Health Physics of Magnetic Resonance Imaging
What Is It?

- Very strong static magnetic field in the bore and strong fringe magnetic fields outside, near the bore
  - Moving object through a static magnetic field induces a current
- Pulsed gradient magnetic fields (a few 100 Hz)
- Pulsed RF fields during the MRI scan process
Why Do We Care?

• Ontario Ministry of Labour
• European regulators are considering restricting static magnetic field strengths
  – Current density limits for any time-varying magnetic field
• Resolution depends on magnetic field strength
• May stifle development of high resolution scanners if European market isn’t accessible
• Regulations may eventually spill over to North America
Why Do We Care?

• European Commission reports: Physical Agents (EMF) Directive
  – Directive 2004/40/EC
  – Postponement until 2012 due to “new scientific evidence” related to MRI
  – RF exposure limits, insufficient data to regulate static fields, especially for short duration exposures

• ICNIRP
  – RF and static magnetic field guidelines
  – EC has adopted 1998 guidelines through the EMF directive
Magnetic Resonance Imaging
MRI Scanner

MRI Scanner Cutaway

- Radio Frequency Coil
- Gradient Coils
- Magnet
- Scanner
- Patient
- Patient Table
MRI

• Tomographic imaging method in which a static, highly uniform magnetic field ($B_o$) permeates the body section being imaged

• Field induces a net magnetization ($M$), sum of all magnetic dipole moments ($m$) from spinning hydrogen nuclei

• Applied RF signals (42.7 MHz when $B_o = 1T$) excite nuclei (dipole moment flips, phases align)

• Rotating “magnet” induces currents in receiver coils to generate signal
Alignment Of Spins In Static Magnetic Field

Spins do not align perfectly, but rather process around magnetic field lines at Larmour frequency.

Overall magnetisation of nuclei = Sum of vectors from individual nuclei
RF Pulse

Distribution and phase of spin states is perturbed by RF pulse (correct pulse equalizes #spin up/down)

Overall magnetisation of nuclei = Sum of vectors from individual nuclei
Relaxation Of Spins

• Excited ("spin down") nuclei "relax", causing net magnetization vector to return to original alignment
  – Changes in net magnetization during relaxation process detected by receiver coils (Faraday’s law of induction)

• Relaxation characterized by time constants (e.g. T1 & T2)
  – Time constants are tissue-specific
  – Localization of signals through use of magnetic field gradients
  – Elaborate signal processing leads to a 3D map of tissue composition
Relaxation Of Spins

• Longitudinal relaxation (T1)
  – Time required to become magnetized when placed in a magnetic field, or to recover magnetization following a RF pulse
  – Slow process

• Transverse relaxation (T2)
  – Free Induction Decay (FID) signal
  – Measure of how long protons precess in phase after being excited by a 90° RF pulse
  – Rapid process
**T₂ Relaxation**

Overall magnetisation of nuclei = Sum of vectors from individual nuclei

Spins quickly de-phase Free Induction Decay (FID) signal from shrinking net transverse magnetization
$T_1$ Relaxation

Spin up/down equilibrium returns slowly

Recovery of $M_z$ net magnetization

Overall magnetisation of nuclei = Sum of vectors from individual nuclei
Relaxation Of Spins

Longitudinal magnetization recovery (T1)

Transverse magnetization decay (T2)
Why Use MRI?
Safety?

• Occupational RF exposure for those working around MRI is typically not a concern (exposure is well below limits)

• RF exposure to patients for a typical scan usually low enough to not be a concern for patient safety

• However, significant heating may occur if imaging is performed around metallic implants, conductive leads, cables in contact with the patient

• More concerning is the possibility of flying metal objects hitting someone in the room!
Safety?

• For the patient, the benefit should always outweigh the risk
  – Non-ionizing procedure
  – Some uncertainty as to the effects of high strength static magnetic fields

• The main concern is then occupational exposure
  – To what?
Patient Exposure
ICNIRP Recommendations

• 2009 addendum to their 2004 MRI guidelines for patient safety
• No issues for normal operation up to 4 T
• Upper limit should be 8 T, used with clinical evidence
• Experimental usage above 8 T, close monitoring of patients is strongly recommended (especially cardiac monitoring)
Occupational Exposure
Sources

• Radio and extremely low frequencies
  – “Switched gradients” to localize signals (static fields turned on and off 100’s – 1000’s Hz)
  – 10’s – 100’s MHz RF fields to flip spins

• Static magnetic field
  – May appear as $>0 \text{ Hz}$ time varying field when a person walks through it
Switched Gradient And RF Fields

• These are not an occupational concern because technologists are not typically in the procedure room while the MRI is running
Static Fields

• European Commission has recently set out updated regulations (2012)
  – Both field strength directly, and the effects of a body moving through a static field
  – Now reflects recommendations from ICNIRP

• ICNIRP (2009) “Guidelines on Limits of Exposure to Static Magnetic Fields”
Old Proposed EC Limits (2004/40/EC)

<table>
<thead>
<tr>
<th>Static magnetic field</th>
<th>Frequency</th>
<th>Exposure limit</th>
<th>Action value for magnetic flux density</th>
<th>Estimated maximum occupational exposure in the UK</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Hz</td>
<td>None</td>
<td>0.2 T</td>
<td>3 T (clinical)</td>
<td></td>
</tr>
<tr>
<td>&lt;1 Hz (typical)</td>
<td>Current density 40 mAm(^{-2}) to head and trunk</td>
<td>0.2 T</td>
<td>7 T (research)</td>
<td></td>
</tr>
<tr>
<td>(generated by movement of subject)</td>
<td></td>
<td></td>
<td>Possibly up to several hundred mAm(^{-2})</td>
<td></td>
</tr>
</tbody>
</table>

| Switched gradients     | 500 Hz (typical) | Current density 10 mAm\(^{-2}\) to head and trunk | 50 μT | 2,000 μT (to head) |
| RF field              | 10-400 MHz       | SAR 0.4 Wkg\(^{-1}\) whole body average, averaged over six minutes. | 0.2 μT | <0.4 Wkg\(^{-1}\) whole body average in most conceivable situations. |
|                       |                   | SAR 20 Wkg\(^{-1}\) to the limbs, averaged over six minutes. |       | Local SAR may approach limit in some instances. |

“Action values” are surrogates for current densities.
Updated Directive (COM/2012/0015)

• Changes for low frequencies only (<100kHz)
  – Amends 2004/40/EC directive

• “Orientation value”: 2T
  – The "orientation value" referred to in point (f) of paragraph 1 corresponds to a field level where no adverse health effect should be noticed under normal working conditions and for persons not being part of a group at particular risk. As a consequence, the depth of the risk assessment procedure can be reduced to a minimum. Compliance with the orientation value will ensure compliance with the relevant exposure limit values for safety and health effects.

• “Action value”: 8T
  – The "action value" referred to in point (f) of paragraph 1 corresponds to the maximum directly measurable field for which automatic compliance with the exposure limit value is guaranteed. Any exposure level between the "orientation value" and the "action value" requires more extensive valuations and preventive measures. Compliance with the action value will ensure compliance with the relevant exposure limit values for health effects.
Static Magnetic Field
Guidelines From ICNIRP 2009
Static Fields

• Magnetic induction
• Electron spin interactions
• Magneto-mechanical
  – Orientation (torque)
  – Translation (linear force)
Magnetic Induction

• Lorentz force on moving electrolytes
  – Induced electric fields and currents
  – Theoretical calculations suggest 100 mA/m² induced densities around the heart at 5 T

• Induced fields/currents due to movement
  – Data suggest induced currents may be substantial during normal movement around or in 2 – 3 T fields
  – Currents/fields increase with walking speed
  – Nausea and vertigo have been reported by people walking through the fringe field of 3 T MRI
Fringe Fields

3T MRI scanner
Electron Spin

• Some metabolic reactions involve an intermediate radical state
  – Spin correlated radical pairs
• Radical pairs recombine to form reaction products
• Rate of product production (due to spin flip from singlet to triplet electronic state) strongly affected by magnetic field strength
Magneto-Orientation

• Paramagnetic molecules experience a torque that minimizes their free energy in the static magnetic field
• Forces are generally considered too small to affect biological tissues *in vivo*
Magneto-Translation

- Occurs in the presence of a magnetic field gradient
- Force in the direction of (diamagnetic) or against (paramagnetic) gradient
- *e.g.* 8 T magnet with 50 T/m falloff can decrease the depth of water in a trough passing through the field
- Corresponds to <40mm H$_2$O pressure, not enough to affect blood flow in a human
  - Small effect in rats though
So What Are The Issues?

• What short term exposure level is appropriate, if any?
  – No evidence of long term or serious consequences, only temporary sensory effects
  – Health effects like vertigo become important if the worker feints
So What Are The Issues?

• What about levels above which there are no human experiences?
• Concern is the lack of knowledge rather than specific knowledge of adverse effects
Exposure Of Workers

• With appropriate advice and training, it is reasonable for workers to voluntarily and knowingly experience possible transient sensory effects like nausea

• No evidence of cardiac effects up to 8 T

• Set limits to minimize sensory effects
Exposure Of “General Public”

• Additional concern of implanted cardiac rhythm management (CRM) devices (pacemakers, et cetera)

• Lower limits recommended, even though direct sensory effects have a higher threshold
ICNIRP Exposure Limits (2009)

Table 2. Limits of exposure\textsuperscript{a} to static magnetic fields.

<table>
<thead>
<tr>
<th>Exposure characteristics</th>
<th>Magnetic flux density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupational\textsuperscript{b}</td>
<td></td>
</tr>
<tr>
<td>Exposure of head and of trunk</td>
<td>2 T</td>
</tr>
<tr>
<td>Exposure of limbs\textsuperscript{c}</td>
<td>8 T</td>
</tr>
<tr>
<td>General public\textsuperscript{d}</td>
<td></td>
</tr>
<tr>
<td>Exposure of any part of the body</td>
<td>400 mT</td>
</tr>
</tbody>
</table>

\textsuperscript{a} ICNIRP recommends that these limits should be viewed operationally as spatial peak exposure limits.

\textsuperscript{b} For specific work applications, exposure up to 8 T can be justified, if the environment is controlled and appropriate work practices are implemented to control movement-induced effects.

\textsuperscript{c} Not enough information is available on which to base exposure limits beyond 8 T.

\textsuperscript{d} Because of potential indirect adverse effects, ICNIRP recognizes that practical policies need to be implemented to prevent inadvertent harmful exposure of persons with implanted electronic medical devices and implants containing ferromagnetic material, and dangers from flying objects, which can lead to much lower restriction levels such as 0.5 mT.
Protective Measures

• Signage for fields > 0.5 mT
  – CRM devices
  – Acceleration of metallic objects

• Administrative controls
  – Procedures that minimize the potential adverse consequences of exposure
  – e.g. a surgeon working in the vicinity of an open MRI, minimizing risk of them becoming nauseous during a procedure
Canadian Guidelines
Safety Code 26

• “Guidelines on Exposure to Electromagnetic Fields from Magnetic Resonance Clinical Systems” (1987)
• Covers static, gradient, and RF fields
• Offers “exposure guidelines”
Patient Exposure

• Static fields < 2 T not hazardous (> 2 T not necessarily hazardous but insufficient data exist, so care should be taken)
• Gradient fields that change no faster than 3 T/s
• RF fields that restrict core temperature increases to 0.5 °C, or any other part of the body to 1.0 °C
  – SAR < 1 W/kg over 25% of the body for exposure > 15 min
  – < 2 W/kg for < 15 min
Operator Exposure

• Should not be exposed continuously to > 0.01 T throughout the day

• Exposure to “higher flux densities” are acceptable (up to 10 min/hr) but number and duration should be minimized
Special Considerations

- Pacemaker patients should be monitored and resuscitation equipment should be on hand (outside the room – doesn’t work > 10 mT)
- Continuous monitoring for discomfort for patients with (large) metallic implants
- Suitability of patients with surgical clips?
- At the time, no specific guidance for pregnant women
Ontario Ministry of Labour

- **Radiation Protection Service**
- Uses guidelines from American College of Radiology (ACR) for safety standards, and:
    - Ministry of Health & Long Term Care
- Divides an MR facility into **zones** based on static field strength, security requirements
  - Signage and access control based on zone
Recommendations For Legislation/Regulation

• MR safety officer
• Demarcation of high magnetic field zones (III & IV), with entry restricted to qualified personnel using physical barriers
• Person/item screening & reporting mechanisms
• Various policies and procedures (pregnancy, time-varying fields)
Recommendations For Legislation/Regulation

• Designated MR personnel
  – Similar to NEWs/X-ray workers

• Design, maintenance, and inspection of facilities based on 2007 provincial report
Static Fields

• 5 Gauss (0.0005 T) divides the environment into safe and unsafe regions
  – 0.5 mT corresponds to a level several times greater than where a static field may interfere with implanted devices such as pacemakers
Static Fields

• Best practice is to contain 0.5 mT field line in the MR suite, but it is acceptable to allow a small portion of ~1 mT field outside, as long as facilities have mechanisms in place to restrict access for non-MR personnel.
The “Zone” System

Entrance to Facility
Zone I

Patient Dressing/Holding
Zone II

Reception
Zone II

Zone III

Zone IV

Computer Room

Control Room

Magnet
Zone IV

- This is the scanner room itself
- Signage
  - Potentially hazardous due to high magnetic fields
  - “The magnet is on”
- MR technologists must be able to observe and control all access points
- Escape hatch in case of magnet quenching recommended but not yet required
Zone III

• Effectively, the area outside scanner room with fringe fields $> 0.5$ mT
  – Not typically applicable in Ontario, but...

• Future facilities will be built with this “buffer zone” in mind
  – Access restricted to MR personnel, individuals escorted by same
  – Regions with fields $> 0.5$ mT clearly marked as “potentially hazardous”
MR Personnel

• Level 1
  – Passed minimal safety training
  – May work in Zone 3

• Level 2
  – More extensive training, broader aspects of safety (e.g. RF burns, neuromuscular excitation from rapidly changing gradients)
  – MR safety officer identifies necessary training, qualified individuals
Other Safety Considerations

- Non-magnetic fire fighting equipment
- Fire plan for major fires in Zones III or IV
  - Serious consideration of quenching magnet
- Plan for dealing with cardiac arrest or other medical emergencies
  - Patient must be moved to a magnetically safe location since the magnetic field may hinder resuscitation attempts using defibrillator
Consequences Of Magnet Quenching

• Liquid helium is vented from superconducting magnet

• Gas must be vented from the building into a restricted area
  – You don’t want pedestrians walking into a cloud of super-cooled helium!

• Evacuate all persons from the room as quickly as possible, especially if venting is incomplete
  – White clouds/fog around scanner
Warning Signs

- **DANGER**
  - **Restricted Area**
  - **Powerful Magnet Always On**
    - ICD’s, implantable cardiac defibrillators, and Cardiac Pacemakers are NOT ALLOWED.
    - Individuals with implanted devices or objects of metallic nature are not permitted into this area (flying or death may result).
    - If you are unsure if you are permitted to enter, DO NOT ENTER. Consult a radiologist or MRI technologist.
  - **No loose foreign metallic items allowed.**
    - Injury or death or patient can result from metallic objects, hearing aids, ICDs, and other electronic items may be damaged.

- **MRI Safety Signs**
  - **Non-Magnetic MRI**
  - **MRI SAFE**
  - **Magnet In Use**

- **DANGER**
  - **HIGH MAGNETIC FIELD!**
  - **STOP**
  - **DO NOT ENTER IF YOU HAVE ANY OF THE FOLLOWING:**
    - All metal objects, pens, scissors, watches, credit cards, implantable cardioverter defibrillators, pacemakers, oxygen tanks, pagers, and cell phones.

- **DANGER**
  - **STRONG MAGNETIC FIELD**
    - No pacemakers, implanted defibrillators, metal implants, loose metal objects, hearing aids, cell phones or pagers allowed.
    - Authorized personnel only.