Chapter 2

2 Literature review

2.1 Introduction

The physical environment of electromagnetic fields include: the natural magnetic field due to the sum of the internal field of the earth acting as a permanent magnet and the external field generated in the environment from such factors as solar activity or atmospherics; artificial field coming from all devices containing wires carrying direct current, including many appliances and equipment in industry and health care like magnetic resonance imaging (MRI). Magnetic resonance imaging is used to create sectional imaging of the body for diagnosis of pathology or functional disorders in the health profession. Radiology training includes the MRI spectrum (Grandolfo, 1998: 28).

The phenomena that permit MRI are based on magnetism, electricity and radiofrequencies applied according to the principle of nuclear physics and quantum mechanics. For this reason the imaging process was referred to as nuclear magnetic resonance (NMR) (Carlton & Adler, 1996: 664).

The aim of this chapter is to provide the reader with background knowledge of the origin of MRI and a basic understanding off the mechanism involved in MR image formation. Furthermore, to provide an overview of the safety aspect and exposure limits involved with the electromagnetic fields in the MRI environment. Also to familiarise the reader with the parties and procedures involved in the process of setting exposure limits to EMF in the MRI environment and the current position regarding exposure limits in the rest of the world.

2.2 History of nuclear magnetic resonance

Although the origin of atoms dates back to 400 B.C., when the atom was discovered by the Greeks, it was only 2000 years later that Hans Christian Oersted (1977-1851) discovered that electricity produced magnetism (MRI for Technologists, 1995: 1).

Michael Faraday (1831) then stated and proved that if electricity can produce magnetism, magnetism can produce electricity (Carlton & Adler, 1996: 62). Faraday's two laws of electromagnetism stated:

- that a change in the magnetic flux linked with a conductor induces an electromagnetic force (EMF) in the conductor [law of induction];
- that the magnitude of the induced EMF is proportional to the rate of change of the magnetic flux linkage. Faraday is regarded as the father of electricity (Graham, 1996: 169). The laws of Faraday form the basis of MR signal detection and modern-day magnetic resonance imaging (MRI for Technologists, 1995: 2); (MRI for Technologists, 2001: 2). The mathematical equation for the law of induction: $E = -N\Delta\Phi_B/\Delta t$, where:
    - E = *electromotive force (emf) in volts;*
    - N = *number of turns of wire;*
    - $\Phi = BA$ = *magnetic flux;*
    - B = *external magnetic field;*
    - A = *area of coil* (Hall, 2001:234).

In 1860 Sir James Maxwell of Scotland discovered that magnetic lines of force could be expressed mathematically. He proved that electrical and magnetic lines coexist at 90^o to each other. MRI signal from the spins can only be detected when the spins are at an angle to the main magnetic field, and the best signal will be when the electric and magnetic lines are at a 90 degree angle with each other (Westbrook, Kaut Roth & Talbot, 2005:15). During the same year, Heinrich Hertz of Germany discovered that invisible electromagnetic waves do exist. He also discovered that all the electromagnetic waves have identifiable values, which led to the discovery of the electromagnetic spectrum (MRI for Technologists, 2001: 1).

Wilhelm Conrad Roentgen (1895) was the first to discover high frequency electromagnetic x-rays after which Frederic Joliot and Marie Curie discovered gamma rays. This discovery demonstrated that high frequency wave energies are identifiable, detectable, can be measured and often cause biological damage (MRI for Technologists, 1995: 3).

The 20th Century is synonymous with the atomic era. During this century many physicists, scientists and physicians collectively set the stage for NMR/MRI. During World war II physicists like Albert Einstein (1905) set the law of conservation of energy, Ernest Rutherford (1911) recognized the nucleus, J. J. Thompson showed objective proof of the existence of electrons, Niels Bohr (1913) opened the door to quantum physics, and Otto Stern developed a method to measure magnetic dipole moment; all contributed to the birth of NMR. However, Wolfgang Pauli (1931) was the first to coin the phrase "nuclear magnetic resonance" and Isidor Isaac Rabi (1913) conducted the first NMR experiment (MRI for Technologists, 1995: 5).

Although Pauli was the first to suggest that some nuclei spin, the two physicists Swiss born Felix Bloch (1905-1983) at Stanford and the American Edward Purcell (1912 -) at Harvard, continued to explore the mystery of the atom, discovered and implemented the use of atomic energy for analytical purposes in 1946. They discovered that a pure substance could be analyzed into its frequency components solely from their molecular perspective. This principle is called spectroscopy. Bloch and Purcell received the Nobel Price in 1952 for their contribution to science and technology (Carlton and Adler, 1995:664). For the next 25 years spectroscopy flourished and more than 100 NMR units where manufactured. Spectroscopy was initially used as an analytical tool in the industry. At this stage human NMR images were viewed as impossible and lunatic (MRI for Technologists, 1995: 5).

During the late 1960 to early 1970 several researchers developed the basis for diagnostic MRI. Jasper Jackson was the first to produce MR signal from live animals. In 1972 Paul Lauterbur produced the first MR image. He designed and implemented the use of Gx, Gy and Gz gradients for spatial encoding. The physicist/physician Raymond Damadian reported NMR differences between normal tissue and tumours (Carlton & Adler, 1995: 664). In 1970 Raymond Damadian started to build a whole body scanner for body imaging. He and his team spent seven years on designing and building this scanner. They performed the first diagnostic, whole body trans-axial proton density weighted slice image on 3rd of July 1977. This one slice took 4 h 45 min to complete. The patient had to be physically moved 106 times with a trambler to accomplish spatial excitation (Shellock & Kanal, 1994: 167). He named the scanner the Indomitable. The Indomitable is currently located at the Smithsonian Institute of Technology in Washington, D. C. (MRI for Technologists, 1995).

Several other scientists and physicians contributed to MRI over the past 30 years, like Prof. Dr. R. R. Ernst from Switzerland, who created the phase *vs.* frequency coordinates on the MR matrix for faster imaging. He also implemented the Fourier transformation (FT) imaging process (MRI for Technologists, 1995:8). Fourier transformation forms the heart of MRI mathematics and was first introduced by the French Mathematician Jean-Baptiste Fourier (1768-1830) over 200 years ago. Fourier transformation is a complex mathematical process currently used to translate a raw MR signal into spatial location (Dowsett, Kenny & Johnston, 1998: 18).

Damadian and Lauterbur's discovery was the beginning of MRI unit manufacturing. By 1995 there were over 2000 MR systems in the United States and approximately the same number throughout the rest of the world. The rapid growth of MRI like magnetic resonance angiography (MRA), magnetic resonance spectroscopy (MRS), higher gradients, and faster pulse sequences emphasized the essentiality of MRI safety (MRI for Technologists, 1995: 9).

The electromagnetic spectrum is the categorical arrangement of wave energy corresponding to their properties. The electromagnetic spectrum ranges in frequencies from lower than 10^6 (0 Hz) to higher than 10^{20} waves per second. Radio waves are in the lower frequency range of less than 10^{-1} waves per second. The size of radio waves ranges from a basketball to a soccer field, and even larger. Therefore their wavelengths are from 0.1 m up to 100 m and larger. Radio waves are usually caused by microwave ovens, frequency modulation (FM) radio and amplitude modulation (AM) radio towers, television and other (Electro-optical Industries, 2000: 2). Radio frequencies (RF) are sometimes used as a generic term for frequencies up to 300 GHz but the term microwaves is more usually applied to the frequency range 300 MHz to 300 GHz (wavelength interval 1 m to 1 mm) and RF restricted to frequencies below 300 MHz (Mild,1998: 7).

Electromagnetic emission can be defined as the propagation of energy through space by electric and magnetic fields that vary in time (Newhouse & Wiener, 1991: 24). The electromagnetic waves in the MRI environment, namely static magnetic fields, radiofrequency and gradient fields are non-ionizing (Westbrook & Kaut, 1998: 234).

Non-ionizing electromagnetic waves consist of photons with energy levels less than 10 eV. These photons do not have sufficient energy to set ions free from an atom during a collision with such an atom (Mild, 1998: 7). The electromagnetic fields consist of the electric field E (V/m) and the magnetic fields (A/m). In the far-field the E-field and the H-field are strongly independent. However, in the near-field the H- and E-fields must be measured separately. In MRI imaging the health worker and the patient within the MRI room, during an examination, will be in the near-field [1 x λ (m)] at the lower frequencies (0 – 30 kHz). However, at the higher frequencies (> 30 kHz) they will be in the far-field [3 x λ (m)] (Narda Test Solutions, 2004: 2).

Microwaves, infrared light waves, visible light and ultraviolet light waves make up the central part of the spectrum. These wavelengths vary from 10^{-3} m to 10^{-8} m and have frequencies from 10^{12} to 10^{17} waves per second.

The upper end of the spectrum is made up of ionizing soft X-rays, X-rays and gamma rays in the frequency range of 10^{16} to 10^{20} and even higher. These wavelengths are very short (10^{-8} up to 10^{-12} m and even smaller). The waves have energy levels in the range 100 eV up to 1 000000 eV and higher. Therefore these waves have sufficient energy to set an ion free from an atom during a collision with such an atom. These waves are thus called ionizing radiation (HEASARC, 2006: 7).

2.3 Mechanism of magnetic resonance imagers (MRI)

The MRI unit consists of an enclosed room, lined with copper sheet on the walls (Faraday cage) and copper wire mesh in the windowpane. Although costly, it provides effective protection for the extremely sensitive receiver within the magnet from interfering environmental RF signals. The magnet, shim, gradient and RF coils are housed in the MRI room (Westbrook & Kaut, 1998: 3).

Magnetic resonance imaging uses magnetism and RF to create diagnostic sectional images of the body. The processes that permit MRI are based on the principles of nuclear physics and quantum mechanics. This is also the reason why the imaging process was originally called nuclear magnetic resonance (NMR). In order to understand how MR images are created and viewed, it is critical to understand the physical concept involved in MRI (Carlton & Adler, 1996: 664).

The creation of an image during clinical MRI is based on the fact that the MRI active nuclei have a tendency to align their axis of rotation to an applied static magnetic field. The nuclei most commonly used in MRI are those with an odd mass number (usually odd number of protons and even number of neutrons). The hydrogen (^1H) nuclei are the most abundant of these nuclei in the human body and are usually referred to as the MR active nucleus. Hydrogen has only one proton in its nucleus. Therefore, the hydrogen nucleus is sometimes referred to as a proton. The nucleus is a tiny but highly charged (positive charge) piece of matter, and spins about its own axis. Due to the laws of electromagnetic induction, nuclei that have a net charge and spin about their own axis acquire a magnetic moment and are able to align with an applied external static magnetic field. The process of this interaction is called angular moment (spin). In the external static magnetic field the spinning nucleus starts to wobble like a spinning top when it loses momentum. The wobbling is actually a rotation of the rotation axis and is called precession (Carlton & Adler, 1996: 665). Nuclei with an even number of protons and neutrons exhibit no spin. The laws of electromagnetism state that a magnetic field is created when a charged particle moves around. Therefore, the hydrogen nucleus induces a magnetic field around itself, and acts as a small bar magnet (dipole). The north/south axis of each nucleus is represented by a magnetic moment, and has vector properties. The spin is quantized and characterized by the spin quantum number, *I*, which may be either an integer or half-integer. The total net magnetic moment of all the hydrogen (^{1}H) nuclei (proton), aligned parallel and anti-parallel to the external static magnetic field are called the nuclear magnetization vector (NMV). The interaction of the NMV with the static magnetic field (B$_{0)}$ forms the basis of MRI (Westbrook, Kaut Roth & Talbot, 2005: 8).

The NMV can only be measured when it is perpendicular to the external applied static magnetic field. By applying a burst of a magnetic field (radio-frequency field switch on and then off again) that oscillates at the same frequency at which the protons are spinning, the NMV can be flipped from being aligned with the magnetic field, to a 90 degree angle with the magnetic field. Radio frequency fields (‘second magnetic field” B^1) are used to excite the NMV to rotate to the static magnetic field. The best RF signal detected is usually at a 90 degree angle to the static magnetic field. The rotating net magnetization will induce a voltage or RF pulse (at the Lamor frequency) in a receiver coil placed close to the anatomy under examination. This is then the NMR signal that is detected. Different molecules possess different relapse frequencies which play a vital role in MRI identification of different molecules or soft tissue structures (Westbrook & Kaut, 1998: 10).

Excitation of the NMV can only take place when the RF fields used are of the same precession frequencies as the hydrogen nuclei. Precession frequency refers to the speed at which the NMV wobbles around B_o after excitation by the RF pulse. Precession frequency, also called the Lamor frequency (of a specific nucleus), of the hydrogen nucleus in a 1.5 T static magnetic field is 63.86 MHz. Precession in a magnetic field requires the coupling and interaction of two different physical properties of the system, electromagnetic and mechanical (Bushong, 2003:10).

During the rotational pathway the MR signal is created and detected by RF receivers. The value of the precession frequency depends on the strength of B_o and the gyro-magnetic ratio (characteristics of the specific nucleus). Therefore, the precession frequency for a specific nucleus will be different in different magnetic field strengths. However, the chemical environment of the nucleus will also influence the resonant frequency of the nucleus. The effect of this influence is also called chemical shift of a nucleus in a molecule. Chemical shift is the basis of widespread use of NMR spectroscopy in chemical analysis (Gowland, 2005: 176). The gyro-magnetic ratio expresses the relationship between the angular moment and the magnetic moment of each MR active nucleus. The gyro-magnetic ratio is unique for each different element's nuclei (Westbrook & Kaut, 1998: 6).

The linear variation of the static field (a magnetic field gradient) through space is responsible for the creation of an image (Hashemi, Bradley & Lisanti, 2004: 162). Thus, the Lamor frequency of the NMR signal codes for spatial position. The magnetic field gradient is switched on and off very rapidly during imaging sequences (Gowland, 2005: 177). The gradient coils are conductors that produce a linear superimposed gradient magnetic field on the main magnetic field. The gradient is defined as the rate at which magnetic field strength changes with position. Typically, a perfectly homogeneous magnetic field contains no gradient. Therefore wire coils (gradient coils) are placed in a three-dimensional way, x-, y-, and z-direction, inside the cylinder of the magnet. The gradient coils are responsible for the rapidly changing electromagnetic fields in the MRI environment. They are responsible for the banging noise one hears during imaging. The flexing and force experienced by the gradient coils from the rapidly changing magnetic field when energized, causes the noise (Bushberg, Siebert & Boone, 2002: 260). When current is allowed to flow through these coils, they act as magnets within magnets, and shape the overall magnetic field to have a particular gradient (Newhouse & Wiener, 1991: 16). This means that the magnetic field within a 1.5 T unit will vary slightly higher than 1.5 T in the centre of the magnet, in one direction of the z-axis where the gradient magnetic fields strengthen the main magnetic field, and slightly lower on the opposite side where the gradient magnetic field opposes the main magnetic field (Elster & Burdette, 2001: 4). Nuclei of the atom of the same element have different precession frequencies at different magnetic field strengths. Therefore it is possible to spatially establish the position of a certain nuclei. The three gradient coils are used for the spatial slice-, frequency- and phase-encoding of the MR image (Westbrook, Kaut Roth & Talbot, 2005: 62).

Gradient switching is one of the greatest factors that will affect the timing of pulse sequences. Each time a gradient is switch on, power is applied to the gradient to eventually reach peak amplitude. Gradient amplitude refers to the strength of the gradient. Gradient strengths are typically between 10 and 60 mT/m. Image resolution is directly affected by gradient amplitudes. High gradient amplitudes are needed for small field of view (FOV) and thin slice imaging. The gradient rise time (time to reach maximum amplitude) plays an important role in MR imaging timing factors. The strength of the gradient over distance is known as the slew rate. Typical slew rates are in the order of 70 mT/m. Gradient strength over distance create different frequency content over distance in the bore. In a 1.5 T MRI unit the centre frequency will be 63.86 MHz, which is the precession frequency (Lamor frequency) of hydrogen at 1.5 T (Westbrook, Kaut Roth & Talbot, 2005: 317).

The magnet is essentially the heart of the MRI system. Field strength, temporal stability and field homogeneity are some of the elements that make up the performance criteria of a particular magnet type. The magnet design plays a major role in these parameters (Bushberg, Siebert & Boone, 2002: 458). Magnets of strength 0.2 T up to 3 T produce the main magnetic fields, also called the static magnetic fields in clinical MRI. The main magnetic field is responsible for the alignment of the nuclei, parallel and anti-parallel to the magnetic field. In solenoid electromagnets the main magnetic field is usually horizontal, but in permanent magnets the field is usually vertical. The direction of the magnetic field is also called the z-axis (Westbrook & Kaut, 1998: 233).

The magnet can either be a resistive, superconductive or a permanent magnet. The superconductive magnets are most widely used for clinical imaging. The superconductive magnets use an air core electromagnet configuration, and consist of a large cylinder, wrapped with a long, continuous strand of superconductive wire. Certain metals (niobium-titanium alloys) exhibit no resistance to electric current when kept at extremely low temperatures. Superconductivity is a characteristic of these metals (Bushberg, *et al.*, 2002: 459). The low temperatures are made possible by liquid helium (boiling point 4 K) as coolant. These magnets achieve high field strengths, from 0.3 T up to 3.0 T in clinical systems. In research, clinically large bore magnets achieving 4.0 T up to 7.0 T are used. The superconductive magnets have high field uniformity. However, several disadvantages of the superconductive magnets include high initial costs, cryogen costs, and difficulty in turning off the main magnetic field in an emergency as well as extensive fringe fields (Carlton & Adler, 1996: 677).

Enclosing walls, floors or ceilings cannot contain the static magnetic field. Stray magnetic field outside the magnet and MRI unit are called fringe fields (Westbrook & Kaut, 1998: 233). The fringe field of the magnet is the magnetic fields surrounding the central magnet. A 1.5 T magnet has a magnetic field of 1.5 T in the centre of the magnet. The magnetic field reduces with increasing distance from the centre point of the magnet. Unshielded magnets have a larger fringe field than shielded magnets. Disruption of the fringe field can reduce the homogeneity of the active imaging volume. The fringe fields are measured in milliTesla (mT) or Gauss (G) (1 T = 1000 G).

The fringe field is usually confined to an acceptable location by shielding within the scan room. The fringe field should always be taken into consideration when positioning new systems. The field strength above as well as below the magnet should also be considered. Shim coils are used for shielding the fringe fields (Westbrook & Kaut, 1998: 235).

Shim coils are active or passive magnetic field devices and are used to adjust the main magnetic field (shielding). They are also used to improve the homogeneity in the sensitive central volume of the scanner. In active shielding, the pattern or spectrum of the field inhomogeneities is mapped and then corrected by setting the shim coils currents via a precision power supply. In passive shielding carefully shaped iron plates are placed inside or outside the magnet. Passive shielding is not power supply stability dependent, but requires considerable time to fit and adjust (Dowsett, Kenny & Johnstone, 1998: 490); (Bushberg, Siebert & Boone., 2002: 464).

The static field effectively exposes staff and patients to both large static fields, a spatial gradient of field (as it falls off around the magnet) and a small time-varying field as they move around in the spatially varying, static field (Gowland, 2005: 177).

Radio frequency transmitter and receiver body coils are located within the magnetic bore. The RF coils can be transmitter and receiver, or only receiver coils. Radio frequency coils need to be tuned prior to each acquisition and also be matched to accommodate the different magnetic inductance of each patient. The RF excitation pulses can be used at different angles and in different orders or repetitions, which will create different pulse sequences (Bushberg, Siebert & Boone, 2002: 461).

The pulse sequences are used to differentiate between different tissues as well as to detect specific pathology. Examples of these pulse sequences are as follow. Fast spin echo (FSE) is a spin echo (SE) pulse sequence (uses a 90^{o} RF excitation pulse followed by one or more 180^{o} RF rephasing pulse), but the scan times are drastically shorter than the conventional spin echo. Fast spin echo uses more than one 180^{o} RF rephasing pulses.

These multiple rephasing pulses are called echo trains. The spatial encoding of the data (filling of K-space) can therefore be performed in a shorter time (Westbrook & Kaut, 1998: 106).

The fluid attenuated inversion recovery (FLAIR) pulse sequence is a variation of the inversion recovery sequence. Inversion recovery is a pulse sequence that begins with an 180° inverting pulse. It inverts the NMV through 180° into full saturation and is then followed by the conventional spin echo pulse sequence (Westbrook & Kaut, 1998: 113). In FLAIR the signal from cerebrospinal fluid (CSF) is nullified by selecting a TI (time to invert) corresponding to the time of recovery of CSF to the transverse plane and there is no longitudinal magnetization present in CSF (Westbrook & Kaut, 1998: 117).

Gradient echo pulse sequence uses a variable RF excitation pulse (not just 90°). The NMV can be flipped through any angle. A gradient pulse is then used as a rephasing pulse (Westbrook & Kaut, 1998: 37).

In the pulse sequence, echo planar imaging (EPI) or diffusion imaging, the filling of K-space is all done after only one repetition. Echo planar imaging is a MR acquisition method that collects all the data required to fill the lines of K-space from a single echo train (Westbrook & Kaut, 1998: 132).

2.4 Safety in magnetic resonance imaging

Magnetic resonance imaging safety entails consideration of two aspects, namely the patient's and operator's safety recommendations. The most important part of patient safety regulations is the screening (for metal implants and foreign metal bodies) of patients before entering the MRI room. A screening document was developed by the International Society for Magnetic Resonance in Medicine (ISMRM) and should be used as a screening guideline at all MRI sites. The patient should also be monitored verbally as well as visually in the bore during an examination (Shellock, 2004: 15). Monitoring should be done for possible claustrophobia and any adverse biological effects due to the static magnetic, radiofrequency and gradient fields (Westbrook & Kaut, 1998: 234); (Bushong, 2003: 404).

Although there is currently no convincing evidence that there is any long-term or irreversible biological effects associated with electromagnetic fields and static magnetic fields used in MRI, screening of patients and personnel remains important, because hazards in MRI do exist (Westbrook, Kaut Roth & Talbot, 2005: 350).

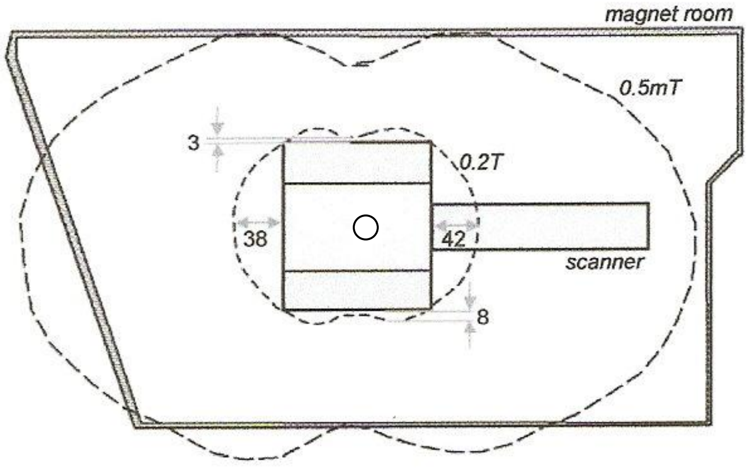
These hazards can be the result of the strong force the static magnetic fields exert on ferromagnetic objects brought into their influence. Conditions and devices which is considered as an absolute contraindication to MR imaging until the contrary is proven, is the presence of:

- An active electronic device in the body, such as cardiac pacemaker, cochlear implant, nerve or bone stimulator;
- Cerebral aneurysm clip;
- Intraocular metal fragments;
- Ferromagnetic foreign bodies;
- Magnetic eye sockets; or
- Any unfamiliar devices (Westbrook, Kaut Roth & Talbot, 2005: 350).

Other potential hazardous situations are things like:

- Jewellery and body piercing;
- Tattoos and permanent make-up;
- Loose ferromagnetic objects in pockets;
- Bras and belts; and
- Credit cards (Westbrook, Kaut Roth & Talbot, 2005: 348).

Figure 2.1: Schematic illustration of spatial regions at 1.5 T MRI units.



(EU Directive 2004/40, 2007: 485).

The area surrounding the isocentre (O in fig 2.1) of the magnetic field is called region one. This region is contained within the bore. The magnetic field strength in the very centre of the bore of a 1.5 Tesla MRI is 1.5 T provided the homogeneity of the magnet is very good. Any ferromagnetic object either inside or outside the body will experience a rotational force called a torque. This torque can cause rotational motion of the object and can cause the object to tear the surrounding tissue. The static field strength decreases with an increase in distance from the isocentre of the magnet and this area is then called region two. Region two is external to the physical magnet and is a gradient field because its strength varies with spatial position. In region two a ferromagnetic object in or outside the body may experience rotational and translational forces. The direction of the translational force will be in the direction of the isocentre of the magnet. Objects not secured will transfer into projectiles towards the bore and result in injuries to either patients or personnel (Price, 1999: 1641).

Reversible biological effects due to the high static magnetic fields do exist, like elevation of the T wave in the electrocardiography tracing. This is caused by blood flow in the vessel through the static magnetic field. In ultra-high static fields (10 T), a potential of 64 mV could be produced across an aorta about 16 mm in diameter (Price, 1999: 1642). Since 2000 the interest in static fields shifted to ultra-high-magnetic-fields systems (3 T and higher) for functional MRI. Although 3 T MRI scanners appeared in the early 1990s, their use has been restricted to research labs until recently. However, they are rapidly becoming the magnets of choice in high profile centres, and in sites dedicated to neuron-imaging (Gowland, 2005:177). The concern for adverse bio-effects due to static fields has increased once more. In the USA more than 30 ultra-high systems in excess of 3 T are in operation (Shellock & Crues, 2004: 636). Even in South Africa 3T MRI units are now operational although, "Safe use guidelines" (Department of Health, 1994: 4) state the static magnetic field exposure limit as 2 Tesla.

Although these ultra-high MRI units are a huge advantage to patient diagnosis, it involves exposing staff that do not benefit directly from the exposure (Gowland, 2005: 179). Staff moving around in the ultra-high fields (2 T and higher), can experience transient sensory effects like dizziness (caused by disturbance of the action of the balance organs), metallic taste in mouth (probably due to electrolysis of fillings), or phosphenes (flashing lights in eyes due to electrical pulses induced in the retina) (Gowland, 2005: 181).

Radio frequency fields cause tissue heating at sufficient power levels, which results in biological effects associated with thermally induced changes. Although no convincing evidence exists for non-thermal biological effects from RF radiation in diagnostic MRI, clear evidence of RF burns in patients is an essential component of MRI safety (Shellock & Crues, 2004: 637). Radio frequency burns can result from inadvertently induced currents in conductive loops placed on the patient's skin surface (Price, 1999: 1643).

Rapidly changing magnetic fields and the auditory noise levels can lead to muscle and nerve stimulation. The mean threshold levels (Ts^{-1}) for various stimulations are: 3.600 Ts^{-1} for the heart, 900 Ts^{-1} for respiratory systems, 90 Ts^{-1} for pain, and 60 Ts^{-1} for peripheral nerves. However, the stimulated threshold varies from individual to individual, some higher and some lower. Peripheral nerve and cardiac stimulation levels are respectively about three and 30 times higher than the Food and Drug Administration (FDA) guidelines. The FDA guidelines are specified as a function of the switching rate (Shellock & Crues, 2004: 636); (Price, 1999: 1647).

All these possible hazardous effects to patients and personnel make the MRI environment a very stressful working environment. An indept discussion on stress, stressors and measuring technique of stress follow in chapter four.

In summary, the most commonly recognized safety policy is the so-called 5 Gauss (5 mT) line. This line goes horizontally as well as vertically. If this safety policy is not always possible, safety rules should include the following: limited access, entrance controlled by lockable door, entrance visible to system operator, visitors screened, and appropriate warning signs posted (Price, 1999: 1648).

In May 1996, the International EMF (IEMF) project was launched by the World Health Organization (WHO) as part of its charter to protect health and in response to public concern regarding EMF exposure. The project is located at the WHO's headquarters in Geneva, Switzerland. The project is run within the Radiation and Environmental Act and has in its action plan on radiation protection, activities which deal with both ionizing and non-ionizing radiation (WHO, 2005: 2). The aim of the project is to assess health and environmental effects of exposure to static and time-varying magnetic fields in the frequency range 0 to 300 GHz. For this purpose this range is divided into the following fields: static (0 Hz), extremely low frequency (ELF, 0 – 300 Hz), intermediate frequency (IF, 300 Hz – 10 MHz) and radio-frequency (RF, 10 MHz – 300 GHz) (WHO, 2005: 4). Initially the IEMF was scheduled to complete their health risk assessment in 2006, however, the latest date will only be 2007 after completion of the WHO's health risk assessment of RF fields. The WHO anticipates that current and proposed research should provide sufficient results within this time frame to allow more definitive health risk assessments (WHO, 2005: 2).

Very little useful research has been conducted on the static magnetic field in MRI up to 2004. Many new technologies in MRI exist and much higher static fields are explored for use. Therefore, the need for further elaboration of static field research was made part of the IEMF project. Extremely low fields (ELF) in MRI are also a concern in MR imaging and benefits will be gained from the project findings on ELF (WHO, 2005: 3).

2.5 Exposure limits to electromagnetic fields (EMF)

Different bodies were responsible for setting limits for exposure to electromagnetic fields, like: the International Radiation Protection Association (IRPA); International Non-Ionizing Radiation Committee (INIRC); World Health Organization (WHO); International Commission on Non-Ionizing Radiation Protection (ICNIRP); United States Food and Drug Association (US FDA), International Electro-technical Commission (IEC) and European Committee for Electro-technical Standardization (CENELEC). These bodies responsible for setting guidelines need scientific information on which to set their limits (Renew & Glover, 2002: 395).

2.5.1 History of exposure limits to EMF

Much research has been done on MRI safety and the biological effects of electromagnetic fields over the past 25 years. Most of the research was done in the USA. In order to create a standard for exposure to electromagnetic radiation the American National Standards Institute (ANSI) developed a voluntary standard for occupational exposure in 1966. This voluntary standard was reaffirmed with minor changes in 1974 (Shellock & Kanal, 1994:183).

Other role players in the creation of the standards were bodies like the FDA of the USA. They issued guidelines to Hospital Investigation Review Boards (IRBs) in “Guidelines for Evaluating Electromagnetic Exposure Risks for Trials of Clinical MRI”. The 1988 version of the data for safety was published in the Federal Register in the USA. The Environmental Protection Agency (EPA) and the Federal Communication Commission (FCC) proposed the adoption of interim standards until such federal guides were adopted. The FCC then decided to use the 1982 ANSI voluntary guidelines for public exposure. The Occupational Health and Safety Administration (OHSA) adopted the ANSI standards for occupational exposure in 1971, and retained its standards in 1984 because it provided useful advice to employers (Shellock & Kanal, 1994: 183).

In 1974, the International Radiation Protection Association (IRPA) formed a working group on non-ionising radiation (NIR), which examined the problems arising in the field of protection against the various types of NIR. In 1977, this working group became the International Non-Ionising Radiation Committee (INIRC). The IRPA/INIRC in cooperation with the WHO, developed a number of health criteria documents on NIR as part of WHO's Environmental Health Criteria Programme, sponsored by the United Nations Environment Programme (UNEP). Each document includes an overview of the physical characteristics, measurement and instrumentation, sources, and applications of NIR, a thorough review of the literature of the biological effects, and an evaluation of the health risks of exposure to NIR. These health criteria have provided the scientific database for the subsequent development of exposure limits and codes of practice relating to NIR. In 1992 the International Commission on Non-Ionising Radiation Protection (ICNIRP) was established as a successor to the IRPA/INIRC (ICNIRP, 1997: 494).

In the absence of detailed and conclusive evidence on the biological and physiological effects of electromagnetic fields, the guidelines given by the International Radiation Association (IRA) as well as those from the National Radiological Board in the UK form the basis of South Africa's Guidelines for static magnetic fields exposure (ICNIRP, 1997: 1). In 2000 guidelines, derived from the 1998 ICNIRP guidelines for time-varying electric, magnetic and electromagnetic fields up to 300 GHz were documented by South Africa's Department of Health, Directorate: Radiation Control. MRI units, currently used in South-Africa, fall into the 10 MHz to 10 GHz occupational exposure limit. In table 2.2 the basic restrictions for time-varying electric, magnetic, and electromagnetic fields for frequencies up to 10 GHz, accepted by the Department of Health (from ICNIRP), can be viewed. Basic restrictions between 1 Hz and 10 MHz are provided on current density in order to prevent nervous system function effects. In the frequency range 100 kHz and 10 GHz, the restriction in SAR are to prevent whole body heat stress and tissue heating. However, SAR as well as current density is used in the frequency range 100 kHz to 10 MHz. Power density restriction in the frequency range 10 to 300 GHz is to prevent excessive heating in tissue at or near the body surface (table 2.1) (Department of Health, Directorate: Radiation Control, 2002: 2).

Table 2.1 Exposure limits for time-varying electromagnetic fields for frequencies between 10 and 300 GHz

Exposure characteristics	**Power density (W/m^2)**
Occupational	50
General Public	10

Notes for table 2.1:

1. *"Power densities are to be averaged over any 20 cm^2 of exposed area and any period of $68/f^{.05}$ (where f is in GHz) to compensate for progressively Shallower penetration depth as the frequency increase.*
2. *Spatial maximum power density, averaged over 1 cm^2, should not exceed 20 times the values above."*

(Department of Health, Directorate: Radiation Control, 2002: 3).

Table 2.2: Exposure limits to time-varying electric, magnetic and electromagnetic fields for frequencies up to 10 GHz.

Exposure characteristics	Frequency range	Current density (head & trunk) (mA/m^2) (rms)	Whole-body average SAR (W/kg)	Local SAR (head & trunk) (W/kg)	Local SAR (limbs) (W/kg)
Occupational	Up to 1 Hz	40			
	1-4 Hz	40/*f*			
	4 Hz-1 kHz	10			
	1-100 kHz	*f*/100			
	100 kHz-10 MHz	*f*/100	0.4	10	20
	10 MHz –10 GHz	_	0.4	10	20
General public	Up to 1 Hz	8			
	1-4 Hz	8/*f*			
	4 Hz-1 kHz	2			
	1-100 kHz	*f*/500			
	100 kHz-10 MHz	*f*/500	0.08	2	4
	10MHz – 10 GHz	_	0.08	2	4

Notes for Table 2.2:

1. *“f is the frequency in Hz (hertz).*
2. *Because of electrical inhomogeneity of the body, current densities should be averaged over a cross section of 1 cm^2 perpendicular to the current direction.*
3. *For frequencies up to 100 kHz, peak current density values can be obtained by multiplying the rms value by √2(~1.414).*
4. *For frequencies up to 100 kHz and for pulsed magnetic fields, the maximum current density associated with the pulses can be calculated from the rise/fall times and the maximum rate of change of flux density. The induced current density can then be compared with the appropriate basic restriction.*
5. *All SAR values are to be averaged over any 6-min period.*
6. *Localised SAR averaging mass is any 10 g of contiguous tissue; the maximum SAR so obtained should be the value used for the estimation of exposure.*
7. *For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/2t_p$). For pulsed exposures in the frequency range 0.3 to 10 GHz and for localised exposure of the head, in order to limit or avoid auditory effects caused by thermoelastic expansion, an additional basic restriction is recommended i.e. the SA should*

> *not exceed 10 mJ/kg for occupational and 2mJ/kg for general public exposure, averages over 10 g of tissue."* (Department of Health, Directorate: Radiation Control, 2002: 3).

Reference levels for occupational and general public exposure to time-varying electric, magnetic, and electromagnetic fields for frequencies up to 300 GHz expressed in E-field, H-field, B-field flux density and power density values, can be viewed in table 2.3.

Table 2.3: Occupational and general public exposure limits up to 300 GHz expressed in E-field, H-field, B-field and power density values

Frequency range	**E-field strength (V/m)**	**H-field strength (A/m)**	**B-field flux density (µT)**	**Power density S_{eq} (W/m^2)**
Occupational exposure				
Up to 1 Hz		1.63 x 10^5	2 x 10^5	
1-8 Hz	20 000	1.63 x $10^5/f^2$	2 x $10^5/f^2$	
8 -25 Hz	20 000	2 x $10^4/f$	2.5 x $10^4/f$	
0.025-0.82 kHz	$500/f$	$20/f$	$25/f$	
0.82-65 kHz	610	24.4	30.7	
65-1 MHz	610	$1.6/f$	$2/f$	
1-10 MHz	$610/f$	$1.6/f$	$2/f$	
10 - 400MHz	61	0.16	0.2	10
400-2000 MHz	$3f^{0.5}$	$0.008f^{0.5}$	$0.02f^{0.5}$	$f/40$
2-300 GHz	137	0.36	0.45	50

Frequency range	**E-field strength (V/m)**	**H-field strength (A/m)**	**B-field flux density (μT)**	**Power density S_{eq} (W/m^2)**
Public exposure				
Up to 1 Hz		3.2×10^4	4×10^4	
1-8 Hz	10 000	$3.2 \times 10^4/f^2$	$4 \times 10^4/f^2$	
8-25 Hz	10 000	$4\,000/f$	$5\,000/f$	
0.025-0,8 kHz	$250/f$	$4/f$	$5/f$	
0.8-3 kHz	$250/f$	5	6.25	
3-150 kHz	87	5	6.25	
0.15-1 MHz	87	$0.73/f$	$0.92/f$	
1-10 MHz	$87/f^{0.5}$	$0.73/f$	$0.92/f$	
10 - 400MHz	28	0.073	0.092	2
400-2 000 MHz	$1.375 f^{0.5}$	$0.0037f^{0.5}$	$0.0046f^{0.5}$	$f/200$
2-300 GHz	61	0.16	0.2	10

Notes for Table 2.3:

1. *"f is the frequency as indicated in the frequency range column.*
2. *For purpose of demonstration compliance with the basic restrictions, the reference levels for the electric and magnetic fields should be considered separately and not additively, because the currents induced by electric and magnetic fields are, for protection purpose, NOT additive.*
3. *For frequencies between 100 kHz and 10 GHz, S_{eq}, E^2, H^2 and B^2 are to be averaged over any 6-minute period.*
4. *For frequencies exceeding 10 GHz, S_{eq}, E^2, H^2 and B^2 are to be averaged over any $68/f^{1.05}$-minute period (f in GHz).*
5. *For peak values at frequencies up to 100 kHz, peak current density values can be obtained by multiplying the rms value by √2(~1.414).*
6. *Peak field strength values at frequencies between 100 kHz and 10 MHz are obtained by interpolation from the 1.5-times peak at 100 kHz to the 32-times peak at 32-times peak at 10 MHz.*

> *For frequencies exceeding 10 MHz it is suggested that the peak power density as averaged over the pulse width not exceed 1000 times the* S_{eq} *restrictions, or that the field strength not exceed 32 times the field strength exposure levels given in Tables3.2 and 3.3 (for peak values see MS Excell*^{TM} *document: "Exposure Reference Levels (Average & Peak) – Tables & Graphs.xls").*
>
> 7. *No E-field value is provided for frequencies < 1 Hz, which are effectively static magnetic electric fields. Perception of surface electric charges will not occur at electric field strength of less than25 kV/m. Sparks discharges causing stress or annoyance should be avoided. Electric shock from low impedance sources is prevented by established electrical safety procedures for such equipment"* (Department of Health: Radiation Control, 2002: 5).

Although the ICNIRP guidelines form the basis of the exposure limits in different countries, most countries compiled their own documents. The USA, Canada, Germany, UK and Italy have already investigated the safety aspects of the MRI environment, mostly patient safety aspects. (Reports from the Canadian Coordinating Office for Health Assessment, 1993: 593).

In the USA the American National Standard Institute (ANSI), the Institute of Electrical and Electronic Engineers (IEEE) and Food and Drug Association (FDA) are involved in the setting of limits for exposure to EMF. Currently the IEC 60601-3 series prescribe the standards for radiation protection. The Association for Advancement of Medical Instrumentation (AAMI) in conjunction with ANSI presented the AAMI/ANSI 60601-1 in 2006, which is essentially the same as the IEC/EN 60601-1 document. Current standard for exposure to EMF in the USA involve a 4.1 T threshold for static fields, 4 W/kg/15min SAR for body and a 3 W/kg/10min for head in RF, and state to avoid painful nerve stimulation in time-varying fields. A work group has been appointed to explore the occupational exposure to EMF. Future based standards are expected to be effective between 2009 and 2012. USA is expected to adopt whatever transition is agreed to between International Electro-technical Commission (IEC) and European Committee for Electro-technical Standardization (CENELEC) (Schmidt, 2005: 2). Canada as well as New Zeeland adopted the USA standards (Armstrong, 2005:3).

UK used to set its own standards for exposure limits to EMF via the Health Protection Agency (HPA) and the former National Radiological Protection Board (NRPB).

However, in March 2004 the NRPB recommended that the UK should adopt the ICNIRP guidelines, published in 1998. The recommendation was then accepted by the Government (Electromagnetic Field exposure limitation and the future of MRI, 2005: 973)

The exposure limits to EMF in Europe were set by countries individually. However, in 2004 the European Union (EU) adopted a Directive limiting occupational exposure to EMF. The Physical Agent Directive includes MR, but only occupational exposures and must be incorporated into domestic law by each EU member state by 30 April 2008. Due to an outcry from the MR community the implementation of the Directive has been postponed to be implemented between 2009 and 2012. It currently includes exposure to time-varying magnetic field generated by the gradients (gradient fields, 100 – 1000 Hz) and the radiofrequency fields (RF, 10 - 100 MHz), which are both generated during active pulse sequences (EU Directive 2004/40, 2004:483).

In table 2.4 the proposed occupational exposure limits to EMF (EU Directive) in the MRI environment can be viewed. Although the 2 T static field limit has been removed from the Directive, it may still be introduced at a later stage by a review currently being undertaken by ICNIRP. The estimate limits for the static field is based on someone entering the magnet bore for cleaning purposes or to position experimental apparatus. Due to no static field limit, the gradient field limit poses the biggest problem. The gradient field (time-varying field) is based on a health worker standing very close to the bore during imaging. The gradient field limits are absolute without the scope for time averaging. Therefore, it will become illegal for a Health worker to lean into the bore even for a brief moment. The RF exposure is averaged over the whole body and seems unlikely to be exceeded in the near future (Electromagnetic field exposure limitation and the future of MRI, 2005: 973)

Table 2.4: Proposed exposure limit and action values for occupational exposure to electromagnetic fields at typical MRI frequencies

Field	**Exposure limit**	**Action value (Magnetic**

		flux density)
Static Magnetic field (f= 0 Hz)	2 T[a]	0.2 T
Gradient fields (e.g. f = 500 Hz)	10 mA/m^2 (3 – 1000 Hz) f/100 mA/m^2 (1 – 100 kHz)	2.5 x 104/f uT (e.g. 50 uT for 500 Hz)
RF field (f = 10 – 400 MHz)	10 W/kg (SAR – head and trunk) 20 W/kg (SAR – limbs)	0.2 uT (== 10 W/m^2)

RF, radiofrequencies: SAR, specific absorption rate.

[a] Limit removed from current version.

(Electromagnetic field exposure limitation and the future of MRI, 2005: 974)

According to literature no evaluation was previously done on the South African standards. However, the South African forum for Radiation Protection (SAFRP) made several comments regarding the 1991 IRPA guidelines on protection against NIR (South African Forum for Radiation Protection, 1991:1-11).These comments and recommenddations were based on the NIR spectrum, aim of IRPA guidelines, biological effects and general principles for protection against NIR.

NIR spectrum included all electromagnetic radiations with wavelength equal to or greater than 10^{-7}m. This wavelength spectrum included:

- Ultraviolet (UV) radiation (100 – 400 nm);
- Visible light (400 – 760 nm);
- Infrared radiation (760 nm – 1 mm);
- Radiofrequencies from upper limit microwaves (300 GHz), radio-waves (100 kHz or 3 km) and the ELF range (below 300 Hz)

IRPA guidelines were mainly aimed at defining standards related to exposure to NIR, either of the tissues or the whole body. The purpose of these standards, also called product performance standards, was to minimise health effects by ensuring safe operation of the products.

Biological effects or physiological importance due to the various type of NIR varies and depend on a number of factors like:

- Parameters that will determine the penetration depth of the incident radiation (e.g. resonance, power density, coherent, non-coherent, continuous, modulated or pulsed);
- Parameters that will contribute to exposure conditions (continuous or intermittent exposure) or spatial distribution (whole body or partial body);
- Parameters that will contribute to biological effects (as in ionising radiation);
  - Deterministic effects, where the severity varies as a function of the exposure (usually above limit exposure);
  - Stochastic effects, which is where the probability of occurrence increase with incident exposure (South African Forum for Radiation Protection, 1991: 2).

The protection doctrine on NIR, established by IRPA/INIRC, includes the following general principles;

- Compliance with the health protection standards in IRPA/INIRC guidelines for occupational and general public exposure;
- Performance standard to guarantee the compliance with health protection standards;
- Protection measurement to be implemented if safety of exposure can not be guaranteed (South African Forum for Radiation Protection, 1991: 3).

The recommendations were not final because the IRPA invited comments from interested organisations. In 2002 new guidelines were recommended by the SAFRP after the ICNIRP published new recommendations on NIR to time-varying electric-, magnetic and electromagnetic fields up to 300 GHz (ICNIRP, 1997: 494-522); (Department of Health: Radiation Control, 2002: 24).

In Germany the Berufsgenossenschaft (BG) Fur Feinmechanik und Elektotechnik (Ordidge, Fullerton & Norris, 2000:1) and in USA the American Conference of Governmental Industrial Hygienist were the bodies who provided these countries with their occupational limits for EMF at MRI units (Bailey, Su, Dan Bracken & Kavet, 1997: 435). A review of Canadian MRI exposure guidelines raised some uncertainties regarding the safety of control subjects' exposure to the magnetic fields. In the UK, magnetic field strength ranging from 1.5 T up to 4 T is operated. Bailey *et al*. came to the conclusion that theoretically and experimentally the static field appears to have a very high threshold of safety to human tissue at least well above 4 T. Almost all human tissue are diamagnetic, which, means that most human tissue tend to be expelled from magnetic fields (Schenck, 2005: 192). Biological processes at cellular and subcellular levels are driven by several types of forces like:

- Tissue elasticity and viscosity;
- Random thermal forces;
- Gravitational and electrostatic components.

The sum of these individual forces determines tissue morphology and motion. Magnetic force measured in piconewtons (pN) is superimposed on these pre-existing forces when the tissue (macromolecules) is places in a magnetic field. The magnetic force on a large protein in even a very high magnetic field MR unit is less than 10^{-6} pN. This means that it is consistent with the observation that magnetic fields do not produce measurable harmful effects on human tissue. However, the sum of a combination of magnetic forces on a large number of molecules can produce a detectable effect (Schenck, 2005:193).

Human studies have been done on static magnetic fields up to 10 T and from clinical evidence involving well over 100 million clinical MRI scans 4 T appears to be a substantial margin of safety for human exposure (Health Sciences Research Ethics Board guidelines, 2001: 3).

2.6 Previous Research Findings of EMF in the MRI environment

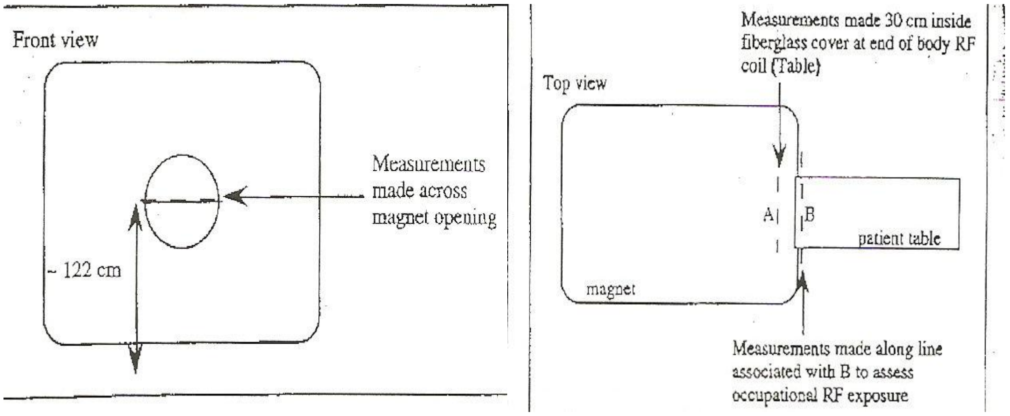
In 1995 Fermlee and Vetter conducted a RF survey at the bore of a 1.5 T MR Imager. The RF field strength was measured with an isotropic field strength meter designed to measure occupational RF exposure. Separate electric and magnetic field measurement probes were used. These probes used the peak detection mode and 8 kHz sampling rate. Phantoms were used for the imaging process and the body coil was used as a transmitter-gain setting. Radio frequency measurement was at the entry to the bore (Fermlee & Vetter, 1995: 571). Different pulse sequences were used and included:

- T1-weighted spin echo where, contrast depends predominantly on the differences in T1 times between fat and water;,
- T2-weighted spin echo where, contrast depends predominantly on the differences in T2 times between fat and water
- Fast spin echo (FSE) imaging where, multiple 180 degree rephasing pulses are used to decrease imaging time (Westbrook, Kaut Roth & Talbot, 2005: 30).

The phantoms used were: Vendor quality-control phantom, body-coil loader, and a human volunteer (Fermlee & Vetter, 1995: 571).

Threshold limit value for occupational RF exposure at 64 MHz is 1 mWcm^{-2}. At a point A just inside the bore ("30 cm inside the fibreglass cover at the end of the body RF coil, inside the") the power density was above 1 mWcm^{-2}. However, at a point B just outside the bore all the values were below the threshold limit. During the measurements the highest exposure came from the fast spin echo (FSE) sequences (Fermlee & Vetter, 1995: 572).

Figure 2.2: Front and top views of the magnet reflect power density measurement positions



(Fermlee & Vetter, 1995: 572).

At high static magnetic field MRI units, the specific absorption rate (SAR) is proportional to:

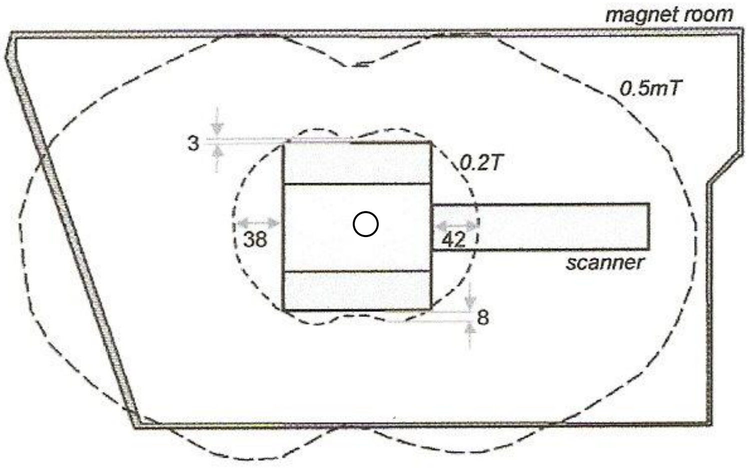
- The square of the static field strength;
- The square of the RF pulse flip angle being used (Elster & Burdette, 2001: 304)

Therefore, 180° RF pulse uses four times the power used by a 90° RF pulse, because the RF pulse is doubled. For this reason FSE sequences give the greatest concern for adverse RF effects, as they use a train of 180° RF pulses (Westbrook, Kaut Roth & Talbot, 2005:344). The RF energy deposited by a pulse producing a given flip angle, say 180°, increases with frequency with the field strength of the applied magnetic field. Therefore in the presence of the ultra-high static field strengths it is necessary to de-rate the maximum number of 180° pulses (but not the SAR) applied in a given time (Hore, 2005: 200).

Static magnetic fields effects at the MRI had been research as early as 1986 (Shellock, Schaefer & Gordon, 1986: 644). Since the early 2000's the interest in MRI research has shifted to the ultra-high static magnetic fields. Although several papers were published regarding the effect or hazards of static fields of 2 T and higher, no similar data on the RF and rapidly changing fields (gradient) were available (Ordidge, Fullerton & Norris, 2000:2); (Schenck, 2005: 199). However, in December 2005 the Health Physics published an article: "IEEE committee on man and radiation (COMAR) technical information statement exposure of medical personnel to electromagnetic fields from open magnetic resonance imaging systems". The research in this article involved the occupational exposure of health workers to static, gradient, and radiofrequency fields during interventional radiology at a 0.7 T Open MRI system. Measurements were done in all three fields and then compared to international exposure limits including those set by IEEE and ICNIRP. The static field exposure limits were well within the limits. The gradient field limits for exposure of the head or torso of a health worker close to the patient imaging centre can exceed the limit values even for times less than a second. Radiofrequency exposure limits can be exceeded if sustained exposure occurs to parts of the body ("IEEE committee on man and radiation (COMAR) technical information statement exposure of medical personnel to electromagnetic fields from open magnetic resonance imaging systems, 2005: 684).

In June 2007 the British Journal of Radiology published research compiled by the Cancer Research UK Clinical Resonance Group on static field fall of around a 1.5 T MRI unit, as well as, occupational exposure to the gradient and RF fields during clinical sequences. This research was done to assess whether the EU directive would have an impact on the clinical use of MRI. They used a THM 7025 Hall probe (Narda Safety Test Solutions) to map the 0.2 T field strength action value line around the scanner. An ELT 400 and a 100 cm^2 magnetic field probe (Narda) were used to measure gradient fields (100 Hz – 1000 Hz) and an EMR-300 Broadband RF survey meter with a Type 18.0 electric field probe (Narda) to measure the RF fields (10 MHz – 100 MHz). The gradient fields were measured during a fast spin echo (FSE) and an echo planar imaging (EPI) pulse sequence which are most frequently used and have high gradient strength. The RF fields were measured during a single-shot magnetic resonance cholangiopancreatography (MRCP) which has a high amount of RF power. The scanner was loaded with a 40 cm diameter cylindrical phantom with a bottle phantom on either side. The body coil was used as transmitter and receiver (EU Directive 2004/40, 2007: 484).

Figure 2.3: Mapping of the 0.2 T field strength action value line around a 1.5 MRI system



(EU Directive 2004/40, 2007: 485).

The results of this study compared to the UE's proposed new exposure limits in fig 2.2 showed that:

- The static field action value will be exceeded at any distance less than 42 cm from the patient landmark position (at the entrance to the bore), which, means that it will be exceeded while positioning a patient.
- The gradient field limits will be exceeded at 52 cm from the patient landmark position, which, means that it will have a severe effect on safe clinical practice.
- The RF limits were not exceeded on this 1.5 T system, but it may be different on open magnets where RF shielding is less contained (EU Directive 2004/40, 2007: 485).

In view of the latest research findings on EMF exposure in the MRI environment, the EU's proposed new exposure limits and the telephonic conversation (14 January 2008: 11:45) with Leon du Toit, Director for occupational exposure at the Department of Health, Directorate: Radiation Control, who stated that their tests in South Africa mainly concern static magnetic field (fringe field) fall of around the magnet, the situation around EMF testing in the MRI environment in South African creates great concern. In view of the temporarily removal of the proposed restriction (in the EU directive) on the static magnetic field, concern arises in South Africa especially in the occupational exposure to gradient and RF fields in the MRI environment.

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