The electromagnetic environment of Magnetic Resonance Imaging systems. Occupational exposure assessment reveals RF harmonics.

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Abstract. Magnetic Resonance Imaging (MRI) systems played a crucial role in the postponement of the former occupational electromagnetic fields (EMF) European Directive (2004/40/EC) and in the formation of the latest exposure limits adopted in the new one (2013/35/EU). Moreover, the complex MRI environment will be finally excluded from the implementation of the new occupational limits, leading to an increased demand for Occupational Health and Safety (OHS) surveillance. The gradient function of MRI systems and the application of the RF excitation frequency result in low and high frequency exposures, respectively. This electromagnetic field exposure, in combination with the increased static magnetic field exposure, makes the MRI environment a unique case of combined EMF exposure. The electromagnetic field levels in close proximity of different MRI systems have been assessed at various frequencies. Quality Assurance (QA) & safety issues were also faced. Preliminary results show initial compliance with the forthcoming limits in each different frequency band, but also revealed peculiar RF harmonic components, of no safety concern, to the whole range detected (20-1000MHz). Further work is needed in order to clarify their origin and characteristics.

1. Introduction
A few years ago, European countries put into force legislative acts to implement the 1999 Recommendation of the Council of the European Union for the protection of the general public from Electromagnetic Fields (EMF) exposure. This Recommendation, based on ICNIRP’s (International Commission for Non-Ionizing Radiation Protection) guidelines for EMF (0-300GHz) [1], also formed the basis for the 2004/40/EU Directive concerning the protection of workers from EMF exposure, but this Directive was never implemented due to the strict static magnetic field occupational limits stated, that would restrict the use of MRI systems. ICNIRP made significant changes in its guidelines for the 0-100kHz frequency region in 2010 [2]. These new guidelines, together with the former ones, which are still valid for high frequencies, formed the basis for the new Directive (2013/35/EU) [3]. This is part of the overall legislation for Occupational Health and Safety (OHS) and during its implementing process into national law, various work places (including MRI [4]) are assessed for EMF occupational exposure, through the collaboration of the Ministry of Labor with the Non-Ionizing Radiation Office of the Greek Atomic Energy Commission (GAEC). Note that the complicated Quality Assurance (QA) and safety issues in MRI are covered in Greece by a complete QA MRI protocol [5].
2. Materials and methods

2.1. NMR and MRI electromagnetic characteristics

Magnetic Resonance Imaging (MRI) is a term invented by radiologists to describe Nuclear Magnetic Resonance (NMR) imaging, a spectroscopic method originally concerned with identifying signals from chemical compounds using small probes (cylinders: 0.2-0.5cm diameter) with no spatial information. Since the 70’s, NMR imaging has evolved as a technique where signal spatial localization with the aid of magnetic gradient fields was feasible. Signals were then obtained from larger probes (cylinders: 1–3cm). Finally, since the 80’s and based on the same localization principles, MRI was introduced as a standard diagnostic method probing the entire human anatomy. As expected, in clinical MRI, signals were then obtained from extremely large probes (cylinders: 60-70cm). In both NMR and MRI techniques, the final signal is detected from selected nuclei being present and magnetically coupled in atoms/molecules, which in turn are moving in different magnetic molecular environments. These magnetic couplings and the actual physical atomic/molecular movements modulate the final signal, which is strongly related to either the magnetic parameters, known as T1, T2 and T2*, or the physical parameters, like molecular diffusion or both. The most studied nucleus in biological NMR and in clinical MRI is the nucleus of the Hydrogen atom. More specifically, NMR and MRI are based on the magnetic excitation of nuclei being present inside a homogeneous, high static magnetic field, ranging from 0.2 up to 40T. In clinical MRI, static fields range from 0.2 up to 8T. Nowadays, NMR and MRI systems are implementations of pulsed nuclear excitation/detection experiments. This means that in both techniques, nuclei are excited utilizing bursts of intense radiofrequency pulses. These pulses are centered on a basic excitation frequency, which is linearly related to the static field strength and in the clinical MRI lies in the range of 8MHz (0.2T) up to 340MHz (8T).

In either NMR or MRI systems the final signal is detected just after the excitation RF pulse, as the nuclei return to thermal equilibrium by emitting time domain recordable RF signals, with basic frequencies lying on the MHz spectrum and depending on the external static field strength. This relaxation procedure is controlled by specific relaxation time constants, namely T1, T2, T2* and the decaying signal contains the sum of the frequencies from all the target nuclei. Most of this signal is picked up in the coil, as an oscillating EMF, generated by the nuclear magnetic moments rotating back to equilibrium. The actual signal cannot be recorded directly, because its frequency is too high (MHz range). It is mixed with a lower frequency carrier signal to produce a low frequency interferogram, which is further digitized and called the Free Induction Decay (FID) signal. Fourier transformation of the FID yields a frequency domain spectrum, which is the final recorded signal [6]. It is the authors’ assumption that nuclei relaxation is not a single dominant frequency phenomenon and their harmonic components pattern should be strongly related to the nuclei magnetic environment [4].

In clinical MRI, spatial localization is achieved by the superimposition of powerful linear magnetic gradient fields ranging from 10 up to 80mT/m and operating in a switching mode with slew rates of 50 up to 300mT/m/ms. Gradient fields are used for slice selection during signal excitation and signal detection steps, frequency encoding and phase encoding procedures during digital imaging reconstruction steps. Gradient switching is achieved by transmitting signals on the kHz range [7].

2.2 The MRI in the new EMF Directive (2013/35/EU)

The new EMF Directive implies a system of multiple exposure limits, with the two basic definitions being: ‘Exposure limit values (ELVs)’ and ‘Action levels (ALs)’ [3]. ELVs are established on the basis of scientifically well-established, short-term and acute direct effects and refer to the internal field (into the human body). They are the substantial limits in order to check for health consequences and there is no way to have direct measured values compared to them, but only through complex computer modeling [8]. ALs are operational levels established for the purpose of simplifying the process of
demonstrating the compliance with relevant ELVs, since external field measurements are directly comparable to ALs. AL overexposure does not necessarily mean that ELVs are also exceeded [9].

The Directive excludes, under a prescribed scheme, MRI systems from the application of the ELVs [3], but MRI personnel are covered by OHS legislation even in the case of derogation. On the contrary, patients whose exposure can be much higher are not considered as general public in order to be covered by the corresponding legislation, but the Justification and Optimization principles are applicable. In both cases the implementation of best practices has multiple benefits.

Measurements of RF electric field and ELF magnetic field were performed next to the examination bed, during the MRI scans for 1.5T and 3T systems, during occupational exposure assessment [4]. The use of Narda IDA-3106 Interference and Direction Analyzer revealed low amplitude RF harmonic components. Three different directional antennas were used.

3. Results
Spectrums and spectrograms (spectrum pattern as a function of time) were obtained with the Narda IDA-3106 for 1.5T systems. The RF safety issues are linked with the 63.5MHz frequency, which is clearly visible and around it many small others harmonics, of no safety concern, exist (figure 1).

![Figure 1](image1.png)

**Figure 1.** Relative comparison between 63.5MHz and harmonic components for 1.5T.

Harmonics can be seen for the 200-500MHz (figure 2) and for the 400-1000MHz regions.

![Figure 2](image2.png)

**Figure 2.** RF harmonic components between 200 and 500 MHz for a 1.5T MRI system.

The RF shielding check with Narda IDA-3106 of one system revealed FM radio interference due to some copper lamina missing from the door (figure 3).

![Figure 3](image3.png)

**Figure 3.** Faulty RF shielding.
4. Discussion

MRI, apart from a very important imaging technique, is also a very interesting and rich electromagnetic environment. Almost the entire EMF spectrum is present during an MRI scan, resulting in a combined exposure to the static & ELF magnetic field and to the RF electromagnetic field. SCENHIR (Scientific Committee on Emerging and Newly Identified Health Risks, of the European Commission) classifies the investigations of suggested health effects in the MRI environment as highly important and urgent [10].

Initial occupational MRI investigation showed compliance with the forthcoming limits, but also revealed peculiar RF harmonic components [4]. The first results presented need to be expanded and clarified for different equipment and clinical practices.

Shielding integrity of the MRI room can be checked by recording the background RF spectrum inside the room and surveying around it. In this way small shielding discontinuities can be identified.

5. Conclusions

The RF harmonic components found are of no safety concern. Their origin is not clear and it is under examination whether they follow any specific pattern or not. Harmonics of the main 63.5MHz frequency are detected, but also other submultiple ones and even the half of the main frequency, are present (overtones and semitones). This seems to be repeated to higher frequencies too. It is the authors’ suggestion that the observed RF frequency patterns are somehow related to the magnetic molecular environments, on which the nuclei are bound or interact with. Moreover, the RF frequency patterns were revealed with the use of directional antennas and were also direction dependent. Further research studies on the specific topic have to be meticulously designed. Questions relating the type of the materials (water, fat, gelatin, paramagnetic solutions, etc.), their actual shapes (e.g. filling hollow spaces) and magnetic field strength, with a specific RF pattern have to be answered.

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