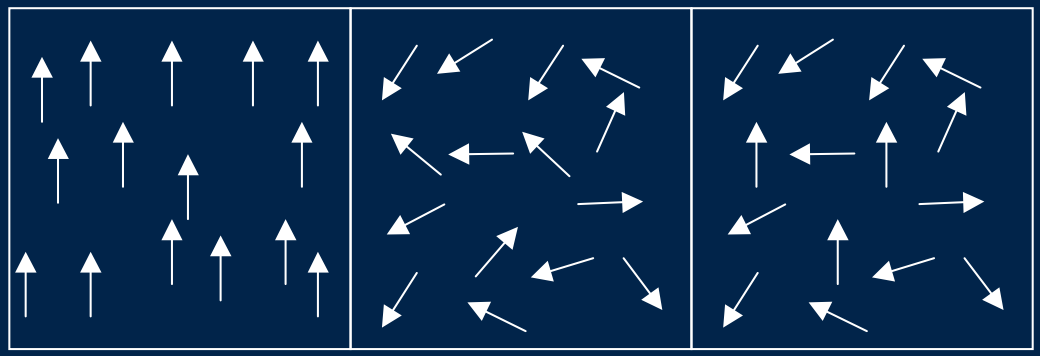
- Types of EMF involved
- The numbers of staff exposed
- The classes of staff exposed
- Exposure limits
- Dosimetry and compliance
- Effects of EMF we know about
- Management

Fields associated with MRI

- Static fields to polarize nuclei
  - 1.5- 3 T or 7T for patients and staff
  - Usually up to ~ 2T for staff
  - Staff moving in these fields can experience time varying fields of ~ 1T/s





B = 1 T	B = 0 T	B = 1T
T = 0 K	T = 310 K	T = 310 K
100% aligned	0% aligned	~3ppm aligned
M	M=0	M

Fields associated with MRI

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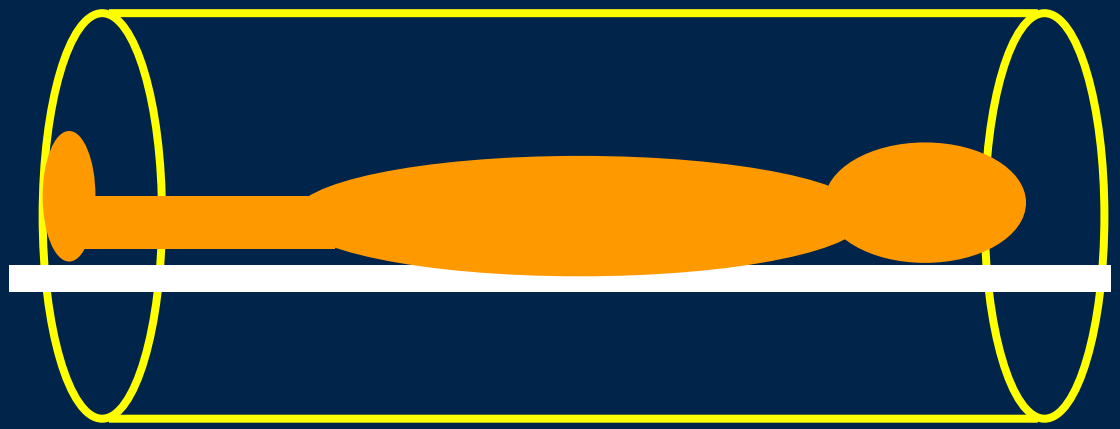
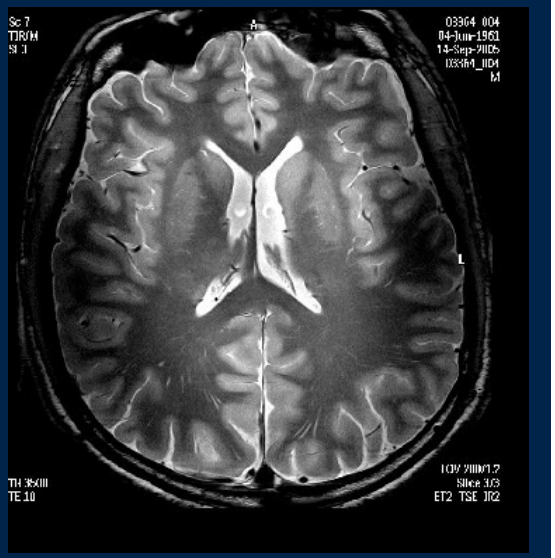
- Gradient fields used for image encoding
  - 33 – 40 mT/m, switched at 125 -200 mT/m/ms
  - Patients exposed to 40 T/s at kHz frequencies
  - Staff standing near the end of the bore exposed to ~4 T/s





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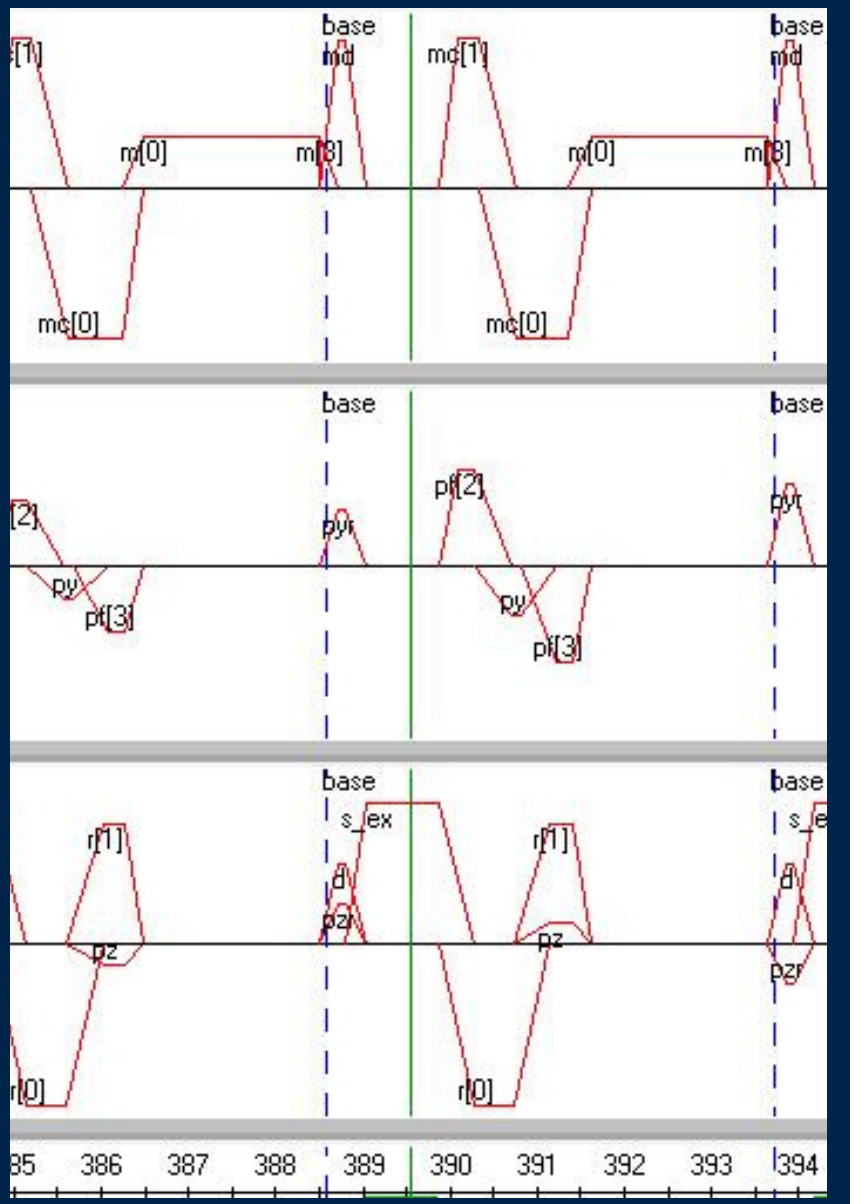
- Gradient waveforms are very broad band
- Short pulses can be repeated at low frequencies



Fields associated with MRI

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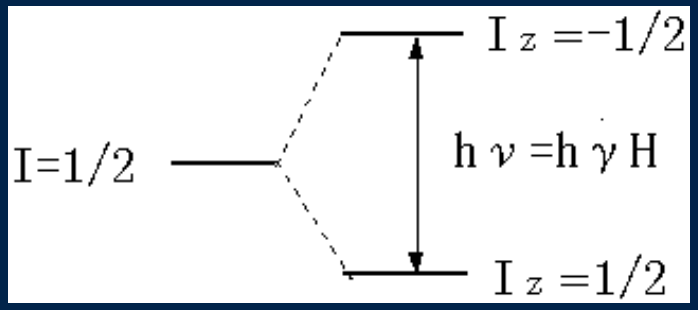
- RF field used to excite nuclear magnetization
- Patients exposed up to 4 W/kg
- Staff not usually exposed at all
  - Except interventional



Numbers and types of staff exposed

Number of scanners in the UK

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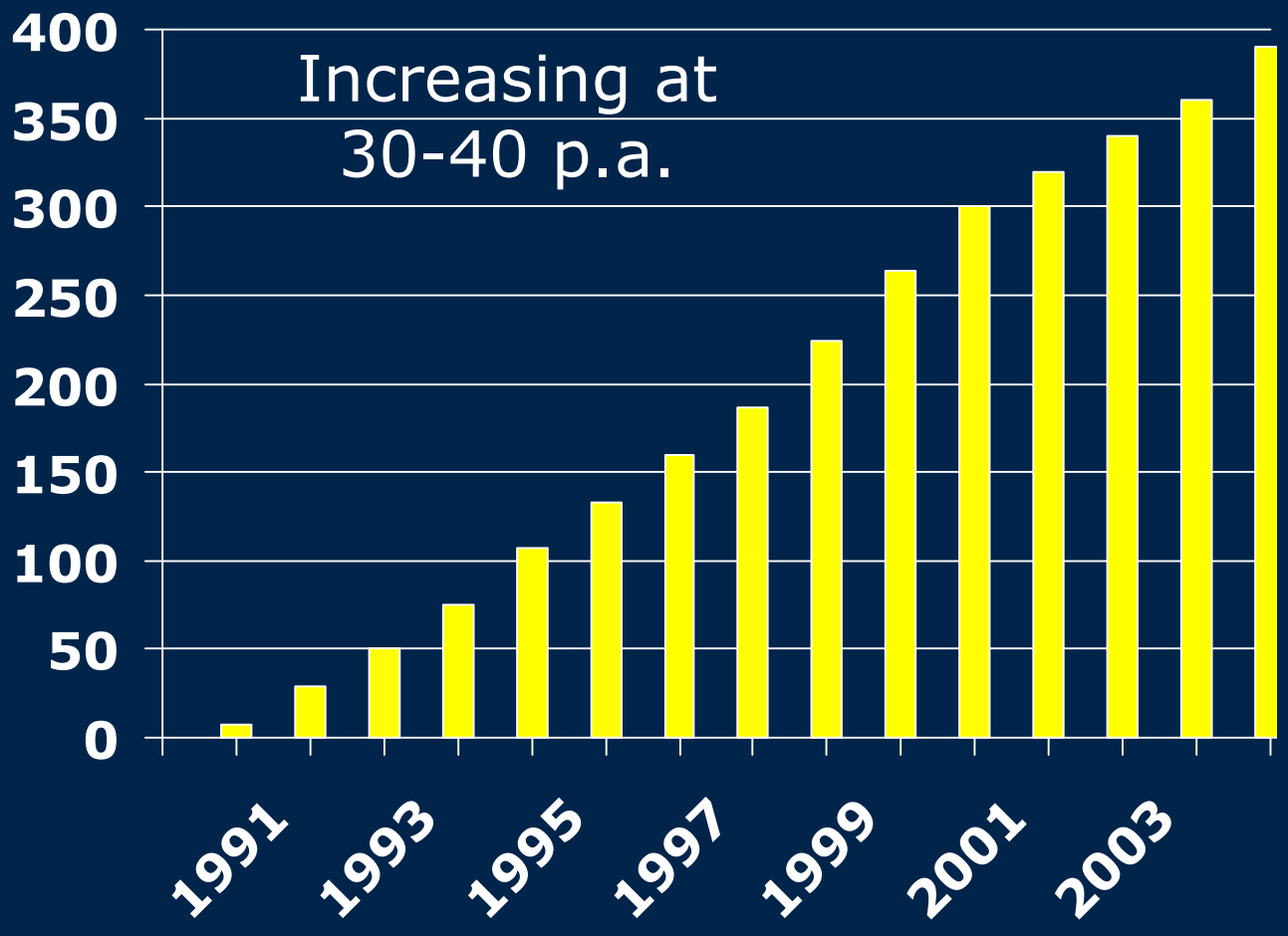

2000-3000 scan per scanner p.a.

800,000 scans p.a. in UK, capacity will increase 10% soon

~2% of the UK population have an MRI scan every year

MagNET

Numbers of staff involved

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- Estimate 600 sites each involving a minimum of
  - 2 radiographers/ technologists
  - 2 radiologists
  - 0.2 service engineer
- Probably also involving
  - 1 physicist
  - 1 anaesthetist
- i.e. At least 4000 staff in the UK exposed

Clinical staff

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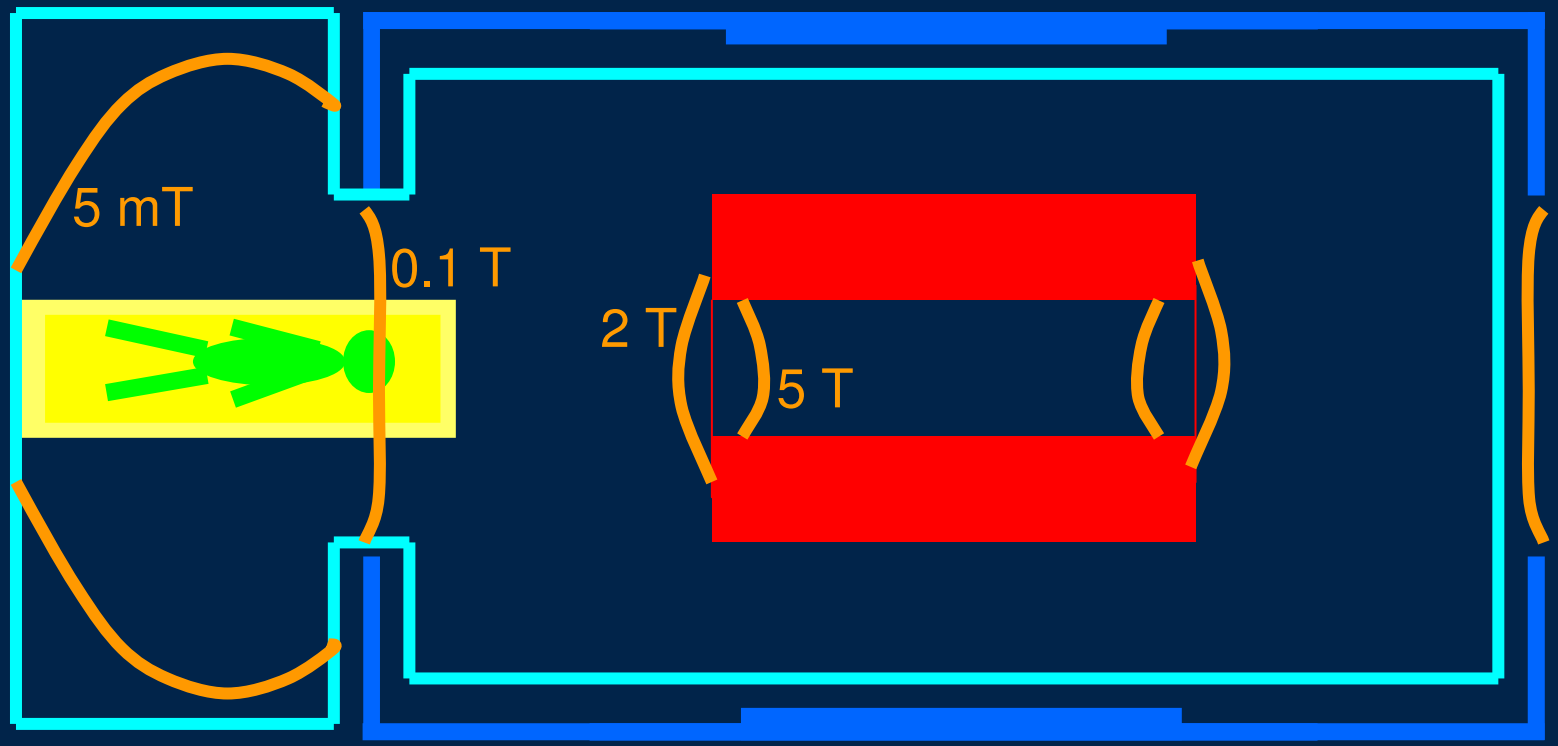
- Radiographers
  - Routine exposure can be minimized
  - Exceptionally it may be desirable for the radiographer to stay close to the subject



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The University of Nottingham

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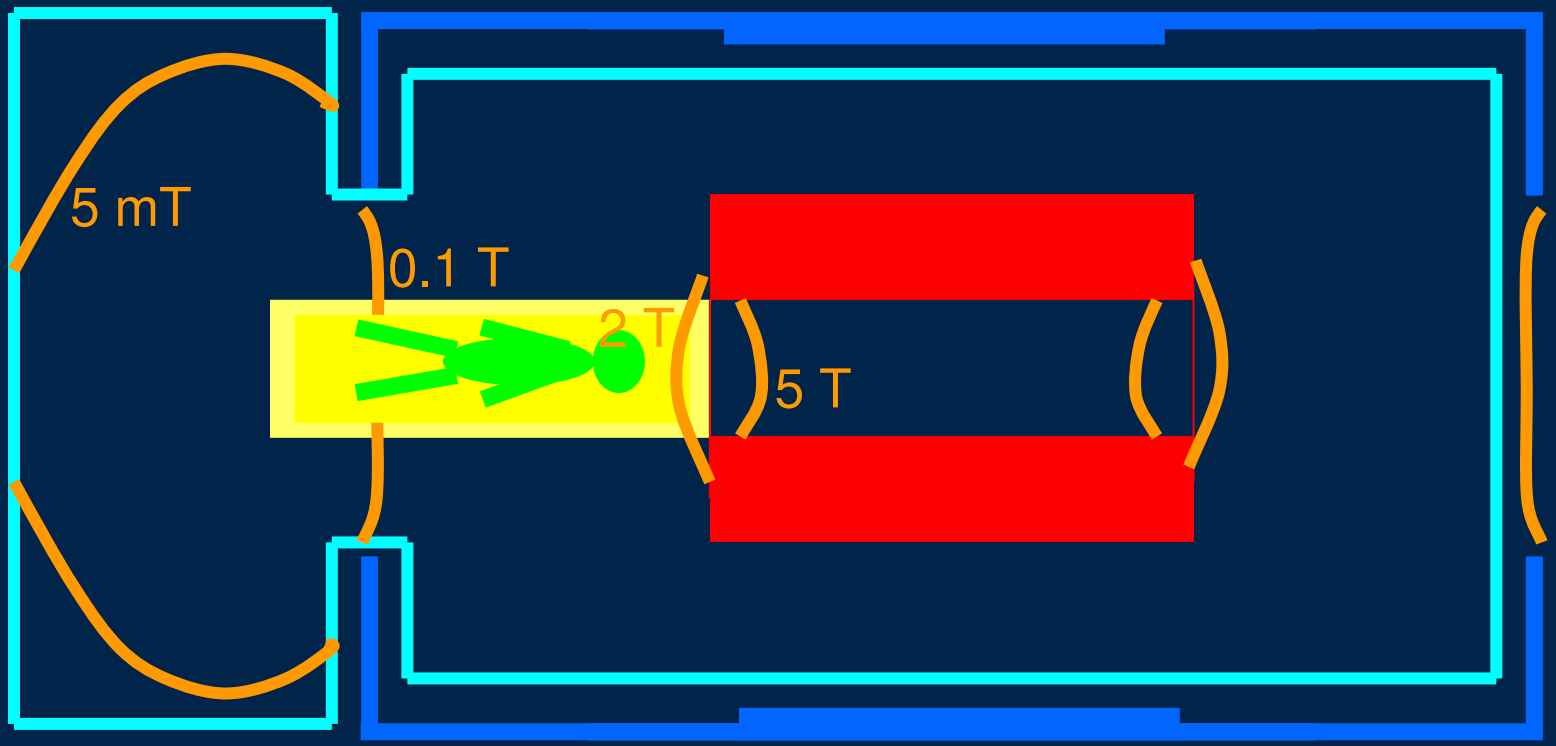
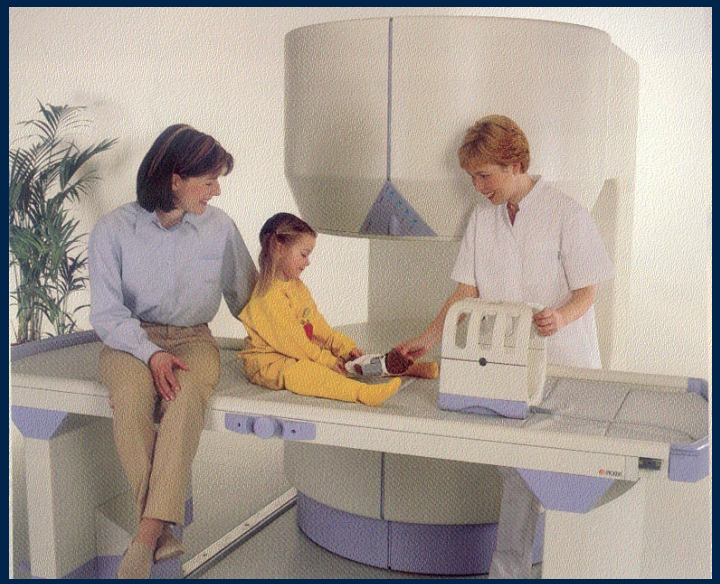
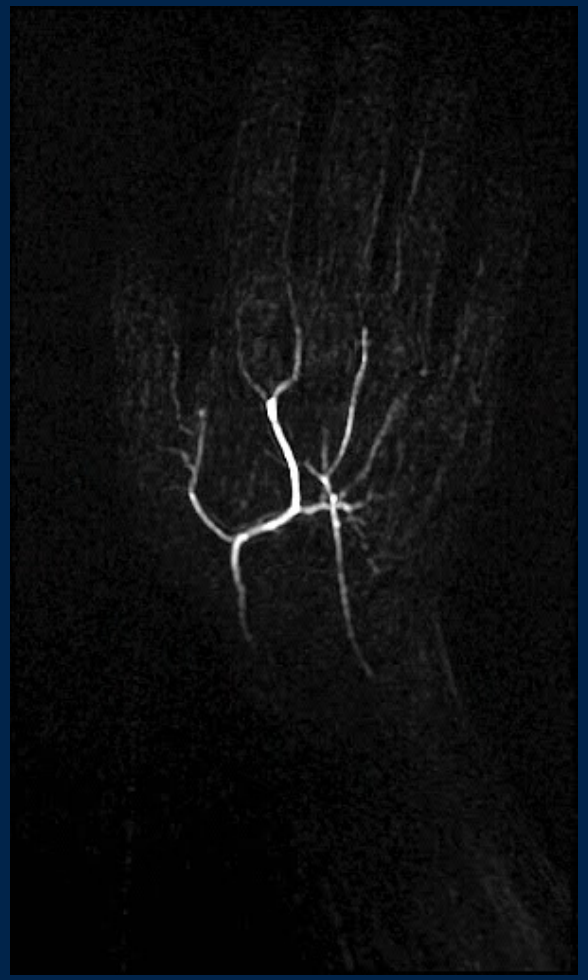


Clinical staff

- Radiologists/ anaesthetists
  - Routine exposure can be minimized
  - Interventional radiologists must stay close to the subject





Engineers and scientists

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- MR physicists/ engineers testing and developing scanners
  - very varied exposures to all types of fields at different times
- Scanner engineers
  - very lengthy exposures to static field possible
- Volunteers (often staff)
  - frequent exposure to entire spectrum of MRI fields

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Future trends

MR market share

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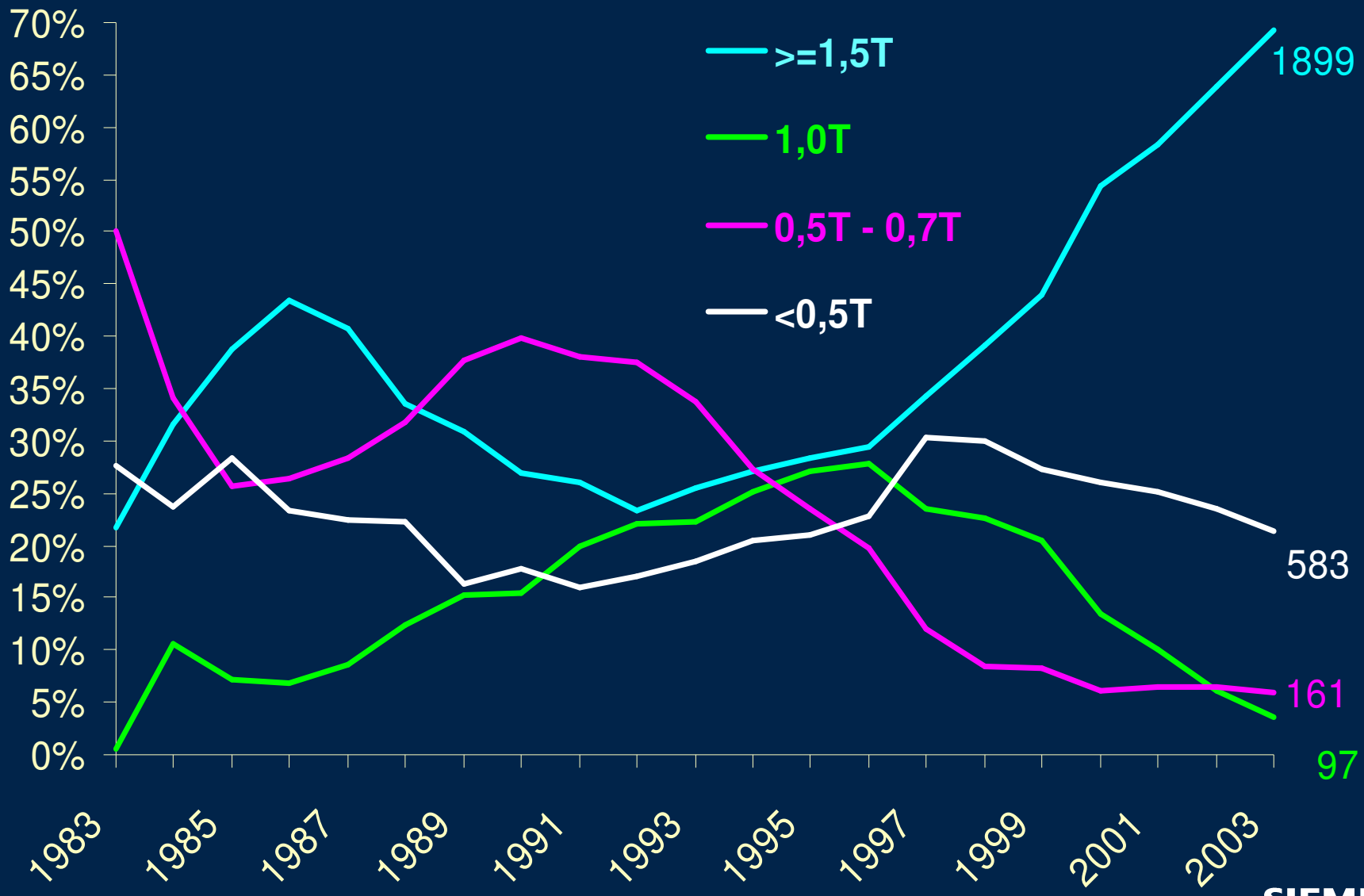

SIEMENS

Projected market- field strength

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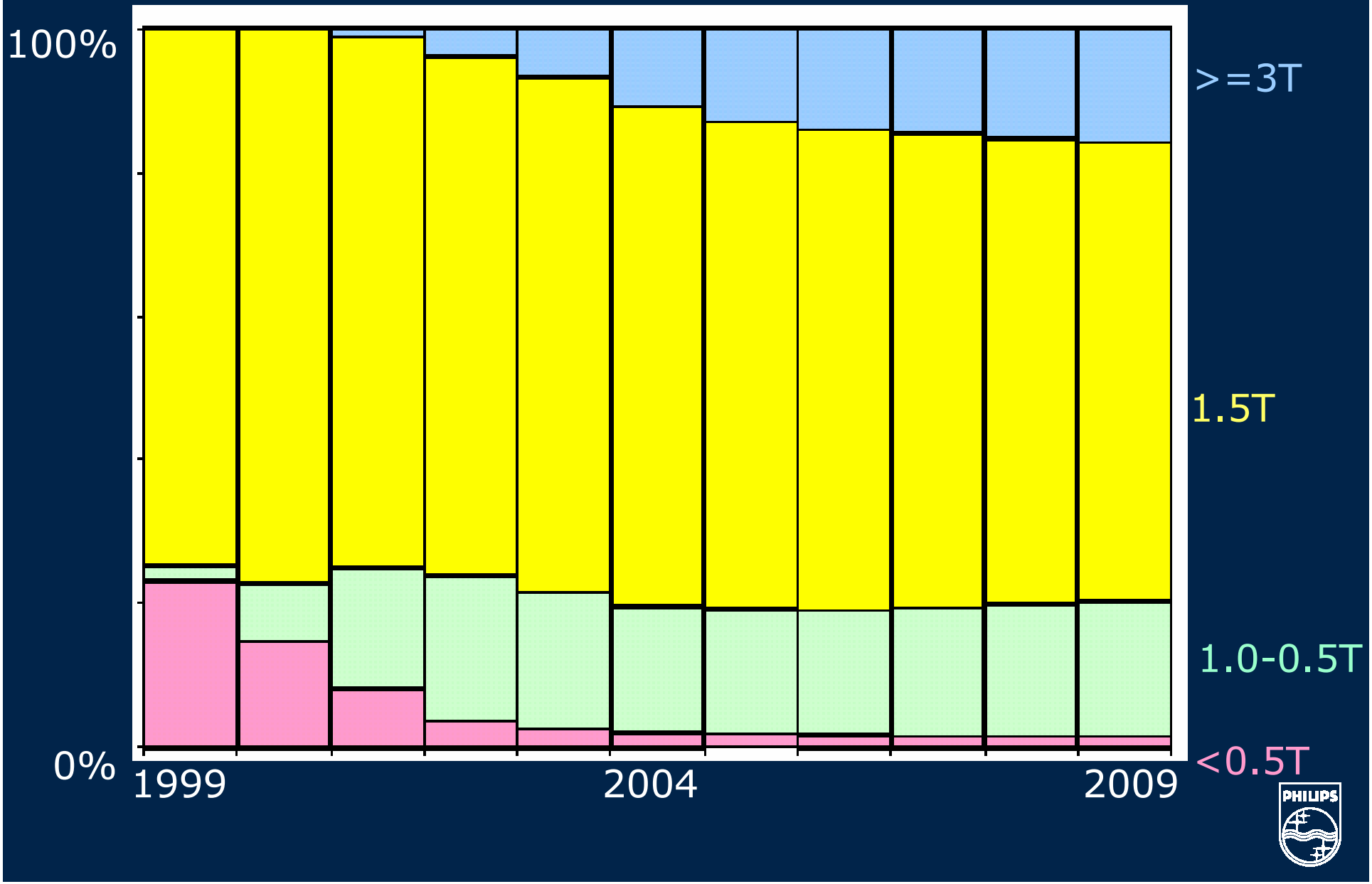

PHILIPS

Ultrahigh field

The University of Nottingham

- High field milestones:
  - 8T to Ohio State University 1998
  - 7T to Minnesota 1999
  - 9.4T to Minnesota 2003
- Expected world market for 7T whole body is ~ 50 systems
- Magnex and Oxford both shipped 9.4T whole body scanners last year.
- 11.7 T scanner to be installed in Paris in the next couple of years

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Magnet design

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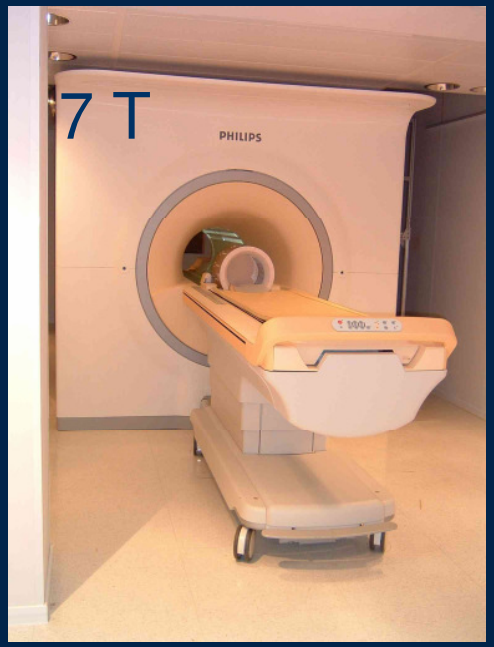
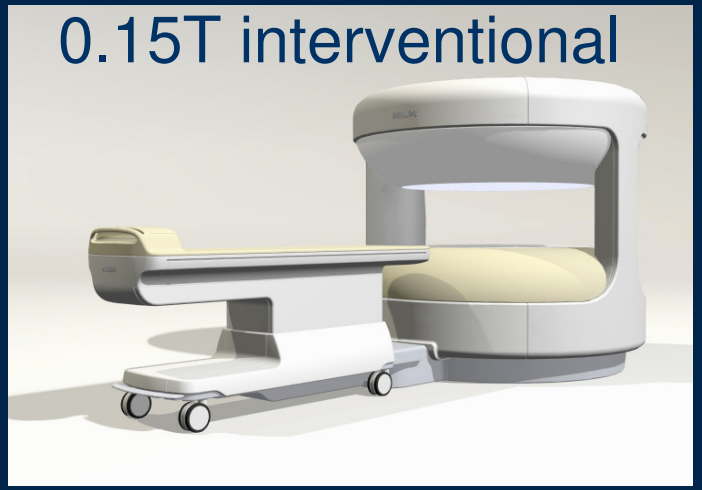
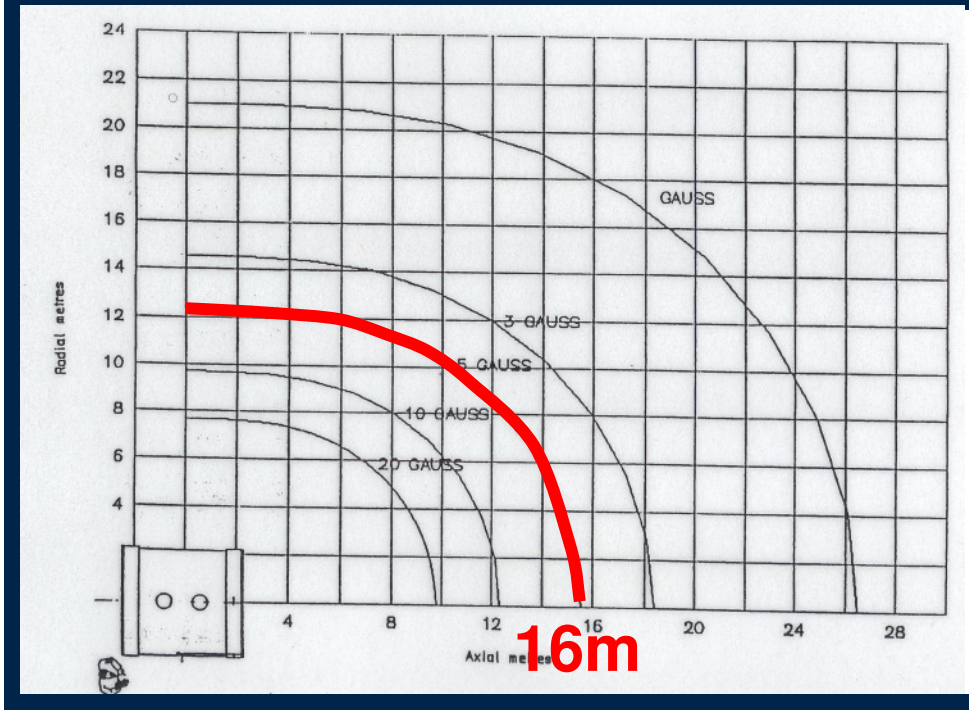




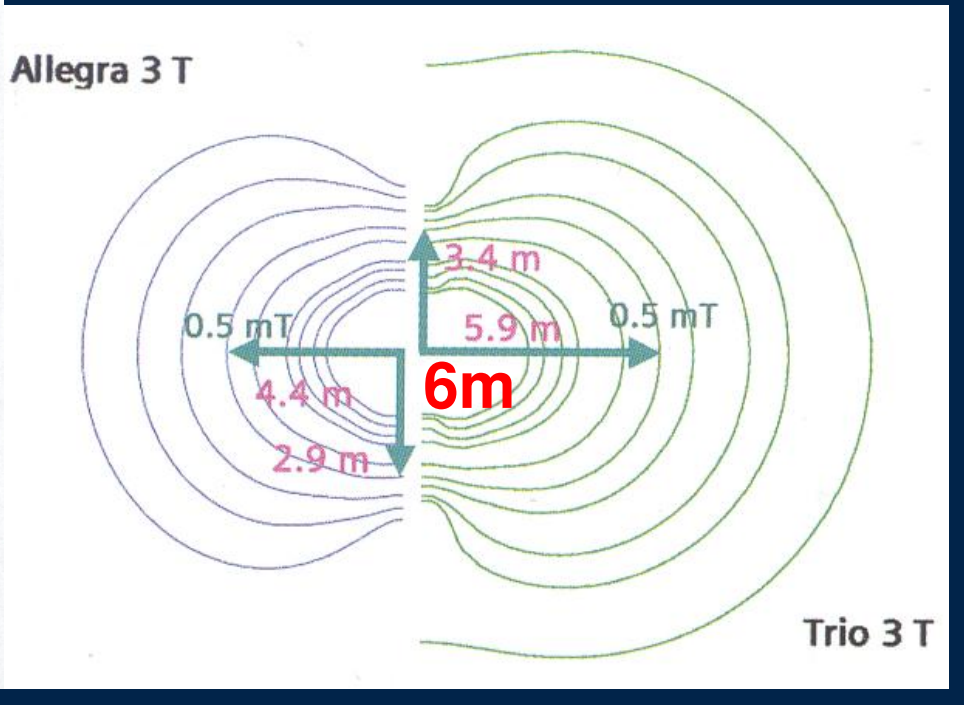
Magnet design

- Magnets are increasingly shielded, to reduce extent of stray field
- However this does increase field gradient

Unshielded



Shielded



Shielding

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- Field gradient determines the force on magnetic materials
  - Projectile effect

$$\underline{F} \propto \underline{B} \frac{d\underline{B}}{d\underline{z}}$$

  - EMF induced in moving conductors
- Shielded magnets are shorter so staff are exposed to larger gradient fields (as they are closer to the gradient isocentre)

iMR- cardiology

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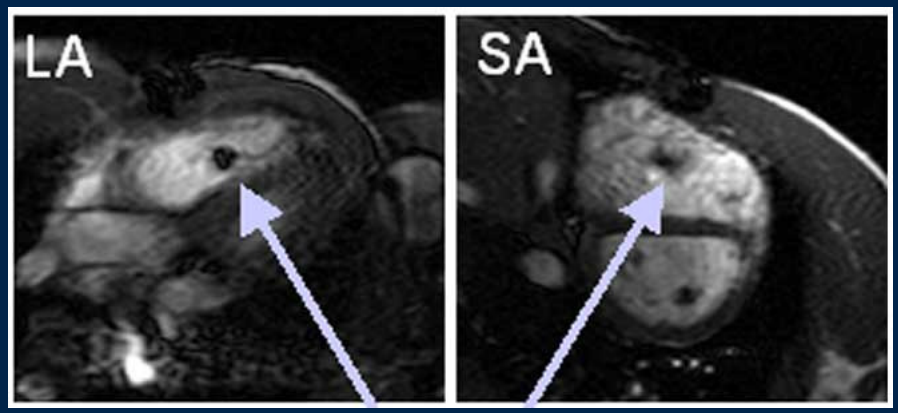
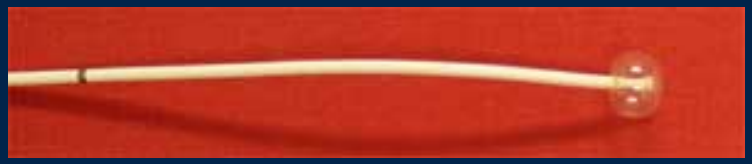
- Although Xrays retain some benefits in this area, MRI can provide valuable additional information
- Risks of radiation injury potential severe





UCSF

iMR: neuosurgery

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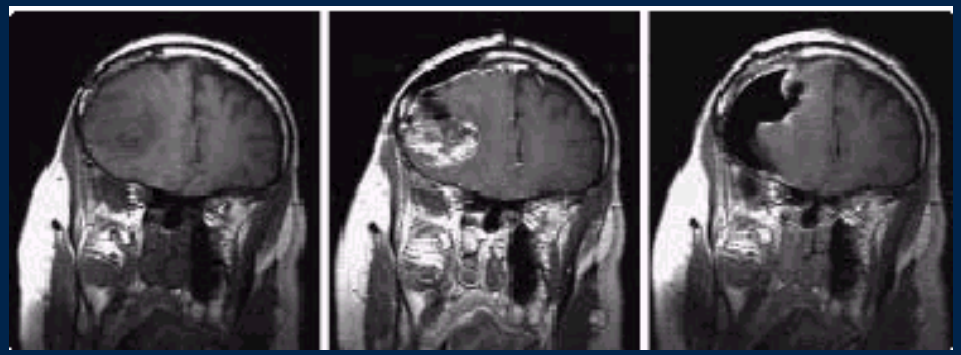
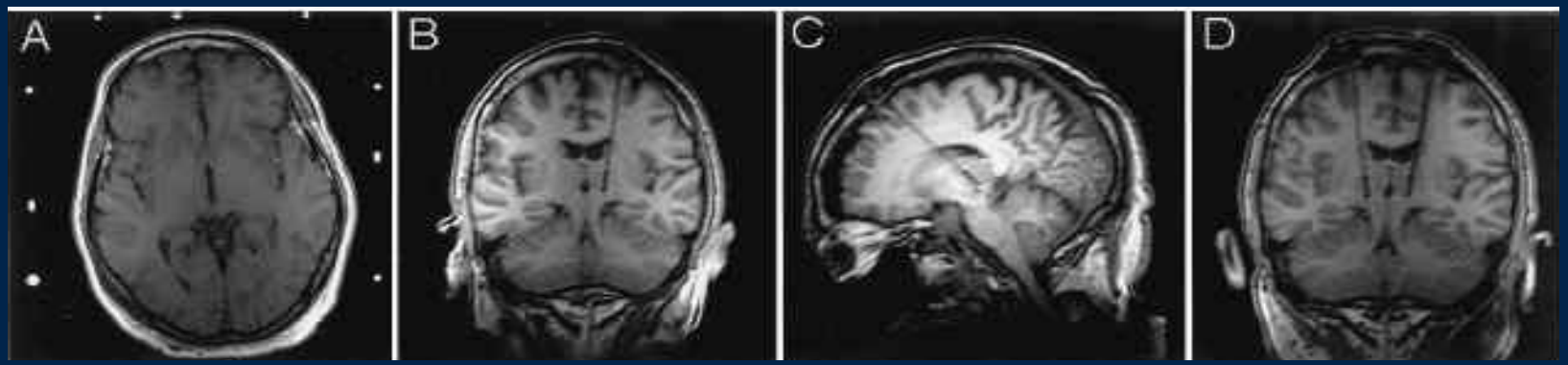
- Monitoring tumour resection



Before, during and after surgery

- Bilateral thalmic stimultor



University of Minnesota

Niche scanners

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- Orthopaedics
- Neonatal scanners

OrthOne

Innervision

University of Sheffield
Bioengineering Institute, University of Auckland

Exposure Limits

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Field	Frequency	Exposure limit	Action value	UK MRI occupational exposure
RF	10-400 MHz	0.4 Wkg^{-1} (head)	0.2 μT	< 0.4 Wkg^{-1}, may be hot spots
Switched gradient field	500 Hz	J = 10 mAm^{-2}	50 μT	~2000 μT
Moving around static field	<20 Hz	J = 10 mAm^{-2}	0.2 T	~100 mAm^{-2}

Why current density?

Steve Keevil

KING'S College LONDON
University of London

Dosimetry and compliance

Dosemeters

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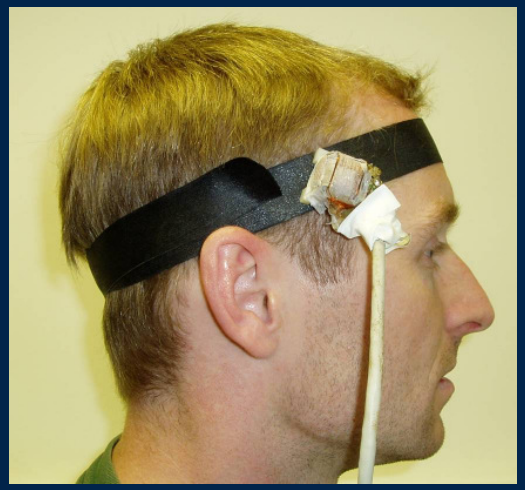
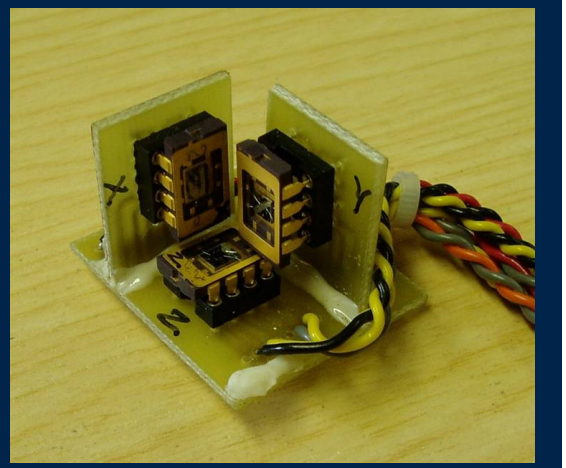
- Not many!
- Only measure magnetic field
- NOTHING measures induced current



dB/dt meter based on orthogonal coils

Narda standards compliance probe % of action value



B meter based on Hall bars operating up to 7T

Can you ensure compliance?

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- How do we relate a varying magnetic field to an induced current (exposure limit)?
  - How would we work out how warm you get inside if we put you in a hot room?
- By mathematical modelling
  - 'Lies, damned lies and statistics'
- How do we know we can trust these models?
  - By experiments
- BUT WE HAVE NO EXPERIMENTS TO TEST THE MODELS

Static field

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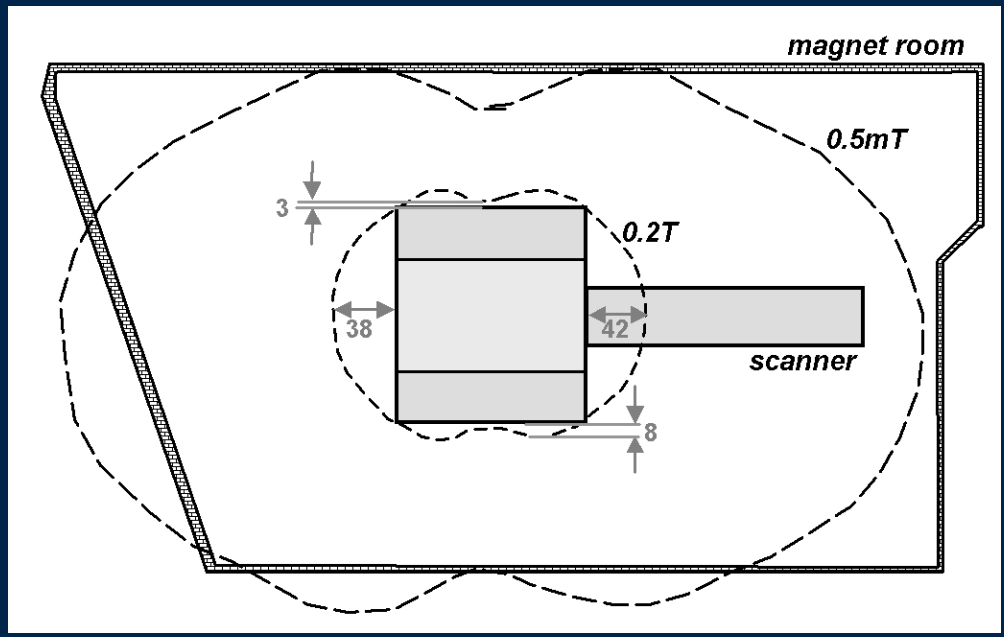
- Action value (0.2 T) exceeded around end of standard clinical 1.5 T scanner



CANCER RESEARCH UK

Sophie Riches
Royal Marsden Hospital

LABOR OMNIA VINCIT

Field plot around 1.5T magnet

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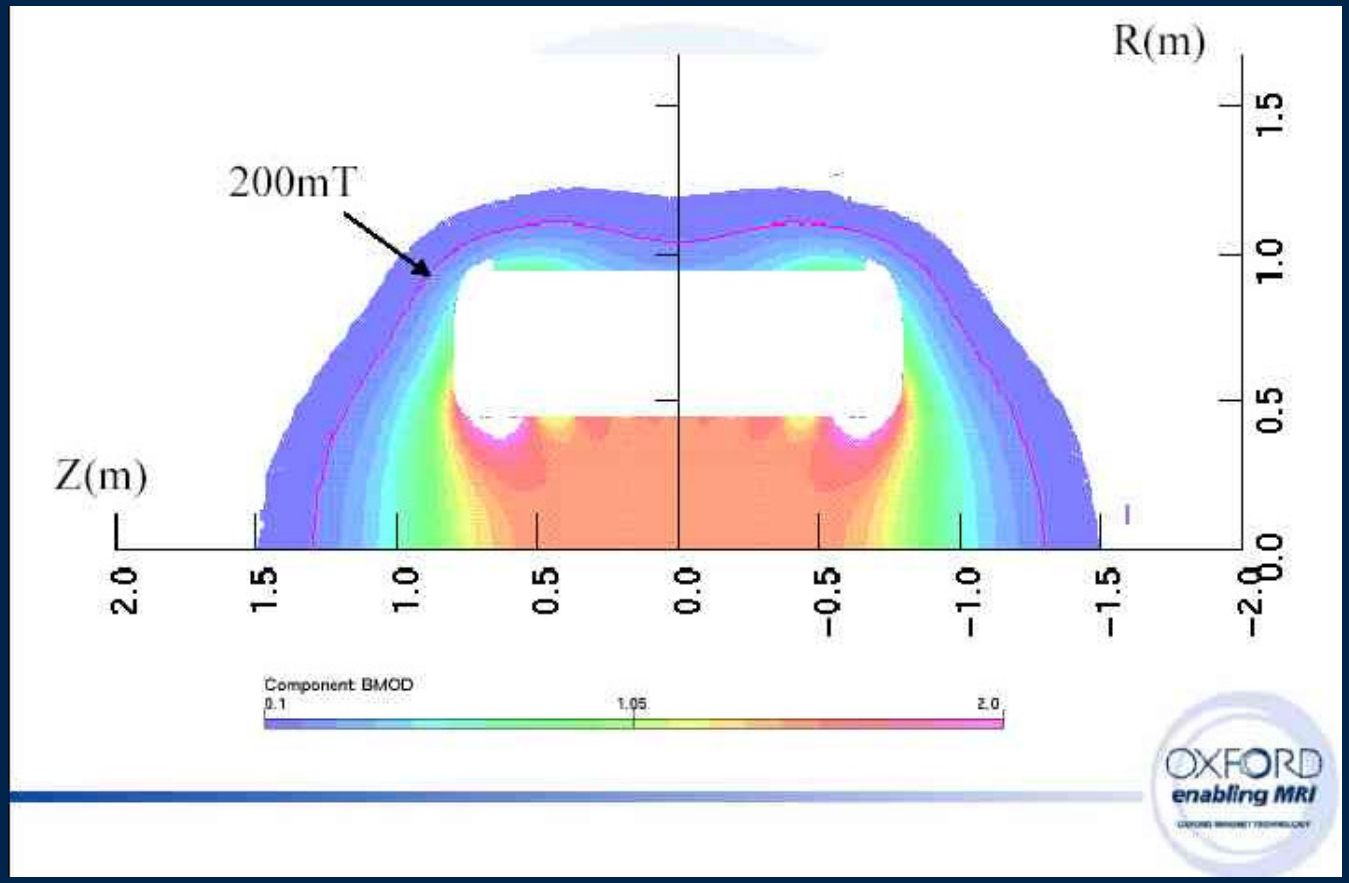
- Field at end of bore of 1.5 T exceeds 2T



Dosimetry- static field

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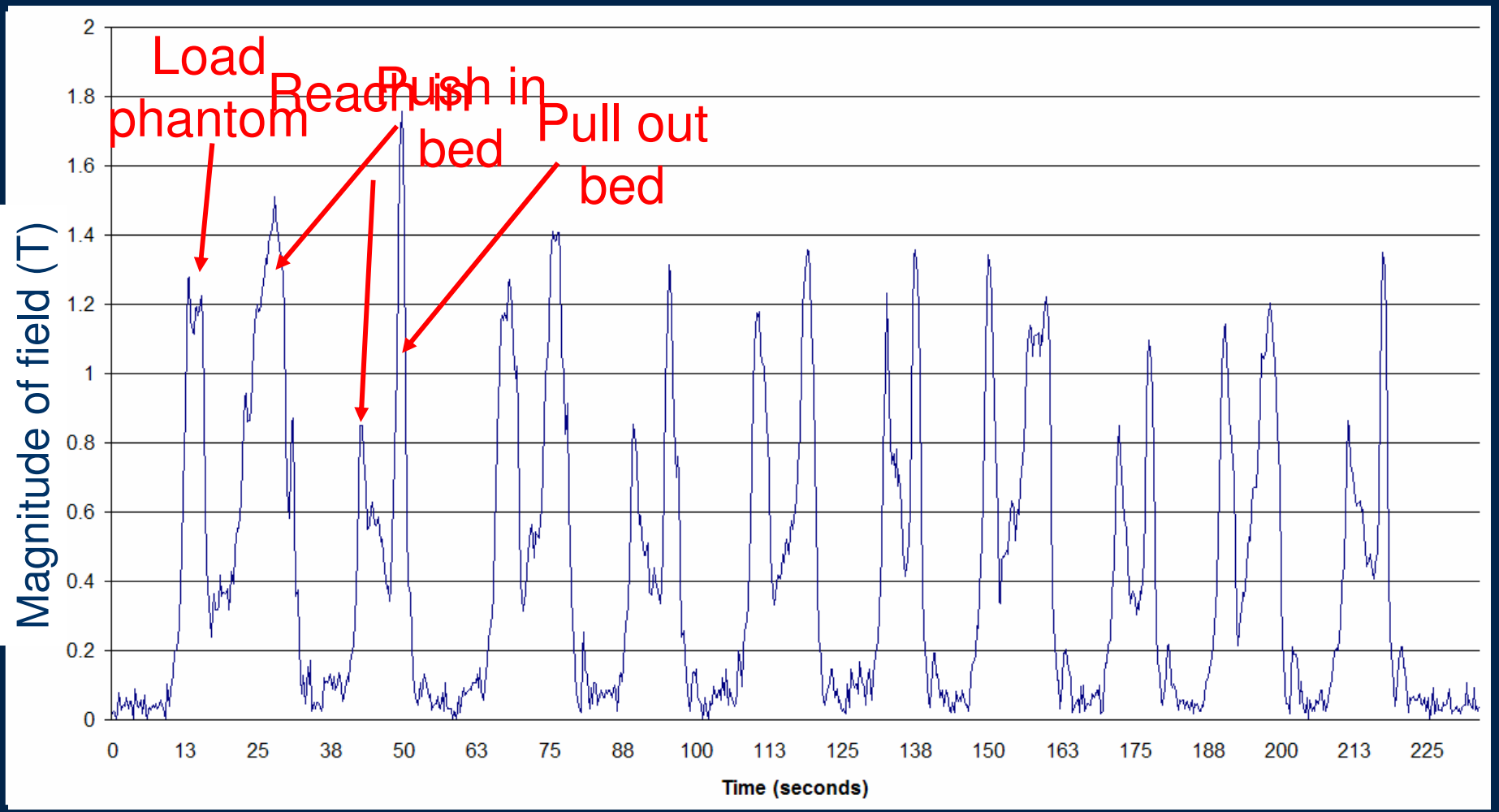
- Subject loading phantom into 7 T 5 times



Dosimetry- static field

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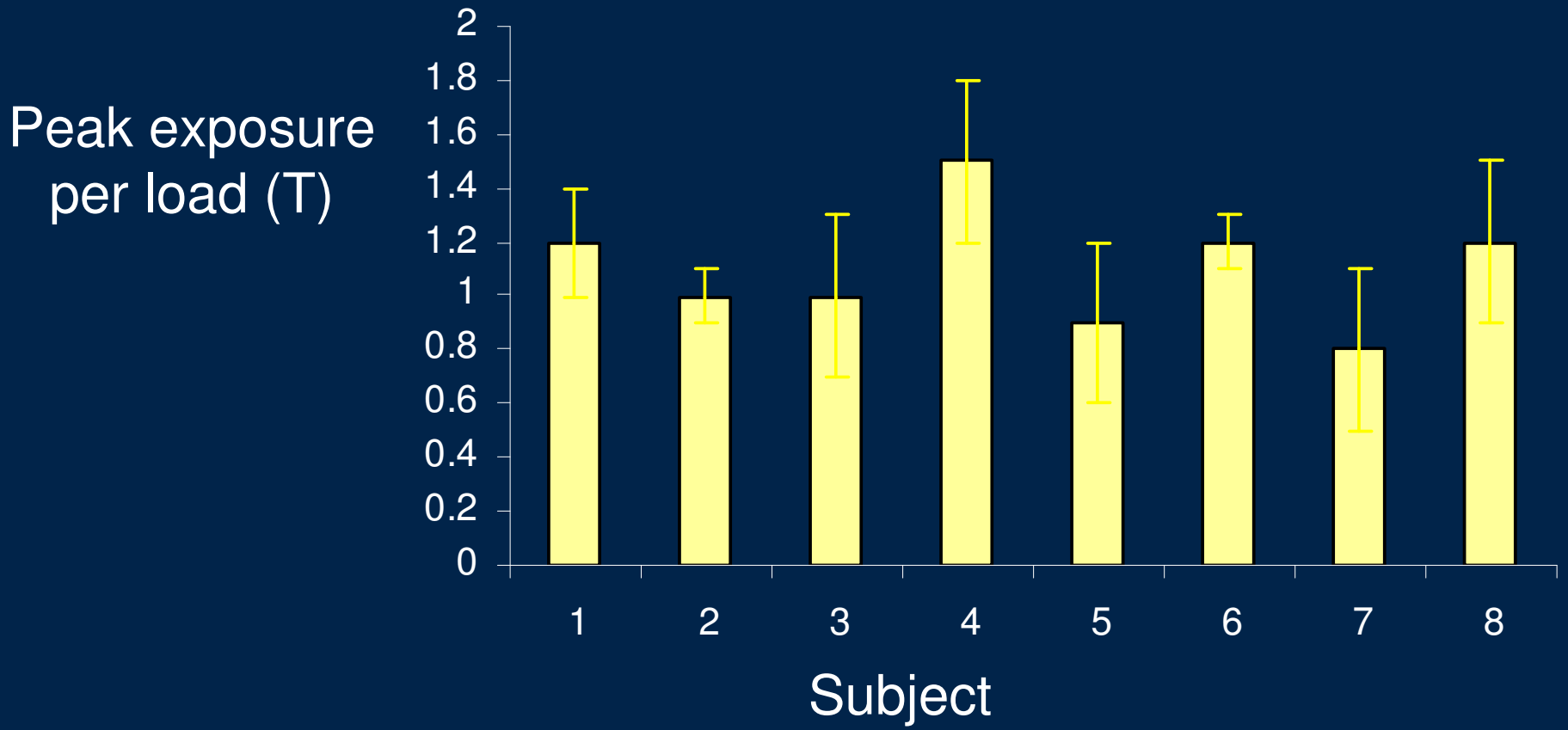
- 8 subjects loading a phantom into a 7T



Dosimetry- static field

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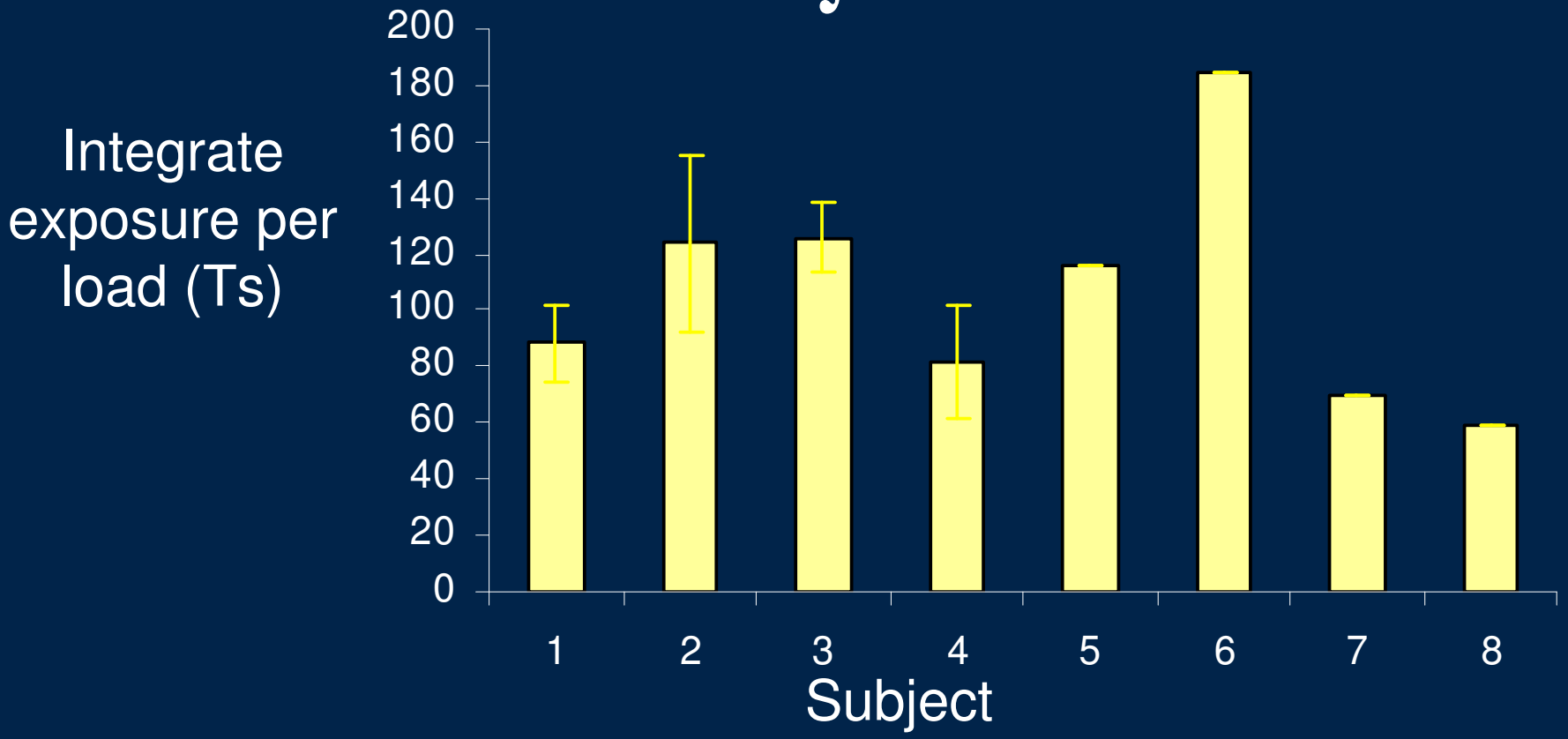
- Integrated exposure= $\int B\,dt$ for $B > 0.2$ T



- Occupational exposure for 4 workers during 4 hour scanning sessions at 3 T was 490 to 2403 Ts

Moving around a magnet

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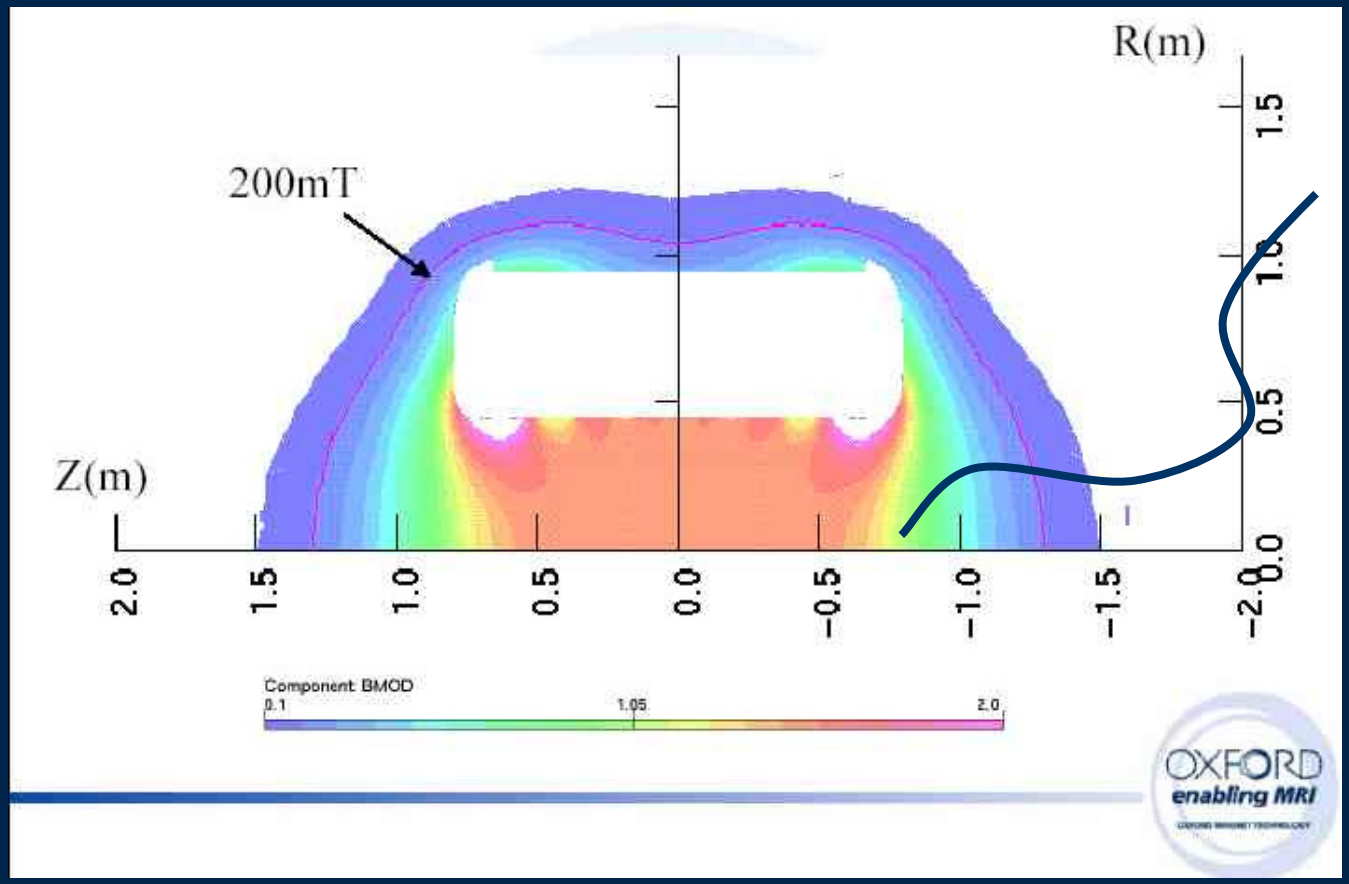
- Moving through a magnetic field gradient creates a time varying field - B at higher frequencies (dB/dt)



Moving around a magnetic field

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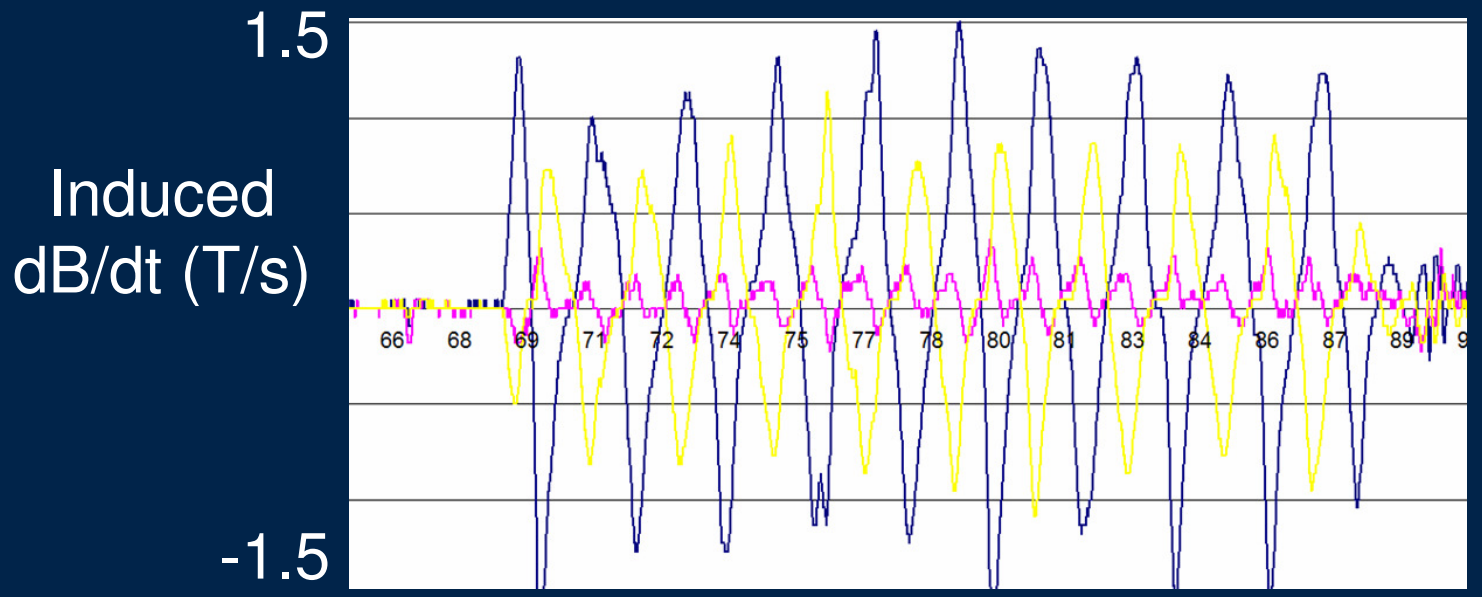
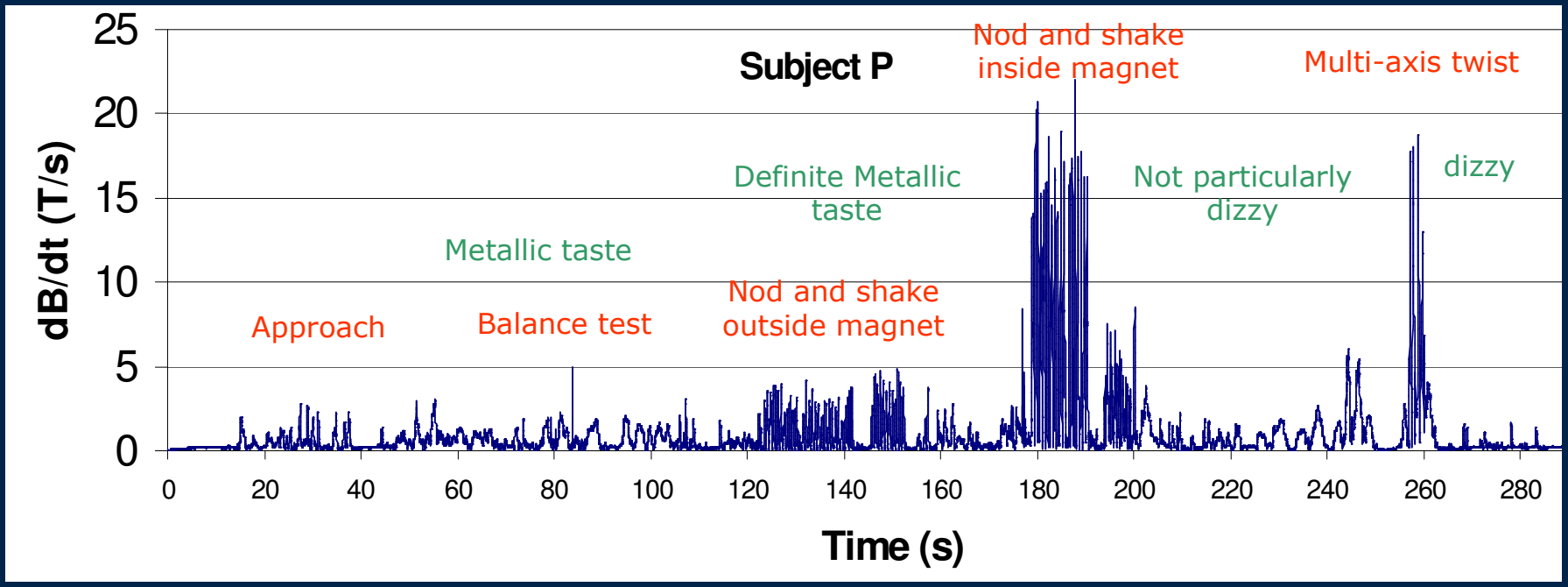
- Regular movements of head in field of ~0.5T and ~2.5 T/m at end of 7T, at 60-120 b.p.m.



Movement in static field



Modelling induced current

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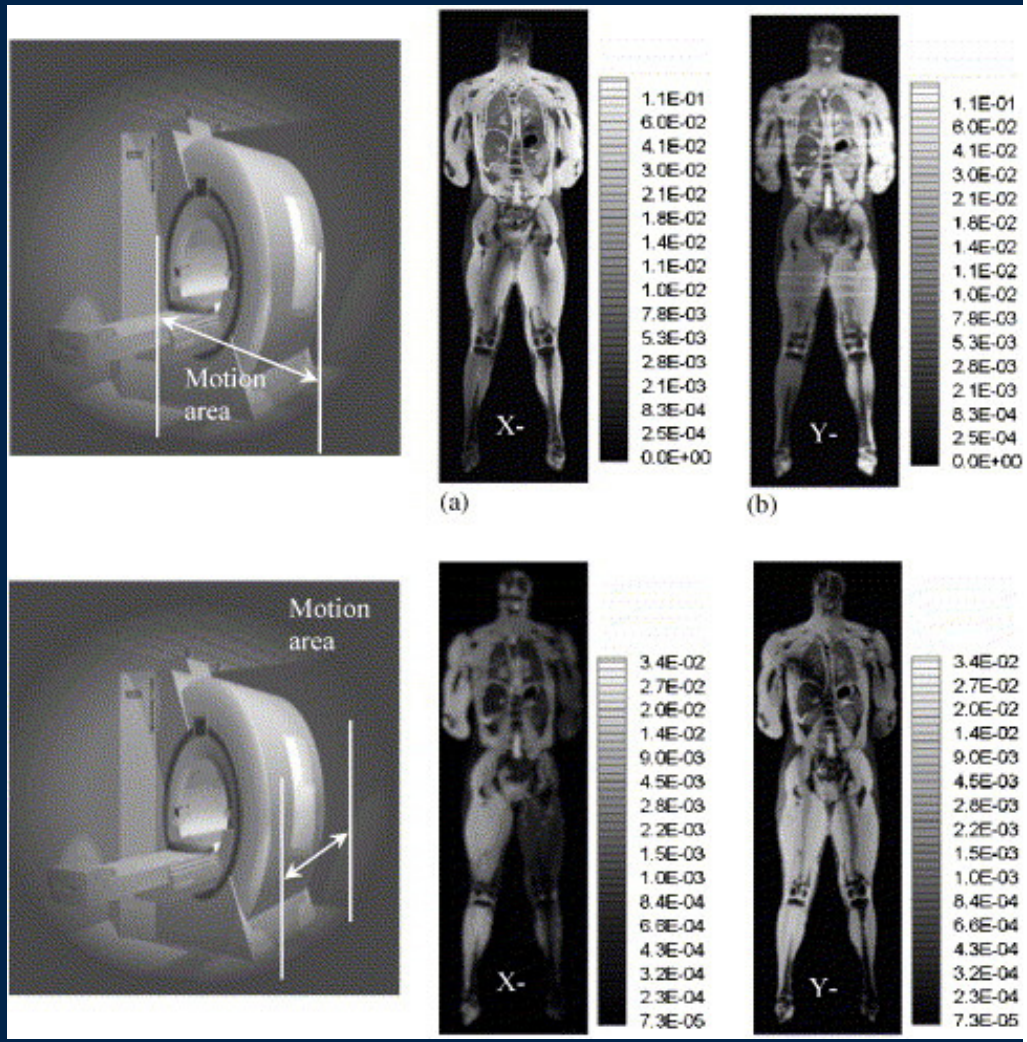
- Movement around a magnet modelled
- 0.5 ms^{-1} around a 4T induced J = 100-200 mAm^{-2}
- 2 ms^{-1} around a 1.5 T: induced J = 300 mAm^{-2}
- Exposure limit = 40 mAm^{-2}
- Testing?



Crozier et al,Queensland

Time varying gradient fields

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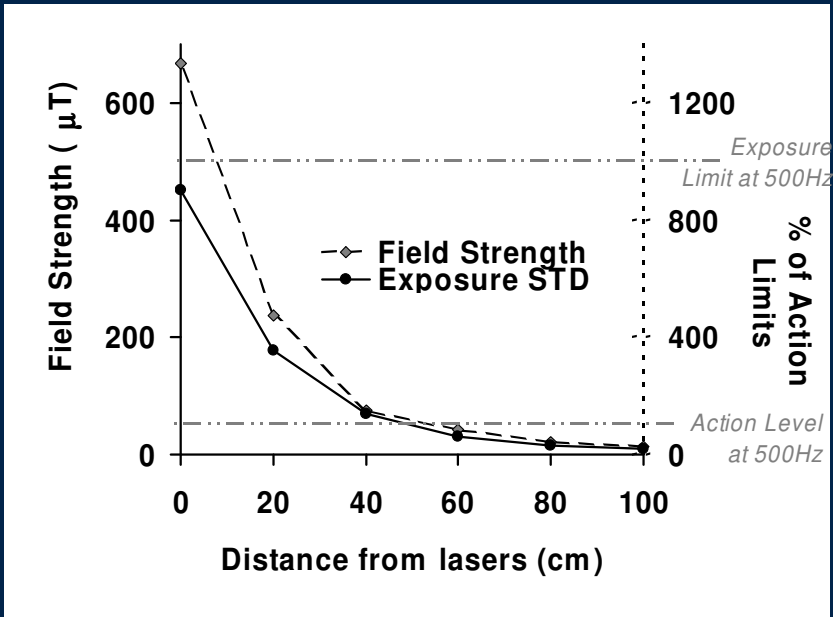

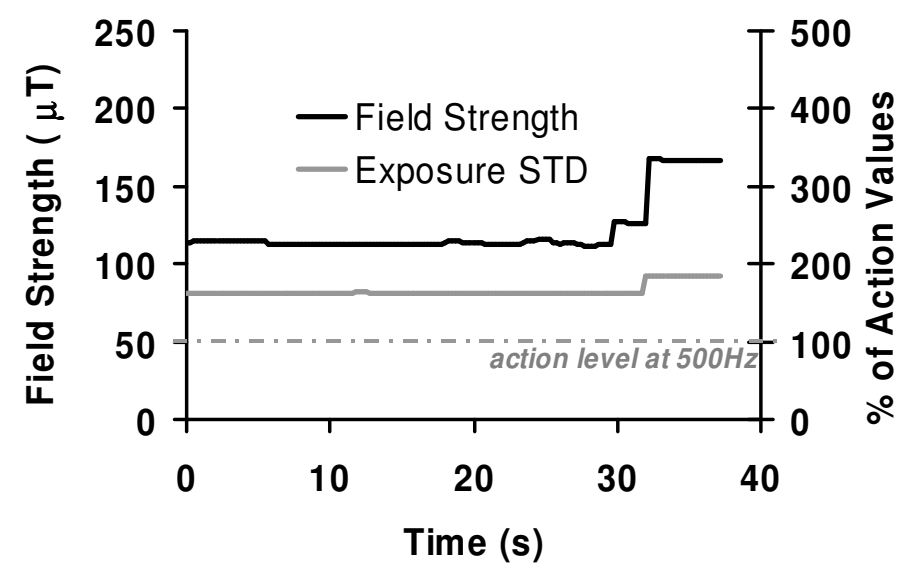

FFE sequence 500 Hz
400 mm FOV

Diffusion sequence at 40 cm from laser pointer

Narda probe

Sophie Riches
Royal Marsden Hospital

CANCER RESEARCH UK

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Gradient exposure at 500Hz

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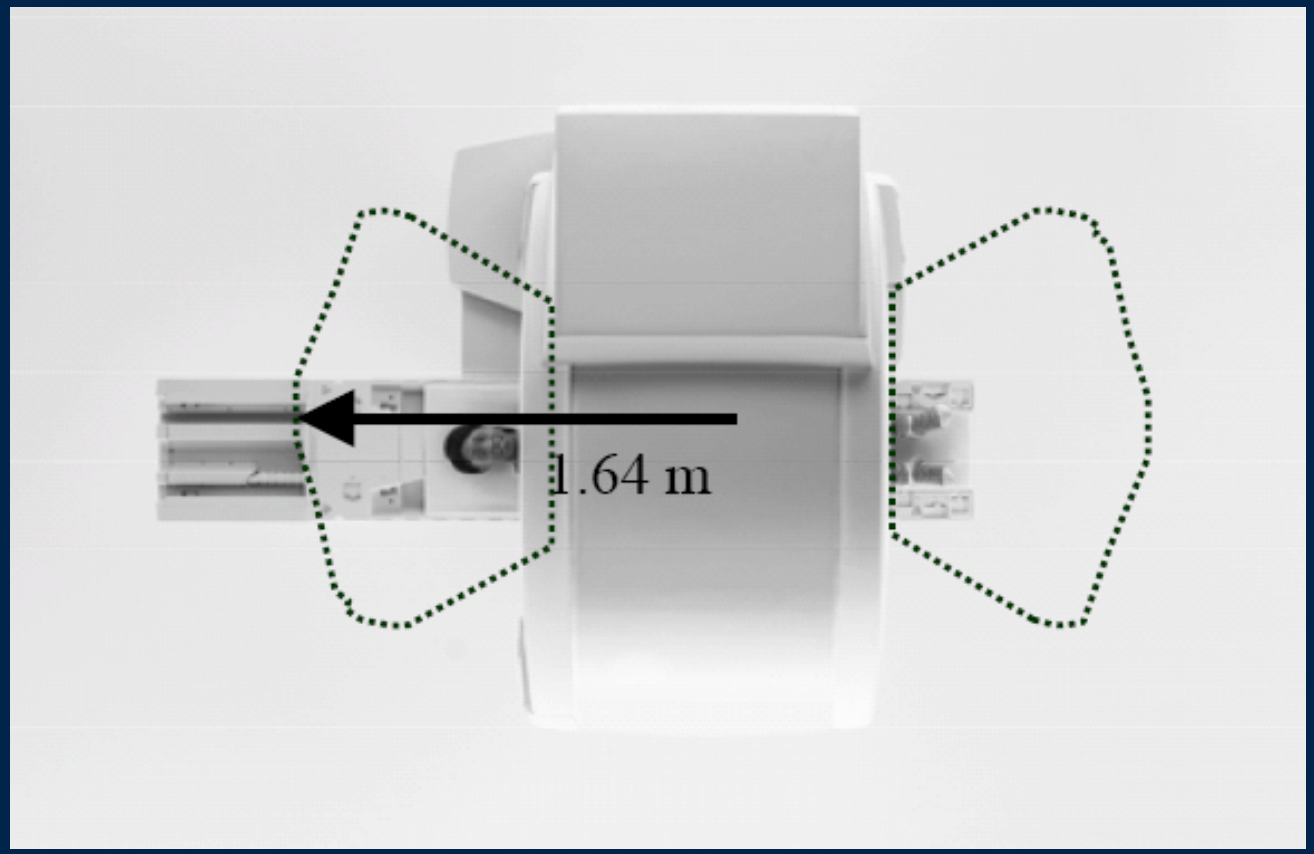
1.5T MR at Guy's Hospital London

KING'S College LONDON
University of London

‘Out of bounds’ region



Typical 30.7 μT isocontour which is action value in relevant frequency range (from COCIR)

Full model of induced current

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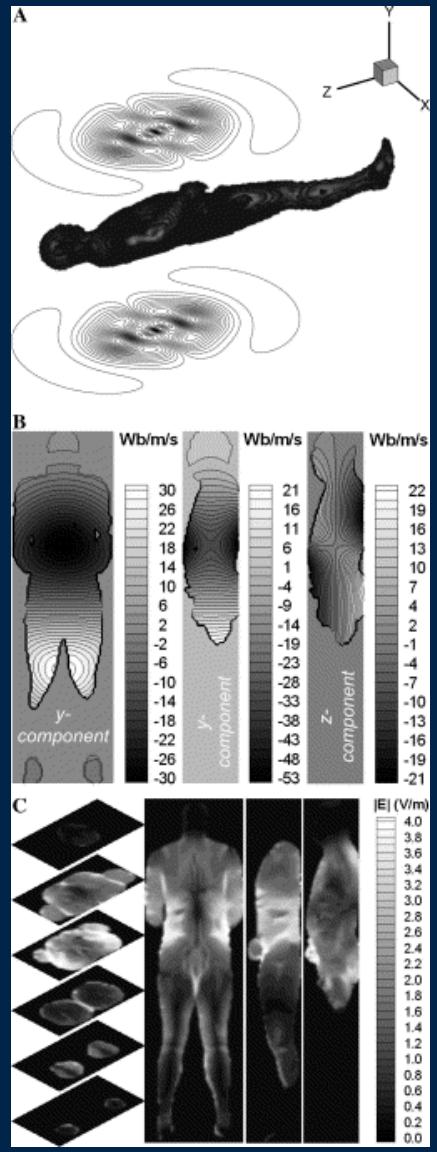
- Calculation of the induced electric fields inside the human whole-body model excited by a typical planar gradient *y*–coil
  - Are we confident this model is correct?

•The distributed equivalent magnetic current profile

•The calculated induced E-field profile.



Crozier et al,Queensland

Definite effects of exposure

Sensory effects

- When moving above 2T people report vertigo, phosphenes and metallic taste
- Phosphenes
  - Rarely reported in 7T magnet- requires rapid movement of head or eyes and low light levels (not dark)
  - Observed for experimental pulses of dB/dt ~ 1.5 T/s in most subjects


DIZZINESS

Causes of vertigo

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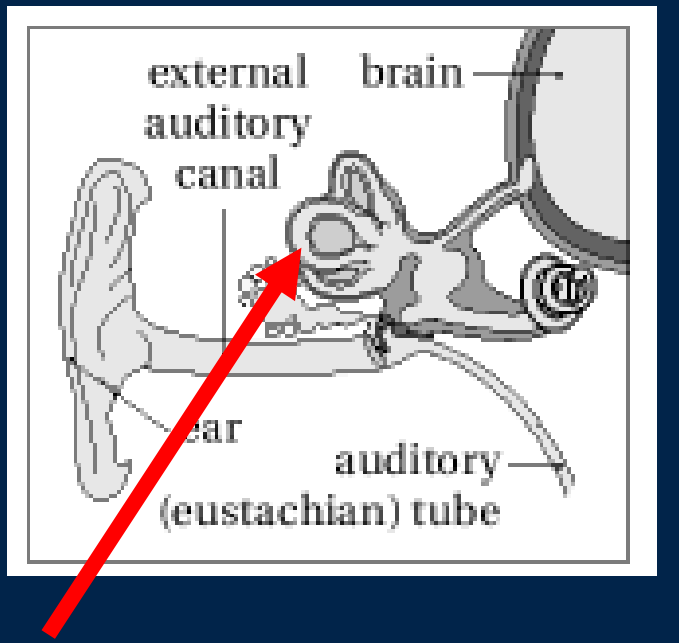
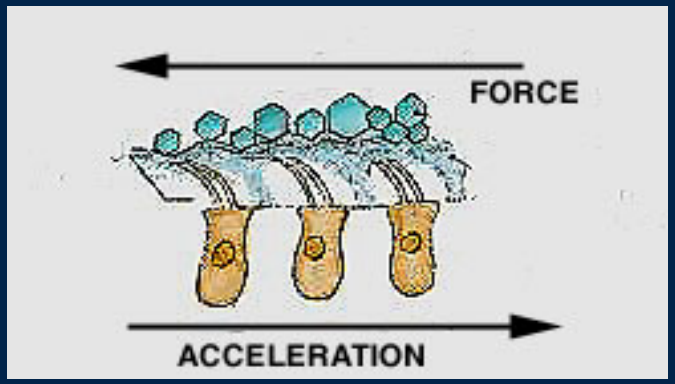
- Assumed interaction with middle ear
  - Magnetohydrodynamic effect
  - Electrical stimulation
  - Direct susceptibility differences
    - Between hair cell and surrounding fluid
    - Acceleration ~ 1% g at 43 T^2m^{-1}



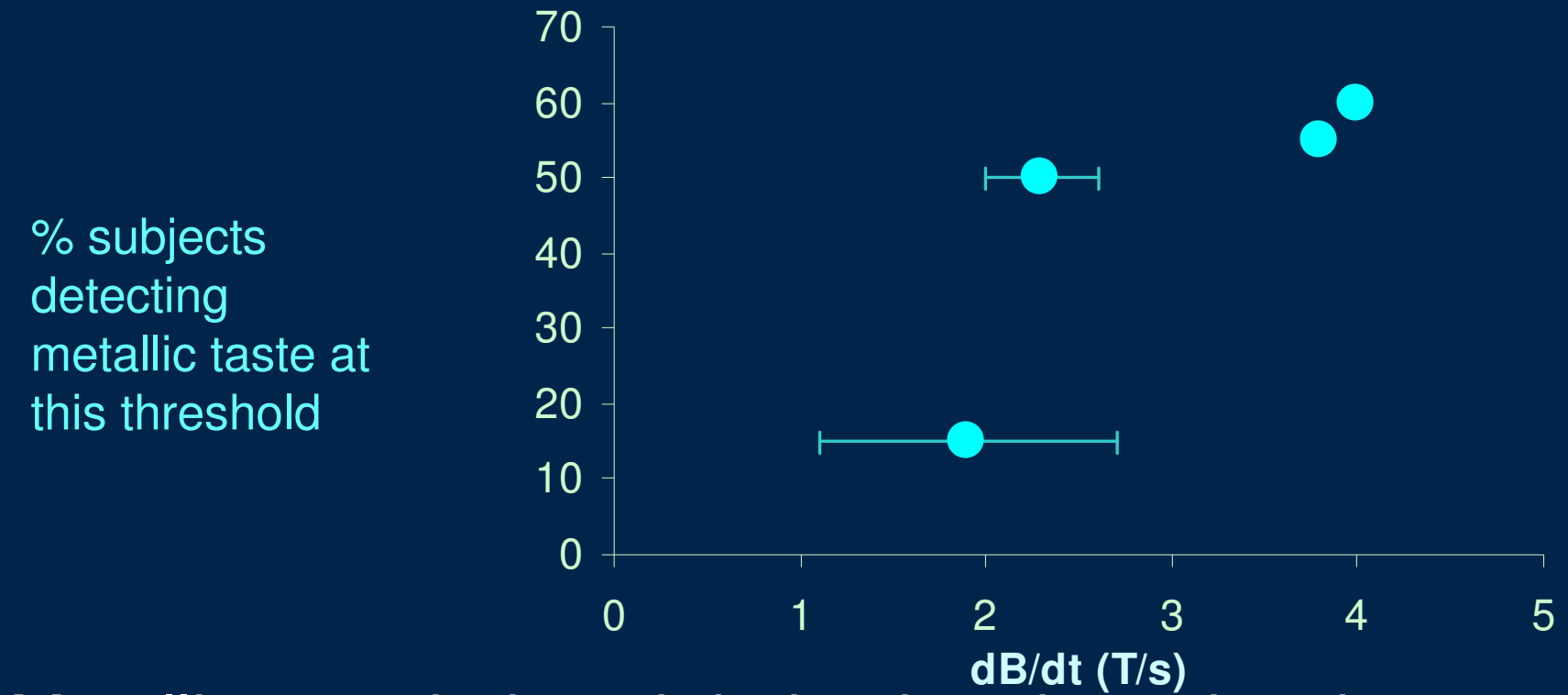


Glover et al, 2007

Metallic taste

The University of Nottingham

- Regular movements of head in field of ~0.5T and ~2.5 T/m at end of 7T, at 60-120 b.p.m.



- Metallic taste induced during head rotation, but not nodding

Magnetohydrodynamic effect

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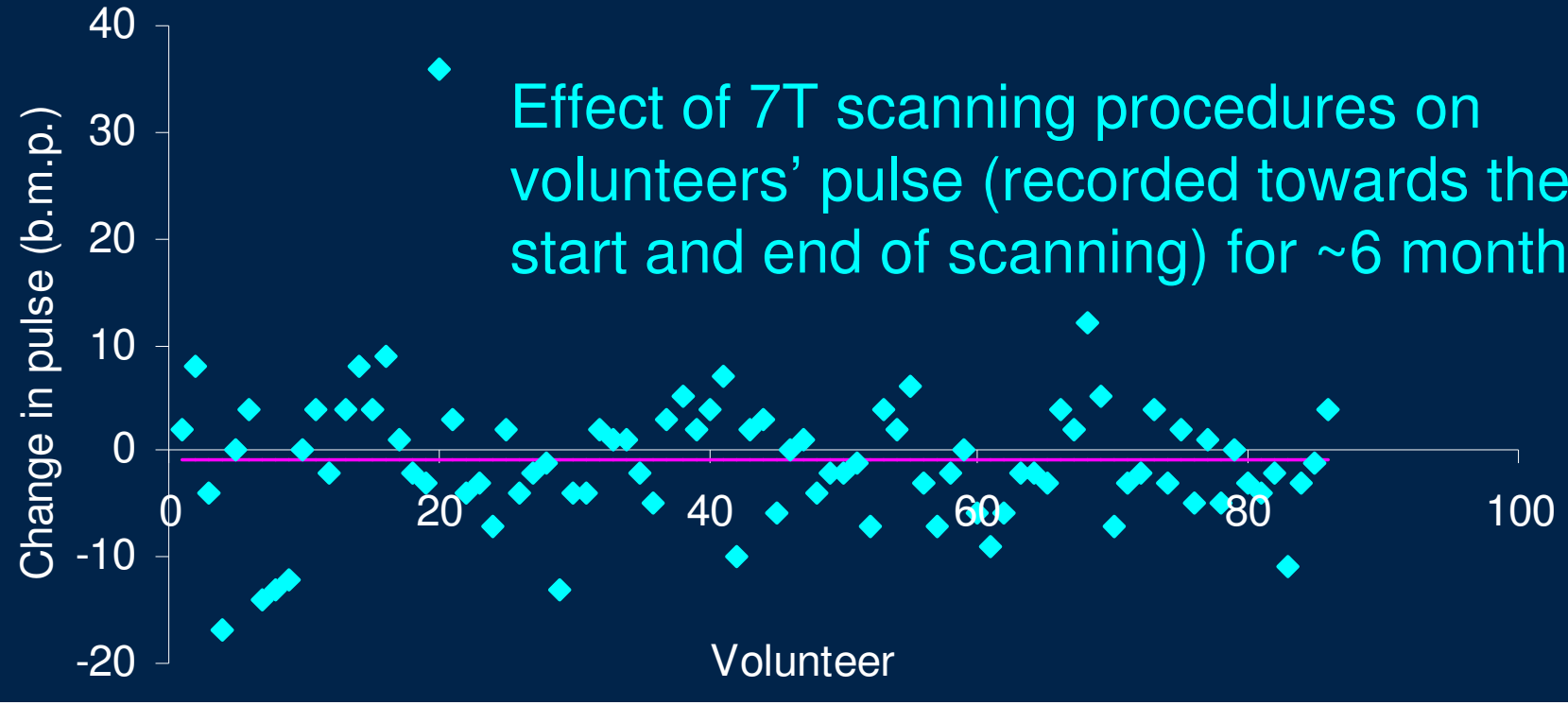
- Movement of charged solution in field will cause force on solution
- No significant change in blood pressure
  - No change observed at 8 T or 7T



Peripheral Nerve Stimulation

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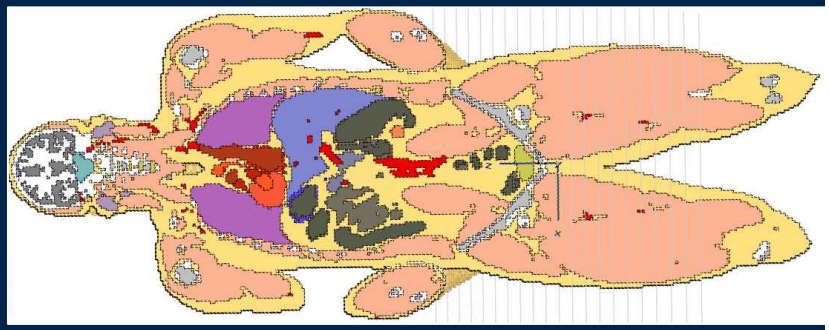
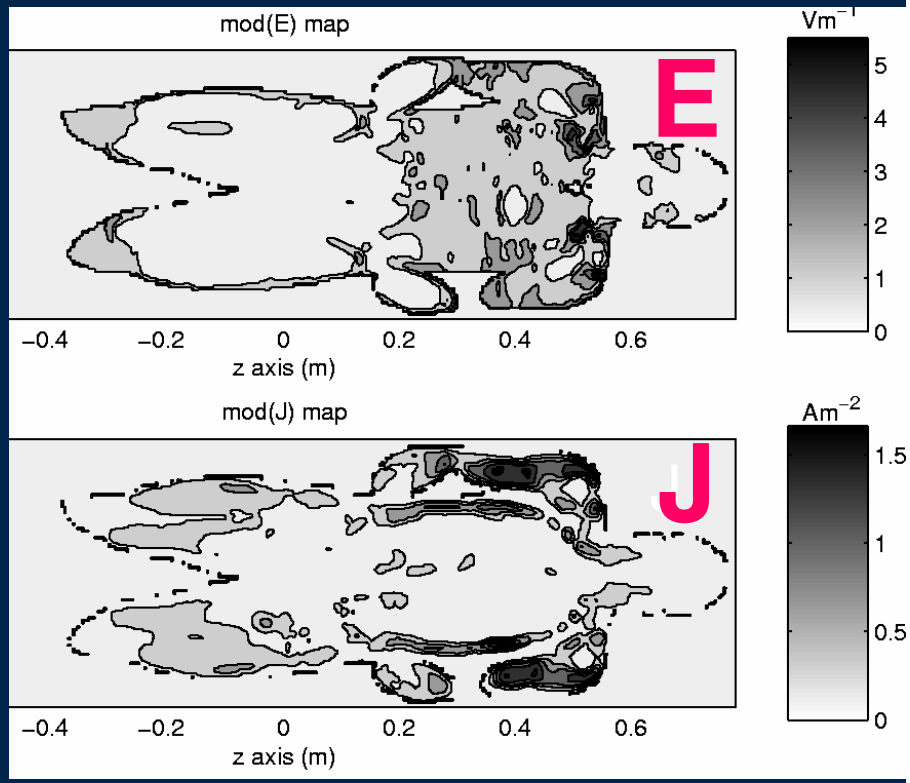
Numerical Simulations

- PNS is associated with hotspots of electric field (E) or current density (J)
- Get “hot-spots” of |E|/|J| in low/high conductivity tissues.



Head-centred coronal slice $y = 0$



RF heating

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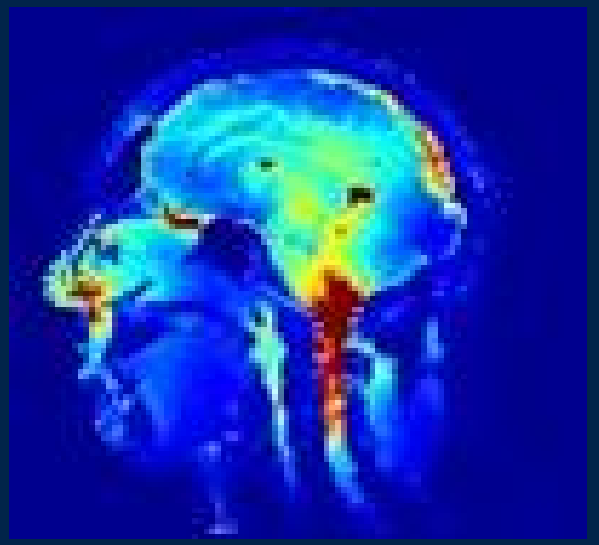
- No expectation that staff will exceed SAR limits under normal conditions
- For iMRI must consider surrounding objects inducing RF inhomogeneity

Accusorb



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Management

Safe Working Practices

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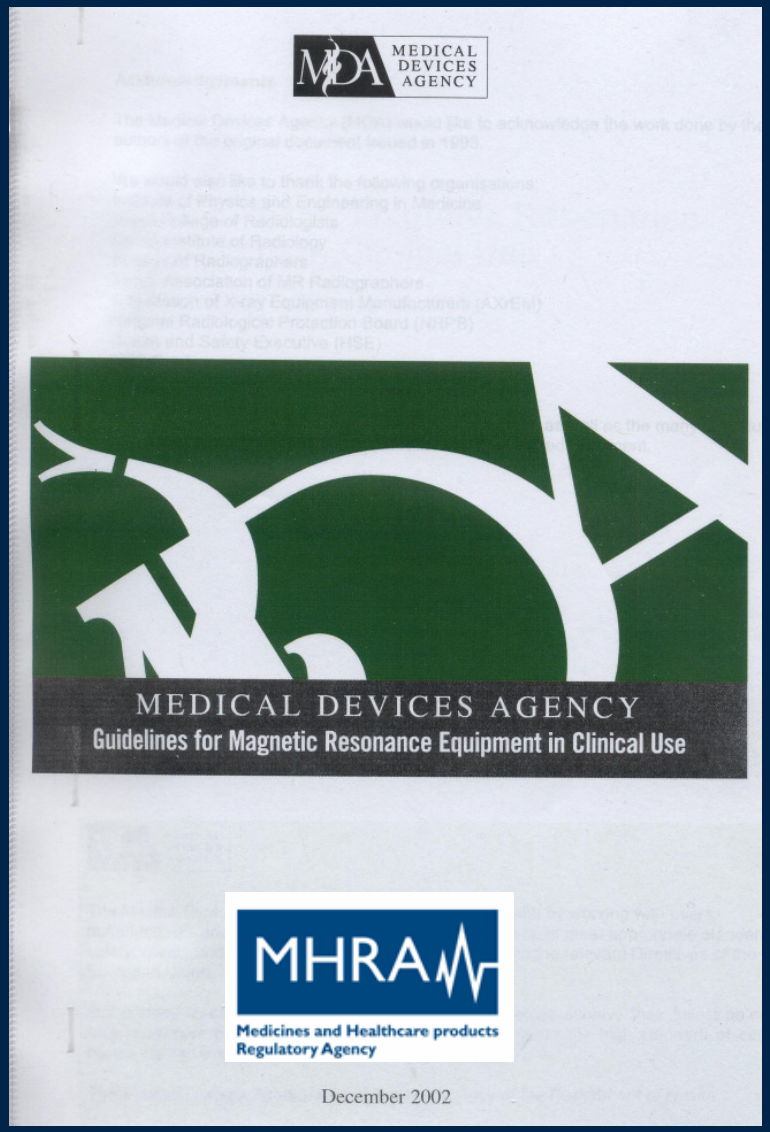

American College of Radiology White Paper on MR Safety

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The following is a report of the American College of Radiology Blue Ribbon Panel on MR Safety, chaired by Emanuel Kanal, MD, FACR, to the Task Force on Patient Safety, chaired by James P. Borgstede, MD, FACR. Under the auspices of the Task Force, the panel met in November 2001 consisting of the following members: A. James Barkovich, MD; Charlotte Bell, MD, (Anesthesia Patient Safety Foundation); James P. Borgstede, MD, FACR; William G. Bradley, MD, PhD, FACR; Joel Felmlee, PhD; Jerry W. Froelich, MD; Ellisa M. Kaminski, RTR, MR; Emanuel Kanal, MD, FACR; Elaine K. Keeler, PhD, (NEMA); James W. Lester, MD; Elizabeth Scoumis, RN, BSN; Loren A. Zaremba, PhD (FDA); and Marie D. Zinninger (American College of Radiology). The following document is intended to be used as a template for MR facilities to follow in the development of an MR safety program.

Recent articles in the medical literature and electronic/print media [1, 2] detailing Magnetic Resonance Imaging (MRI) adverse incidents involving patients, equipment, and personnel spotlighted the need for review. The Panel was charged with reviewing MR safety practices and guidelines and issuing new ones as appropriate for MR examinations and practices today [3–7]. The document restates existing practices and articulates new ones. This document will continue to evolve, as does the MRI field.

There are potential risks in the MR environment, not only for the patient but also for the accompanying family members, attending health care professionals, and others who find themselves only occasionally or rarely in the magnetic fields of MR scanners, such as security or housekeeping personnel, firefighters, police, etc. These MR Safe Practices Guidelines have been developed to help guide MR practitioners regarding these issues and provide a basis for them to develop and implement their own MR policies and practices. It is intended that these MR Safe Practice Guidelines (and the policies and procedures to which they give rise) be reviewed and updated on a regular basis.

It is the intent of the American College of Radiology (ACR) that these MR Safe Practice Guidelines will be helpful as the field of MR evolves and matures, providing patient MR services that are among the most powerful, yet safest, of all diagnostic procedures to be developed in the history of modern medicine.

ACR Magnetic Resonance Safe Practice Guidelines

A. Establish, Implement, And Maintain Current MR Safety Policies And Procedures

1. All clinical and research magnetic resonance imaging sites should maintain MR Safety Policies and Procedures, which are to be established, implemented, maintained, and routinely reviewed and updated, as appropriate. The level of compliance by staff will be assessed and documented annually. The policies and procedures manual should be readily available to the MR professionals on site at all times of operation.
2. These policies and procedures should also be reviewed concomitant with the introduction of any significant changes in safety parameters in the MR imaging environment of the site's MR service (e.g., adding faster/stronger gradient capabilities, higher RF duty cycle studies, etc.) and updated as needed. In this review process, national and international standards and recommendations should be taken into consideration prior to establishing local guidelines, policies, and procedures.
3. Each site will name an MR Medical Director whose responsibilities will include ensuring that these MR Safe Practice Guidelines are established and maintained as current and appropriate for the site. It is the responsibility of the site's administration to ensure that the policies and procedures that result from these MR Safe Practice Guidelines are implemented and adhered to at all times by all of the site's personnel.
4. Procedures should be in place to ensure that any and all adverse events, MR safety incidents, or "near incidents" that occur in the MR site are to be reported to the Medical Director of the MR site in a timely fashion (e.g., within 24 hours/one business day of their occurrence) and used in continuous quality improvement efforts.

Updated 2004

Nottm 7T exposure (7 months)

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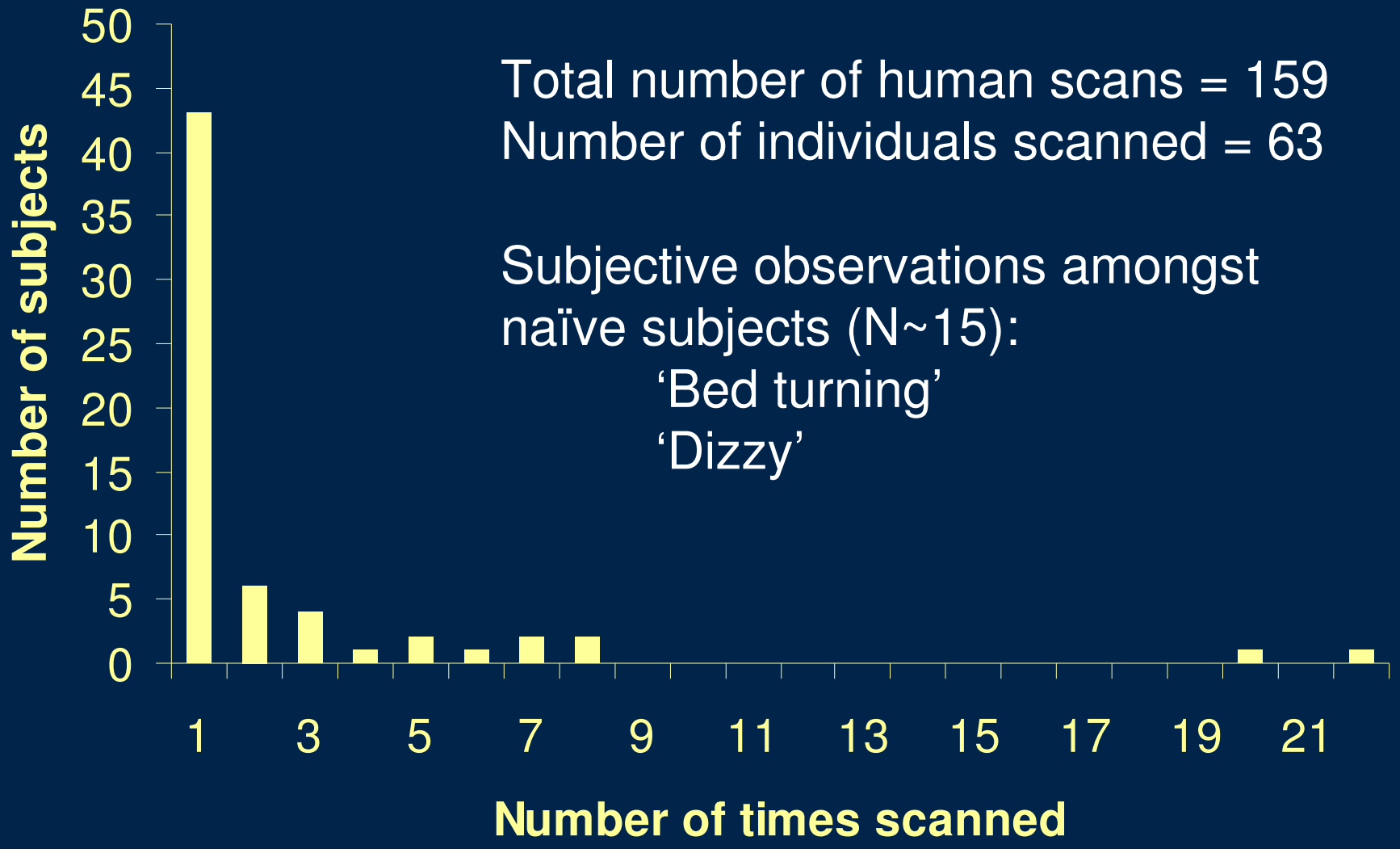

Total number of human scans = 159
Number of individuals scanned = 63

Subjective observations amongst naïve subjects (N~15):

‘Bed turning’

‘Dizzy’

SPMMRC staff exposure (>0.5 T)

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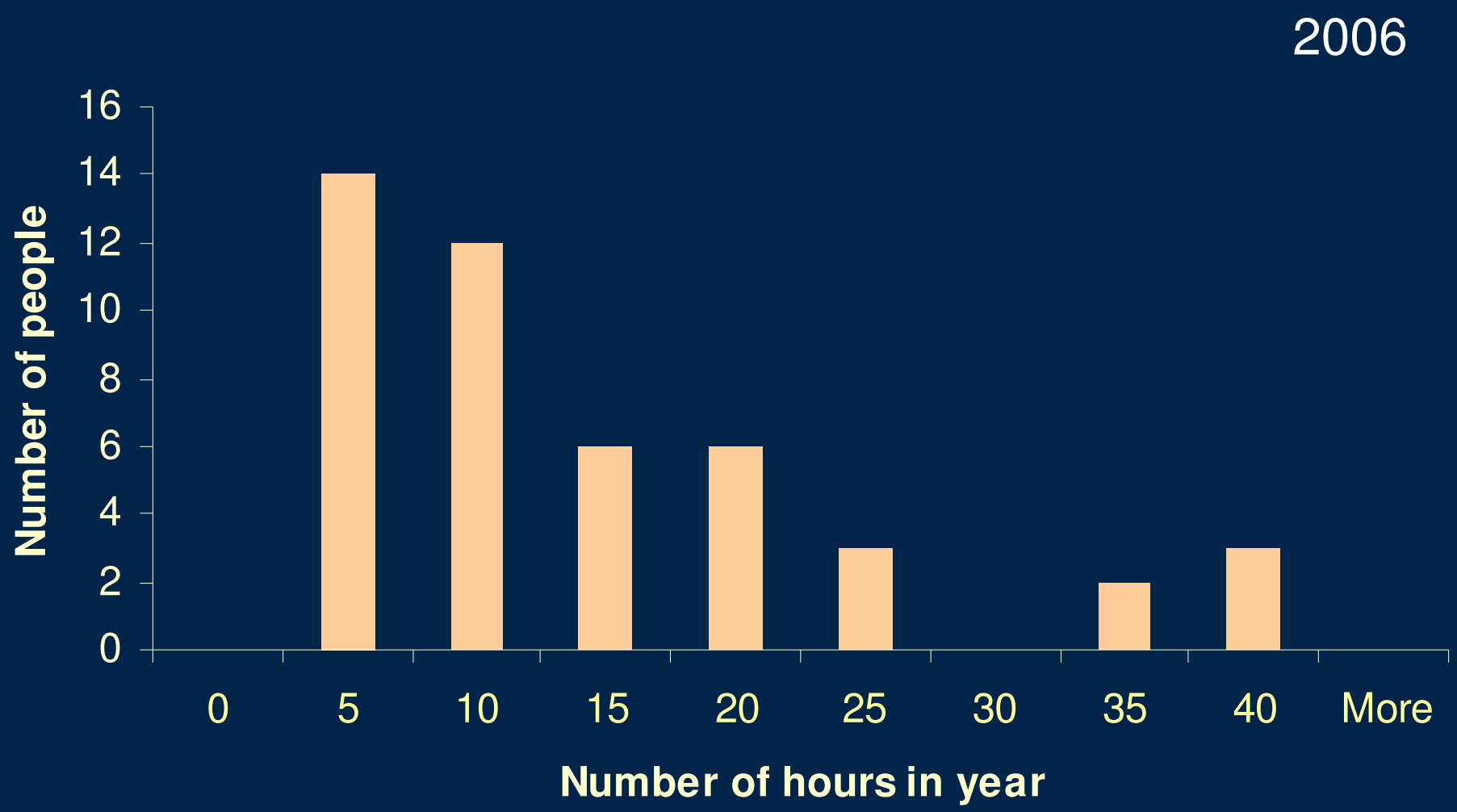


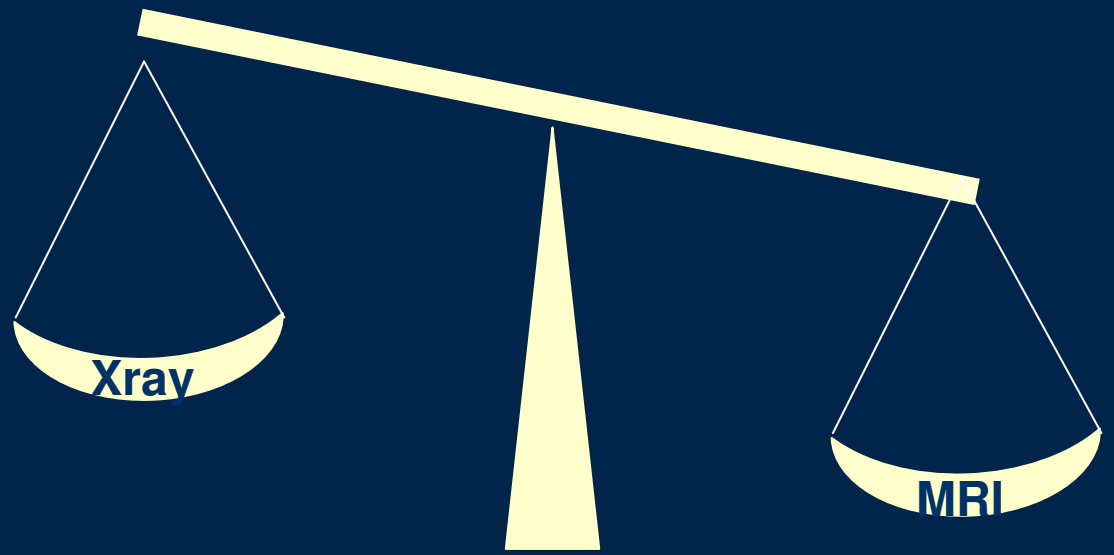
Analogy to ionizing radiation

Radiation exposure

- Any procedures must result in a net benefit
- Radiation dose limits must never be exceeded
- All exposure must be kept As Low As Reasonably Practical (ALARP) taking into account social and economic factors

Radiation exposure

- All exposure must be kept As Low As Reasonably Practical (ALARP) taking into account social and economic factors



ALARP

Precautionary Principle

Staff working with radiation

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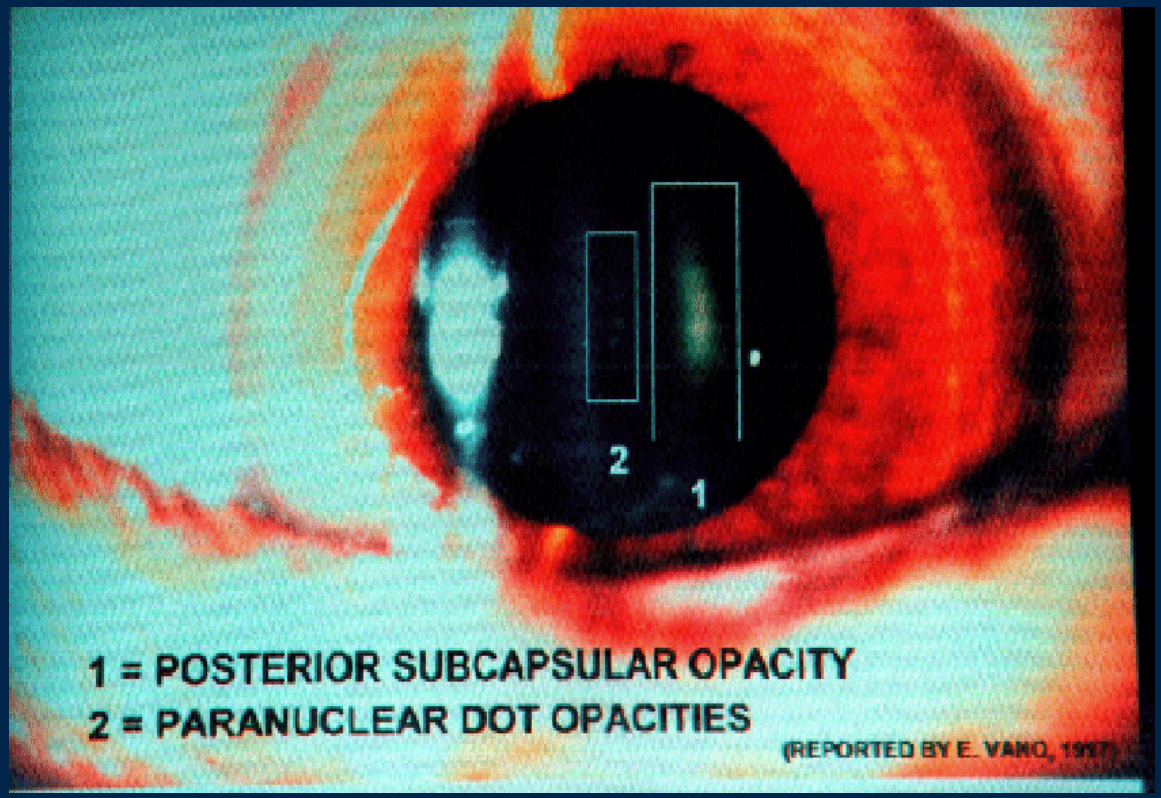
- 10% of practicing interventional radiologists showed signs of catacts in a small study.



Catarct in eye of interventionalist due to repeated use of over the table x-ray tube

ICRP

Ionizing radiation staff

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- Risk of severe stochastic effect (cancer or heredity) due to 1 Sv ~ 6 10^{-2}
- Occupational exposure limit 20 mSv p.a., but typical exposures ~4 mSv p.a. (twice b.g.)
- For 20 year career before the age of 45, total exposure could be 0.08 Sv.
- 0.5% of staff exposed at this level will suffer a severe side effect

How to decide an exposure limt?

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- For radiation it is easy.. We know the risk.
- But why does that make it easy?
- Who chose 20 $mSvy^{-1}$?
- Why is that risk acceptable?

- I asked 21 members of the SPMMRC who are generally
  - used to going in the scanner
  - reasonably well educated about safety
  - Wanting to scan and be scanned for their research

- ‘What is a reasonable exposure limit taking into account safety issues as you understand them, and quality of life factors (i.e. you could be down the pub or reading a book)?’

Poll results

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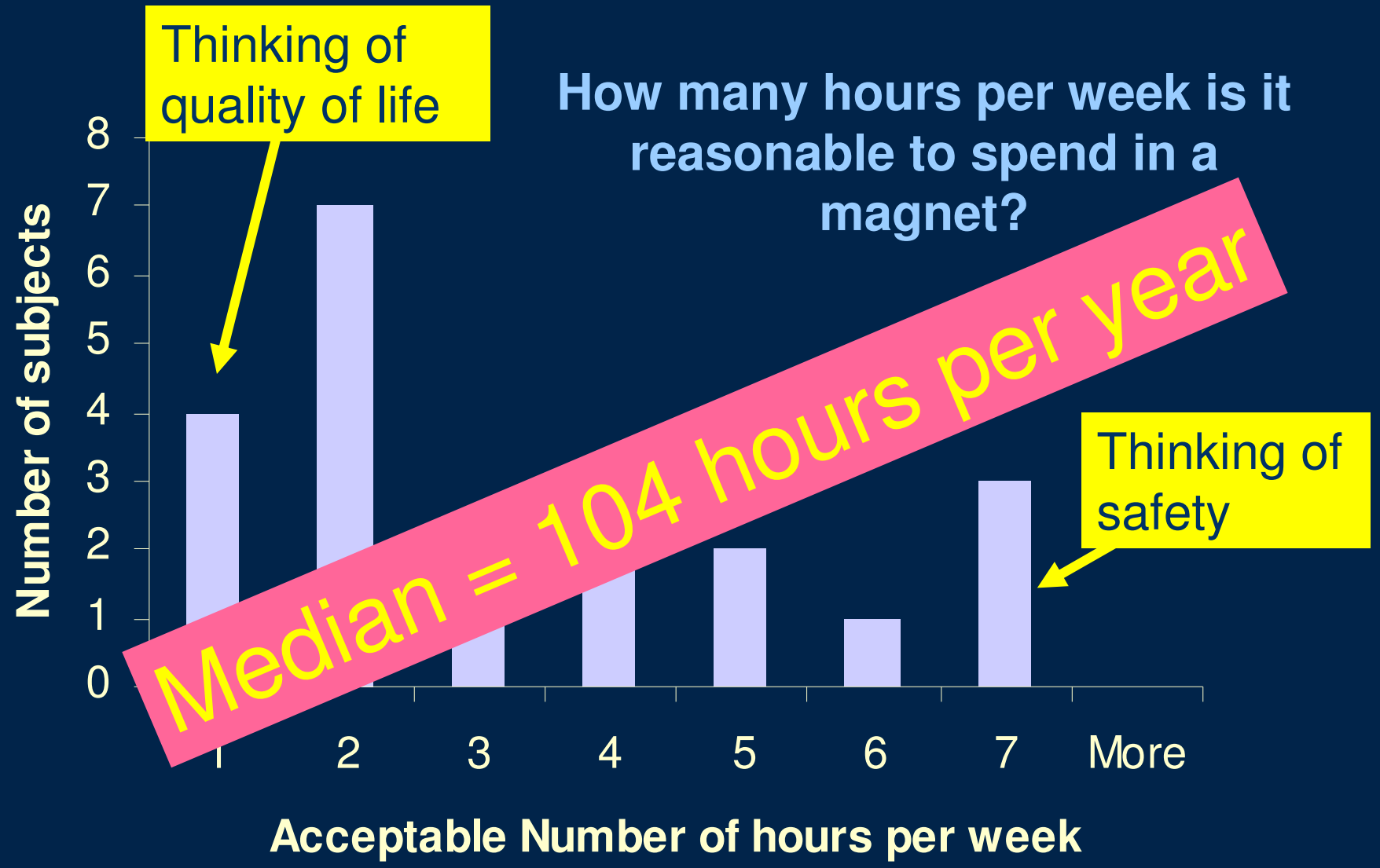

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- ICRP web site