Assessment of the exposure of workers in magnetic resonance imaging[1]

1. Extracted and adapted from the text "Risonanza magnetica: problematiche di sicurezza e livelli di esposizione degli operatori" ("Magnetic resonance: safety issues and exposure levels of workers"), by D. Andreuccetti, G.M. Contessa, R. Lodato and R. Pinto, published in the Proceedings of the XXIV AIRM National Congress "Radiological Risk and Medical Surveillance in Hospital", held in Florence on 28-30 May 2015.

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Introduction

Magnetic resonance imaging scanners (MRI; an example in Figure 1) are increasingly widespread in public and private healthcare facilities. The presence of these diagnostic devices poses significant problems for those dealing with protection against exposure to electromagnetic fields, owing to the complexity of the stray fields and to their considerable intensity. As a matter of fact, occupational exposure in MRI departments was one of the crucial issues in the process of suspension and subsequent revision of European Directive 2004/40 [1], which ended with the publication of the new Directive 2013/35 [2].

Figure 1. *A 1.5 T magnetic resonance imaging scanner.*

An MRI scanner produces three different types of electromagnetic fields.

1. A very intense static magnetic field (SMF) (the whole-body scanners currently most widespread in Italy operate at 1.5 T, but 3 T scanners were introduced quite some time ago, while even higher values are beginning to be used in research applications, especially in the functional field). The intensity of this field determines the magnetic resonance frequency of hydrogen nuclei (protons), at a rate of about 42 MHz per tesla (see Figure 1). The SMF is mainly confined inside a dedicated cylindrical structure (the bore) in which the patient is positioned, but considerable values (progressively lower moving away from the bore) are dispersed throughout the surrounding space. For technological reasons, the static magnetic field is never switched off, not even when the device is unused for a long time, and is therefore always present in the rooms devoted to MRI.
2. A pulsed radiofrequency electromagnetic field (RF field), used to excite the hydrogen nuclei at the resonance frequency; the relaxation that follows when the RF field is deactivated generates the signal underlying the production of the tomographic image.
3. A gradient magnetic field (GMF) at intermediate frequency, which locally modifies the static magnetic field and hence the resonance frequency of the protons, so as to spatially encode the produced signal. The GMF is switched on and off following suitable sequences

(depending on the type of examination to be performed), thus producing a magnetic field that varies in time in a complex manner.

In most situations, healthcare personnel are exposed only to the SMF and to the consequences of movements within it. The personnel, in fact, leave the scanner room during the execution of the examinations, when the GMF and the RF field are activated. There are, however, some exceptions, such as interventional magnetic resonance (i.e. the execution of surgical operations under continuous MRI monitoring, which incidentally does not appear to be practised in Italy), or the case of examinations on sedated subjects, for which the presence of an anaesthetist next to the patient is required, as sometimes happens in paediatric cardiology.

A first study on the subject, funded in 2008 by the European Commission [3], had indicated that — although 90% of the examined procedures appeared to comply with the provisions of Directive 2004/40 — some particular but important situations could fall outside, such as precisely interventional MRI and the cases of very rapid movements in the areas closest to the scanner.

As a consequence of this situation, research initiatives were undertaken in Italy as well, aimed at providing useful elements for the assessment of the exposure of healthcare workers in MRI departments, both on the methodological level (development of instrumentation chains and of measurement and analysis procedures) and on the knowledge level (acquisition of information on the actual exposure levels). ISPESL (merged into INAIL at the end of 2010) launched in 2008 and 2010 two specific research projects on the subject which, moreover, also found room in the strategic programme "Safety and healthcare technologies" of the Ministry of Health (2008 call) and in a targeted research project of the same Ministry (2009 call), devoted to the "Ex vivo and in vitro study of the effects of electromagnetic fields on stem cells and risk assessment of healthcare workers".

Regulatory framework

The above-mentioned Directive 2013/35 establishes a complete set of criteria for the assessment of occupational exposure to electromagnetic fields. As far as limit values are concerned, it draws on the guidelines issued by ICNIRP (International Commission on Non-Ionizing Radiation Protection) in 1998 on high-frequency fields [4][2], in 2009 on static fields [5] and in 2010 on low-frequency fields [6]. ICNIRP also published in 2014 the guidelines concerning the movement of an individual in a static magnetic field and the exposure to magnetic fields varying extremely slowly in time [7]; these, however, have not been incorporated into formal legislative acts so far.

2. The 1998 ICNIRP guidelines cover with continuity the whole frequency range from 0 Hz to 300 GHz, but only the part concerning thermal effects (with frequencies above 100 kHz) was incorporated into Directive 2013/35, which refers instead to the more recent 2010 guidelines for the nervous system stimulation effects at low frequencies.

The 1998 ICNIRP guidelines [4] also constitute the scientific reference of European Recommendation 1999/519 [8] for limiting the exposure of the general public at both low and high frequencies. For various reasons, the regulatory aspects pertaining to the protection of the general public are of interest also to those dealing with occupational exposure.

In the following, we shall therefore refer to the set of ICNIRP guidelines [4], [5], [6] and [7] to compare and discuss the exposure levels encountered in MRI.

Materials and methods

The weighted-peak method

Radiation protection standards specify limit values that vary as a function of frequency: they are therefore applicable in a simple way only to sinusoidal signals. In the presence of signals with complex waveforms, the standards propose processing methods that make it possible to properly weight the contributions at the various frequencies present in the spectrum of the field, taking into account that a different limit value must generally be applied to each of them.

The method best suited to handle the waveforms encountered in MRI is the "weighted-peak method" (or WP method) [9]. This method consists in computing an index, whose value must be lower than 1 to guarantee compliance, through a processing that takes into account both the amplitudes of the spectral contributions present in the considered signal (related to the regulatory reference values at the corresponding frequencies) and their respective phases. The maximum absolute value of the waveform thus processed constitutes the sought index. In formulas, for the X component of the magnetic field we have:

$$\mathrm{WP}_x(t) = \sum_i \frac{B_x(f_i)}{B_L(f_i)\sqrt{2}} \cos(2\pi f_i t + \theta_i + \phi_i) \tag{1}$$

where $B_x(f_i)$ and θ_i are the peak amplitude and phase of the spectral contribution at frequency f_i of the X component of the field, and $B_L(f_i)$ is the ICNIRP reference level at the same frequency (as an RMS value); φ_i is the phase shift that would be introduced, at frequency f_i, by a chain of first-order analog filters, which simulates the response of a nerve cell and is designed to provide a transfer function equal, in amplitude, to the term $1/[B_L(f_i)\cdot\sqrt{2}]$. Analogous expressions hold for $WP_y(t)$ and $WP_z(t)$. Once the indices as a function of time have been computed for the three Cartesian components of the field, the overall WP index is found by taking the maximum value of the square root of the instantaneous sum of the squares of the three components:

$$\mathrm{IndexWP} = \max \sqrt{\mathrm{WP}_x^2(t) + \mathrm{WP}_y^2(t) + \mathrm{WP}_z^2(t)} \tag{2}$$

where the maximum is taken over the whole time span of the exposure duration. Equation (2) can be applied either with hardware solutions, by means of a chain of suitable analog filters, or by software, by means of numerical procedures able to emulate, in the time or frequency domain, the behaviour of the filters themselves.

Gradient magnetic field

Inside the bore of an MRI apparatus, the gradient magnetic field is directed mainly along the principal axis; the GMF vanishes at the centre of the bore itself and varies linearly in space moving away from it along the three directions of a predetermined orthogonal Cartesian reference system. Outside the bore, on the other hand, the direction of the field and its intensity vary in a complex manner in space. Moreover, the gradients along the three directions are activated, independently of one another, for short periods according to a suitable timing, synchronised also with the activation of the radiofrequency field, so as to select the points from which one wants to receive the signal used to reconstruct the tomographic image; consequently, the GMF has a very complex behaviour in time as well (with characteristic frequencies of the order of kilohertz), which requires an adequate choice both of the instrumentation and of the processing procedure, in order to carry out an exposure assessment that is correct from the radiation protection point of view.

The measurement chain adopted for the measurement of the GMF and the acquisition of the signals on which the weighted-peak method is later applied is illustrated in Figure 2. It comprises: (1) a Narda ELT-400 magnetic field probe (Narda Safety Test Solutions, Pfullingen, Germany) equipped with a 100 cm² triaxial isotropic sensor and able to operate in the frequency range from 1 Hz to 400 kHz; (2) an Agilent U2531A data acquisition and digitisation system (DAQ) (Agilent Technologies, Santa Clara, CA 95051, USA); (3) an ordinary portable personal computer with data storage and remote control functions; (4) an original software procedure, developed in Labview 2009 (National Instruments Corporation, Austin, TX 78759, USA), which controls the whole system.

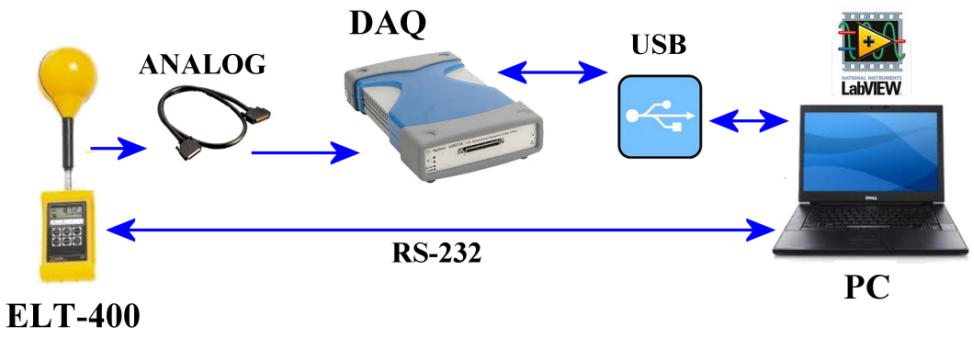

Figure 2. *Diagram of the instrumentation chain for the measurement of gradient fields.*

The ELT-400 probe, set in the mode named "Field Strength" (FS), makes available at its analog outputs three voltage signals instantaneously proportional to the intensity of the three Cartesian components of the magnetic field in which the sensor is immersed. The frequency response is flat starting from a lower limit that can be set at choice among 1, 10 or 30 Hz, up to the upper limit of 400 kHz.

The Agilent U2531A acquisition system (DAQ) is a device equipped with a USB 2.0 interface and four analog inputs, which are digitised in real time with a resolution of 14 bits and a maximum synchronous sampling rate of 2×10^6 samples per second per channel. Three of the inputs of the acquisition system are connected to the three analog outputs of the ELT-400. The latter is also connected to the personal computer through an RS-232 interface. The same personal computer controls the DAQ through the USB interface and transfers the acquired data to its own mass storage. All the functions performed by the control computer are managed through a purpose-developed Labview application.

The measurements of the gradient fields were performed using a sampling rate of 50×10^3 samples per second per channel and acquiring time segments of 10 ÷ 20 s. The ELT-400 probe was set in FS mode, selecting the most appropriate values for the sensitivity and for the lower cut-off frequency of the passband (in most cases, the latter was set to 30 Hz to minimise noise). The acquired samples, transferred to the personal computer, were subsequently processed to derive the radiation protection WP indices mentioned above; to this end, software procedures were developed capable of performing this task operating in the time domain or in the frequency domain.

For completeness, it should be said that the ELT-400 probe features, besides the above-mentioned FS mode, also an operating mode named "Shaped Time Domain" (STD), in which the probe itself is able to show on its display the weighted-peak index, determined autonomously in hardware on the basis of the regulatory limits preset by the manufacturer. Compared with the approach — certainly convenient and quick — based on this functionality of the probe, the one we adopted (sampling, storage and subsequent off-line processing) has the advantage of allowing any assessment metric to be applied in addition to the weighted peak, and of referring to any system of limit values one may wish to consider: a possibility that is certainly precious in a context of research and methodological development.

Radiofrequency electromagnetic field

In an MRI system, the radiofrequency electromagnetic field is the least relevant physical agent from the radiation protection point of view, because the electromagnetic field levels to which the personnel might possibly be exposed would in any case be very low, thanks to the shape of the coils used to generate them, which tends to confine the presence of the RF field to the region occupied by the patient alone.

This does not mean, however, that ascertaining the RF exposure levels is free of difficulties: the intrinsically pulsed time behaviour indeed poses measurement problems that can prove non-trivial, whether direct-detection probes are used or narrow-band instrumentation is employed.

Figure 3. *Narda SRM-3000 analyser and single-axis probes for the electric field, 3531/02 (top), and for the magnetic field, 3551/01 (bottom).*

For the measurements that we shall report in the section devoted to the results, a Narda SRM-3000 Selective Radiation Meter spectrum analyser was used (100 kHz - 3 GHz; Narda Safety Test Solutions, Pfullingen, Germany), equipped with a 3531/02 electric field probe and a 3551/01 magnetic field probe, both single-axis and able to cover the band 100 kHz - 300 MHz (Figure 3).

Static magnetic field and movement within it

The determination of the distribution of the static magnetic field intensity in the space surrounding an MRI scanner does not present particular difficulties and is normally carried out in all facilities hosting devices of this type; for this purpose, commercial sensors are employed whose procurement and use pose no problems. The purpose of the measurements is, in particular, to identify and mark (usually with indications on the floor) the areas subject to limitations according to the national regulations, such as the so-called "controlled access" zones (with field intensity above 0.5 mT) and "buffer (or limited access)" zones (with intensity between 0.1 and 0.5 mT).

The aspects related to movement in the SMF, on the other hand, present greater difficulties for those dealing with radiation protection, but are also of greater interest. Unlike what happens in a motionless subject, translation in a non-uniform field or rotation of parts of the body even in a uniform field cause the induction of voltages and currents in the tissues of the exposed organism, with which well-known (although not yet completely clarified) effects are associated, which led ICNIRP to publish a specific guideline on the matter [7].

The approach adopted to analyse this issue consists in reducing the movement in the static field to the measurement of a magnetic field "perceived" as time-varying (and therefore denoted by the acronym pMFD, from perceived Magnetic Flux Density) by means of a probe rigidly attached to the body of the exposed individual. To this end, a Metrolab THM-1176 triaxial Hall-effect probe was used (Metrolab Instruments SA, Geneva, Switzerland; see Figure 4), which features a measurement range extending from a few microtesla up to 20 T and a passband from 0 to 1000 Hz. The probe was worn by volunteers who mimicked the typical movements of healthcare operators, performing standardised "actions" corresponding to the activities most commonly carried out in the areas surrounding an MRI scanner (Figure 5).

Figure 4. *Metrolab THM-1176 static magnetic field probe.*

Figure 5. *Measurement of the perceived magnetic flux density (pMFD) in case of movement in the static magnetic field, during the execution of movements typical of the preparation of an MRI examination.*

Figure 6. *Detail of a possible way of positioning the probe for the detection of the perceived magnetic field (pMFD).*

During each action the probe was kept in a fixed position, rigidly connected to the head of the volunteer (considered the seat of the main target organs for the effects of extremely low frequency magnetic fields) by means of a purpose-built support exploiting the inside of a cycling helmet (Figure 6).

The probe used is equipped with its own digitisation device with output on a USB interface, which allows it to be connected to a portable personal computer with control and storage functions. For the management of the measurements, the software supplied with the probe was

used, setting it for the maximum allowed sampling rate, equal to 10 samples per second per channel, each of which in turn derived from the average of 10 measurements. In this case as well, the weighted-peak method was used to process, both in the time domain and in the frequency domain, the acquired waveforms.

Summary

A methodology has been presented for the assessment of the occupational exposure to electromagnetic fields of the healthcare personnel working with magnetic resonance imaging diagnostic devices; in particular, the issues related to gradient magnetic fields and to movement in the static magnetic field have been examined in depth.

The methodology makes use of purpose-assembled instrumentation chains and is based on the weighted-peak method for the radiation protection processing of the complex waveforms that characterise the types of sources involved. It was applied in real situations during measurement campaigns carried out at some healthcare facilities in the Rome area.

As regulatory references, we considered European Directive 2013/35 and the ICNIRP guidelines of 1998, 2009 and 2010 which constitute its main scientific foundations, respectively for high-frequency fields, the static magnetic field and low-frequency fields. The recent 2014 ICNIRP guidelines on movement in the static field were also taken into account, at least in part, although these have not been incorporated into any legislative act for the time being. Through the 1998 ICNIRP guidelines, reference was finally made also to European Recommendation 1999/519 for the protection of the general public.

From the results of the measurements performed, it emerged that the exposure to gradient fields can violate not only the 1998 guidelines for the general public but, in many cases, also the corresponding occupational guidelines. It complies, instead, with the less restrictive 2010 guidelines (and hence with the requirements of Directive 2013/35).

The exposure due to movement in the static field turned out to comply with the occupational standards in all the simulated actions concerning the 1.5 T scanner, except for the extreme case in which the exposed subject had introduced and moved their head right inside the bore. Some non-compliances were found, instead, in the case of the 3 T apparatus. Violations of the guidelines for the general public turned out to be frequent for both scanners. The reported data make it possible to demonstrate clearly that compliance with the guidelines for exposure to the static magnetic field is not sufficient to guarantee compliance with the limits set to protect against the nerve stimulation effects that may be associated with movement in the field itself.

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