4th URSI AT-RASC, Gran Canaria, 19-24 May 2024

MRI exposure assessment: an overview of Italian research activity

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Abstract

In this work, the authors report some results of previous studies conducted for assessing occupational exposure in magnetic resonance imaging (MRI) related to gradient magnetic fields and movement in the static magnetic field.
To do this some measurement campaigns were carried out and a procedure approach was developed with the aim of providing and testing an efficient method for exposure assessment.

1. Introduction

MRI has become increasingly pivotal in diagnostic procedures, owing to technological advancements. Presently, in Italy clinical diagnostics predominantly employ 1.5 T and 3 T scanners, while higher field strength systems (7 T and beyond) find application in research. In this context, safety issues for healthcare workers need to be carefully considered and managed. Specifically, within the MRI environment, attention must be given to the Static Magnetic Field (SMF), the Low-Frequency switched Gradient Magnetic Field (GMF), and the Radio-Frequency Field.
Concerning the static magnetic field, two critical aspects necessitate investigation: the SMF itself and the movements through its spatial gradients, which induce electric fields and currents in exposed body tissues.
The present study describes a developed procedure for assessing exposure in MRI. This procedure addresses exposures to low-frequency switched GMF and movement-induced effects in the SMF. The exposure to radiofrequency fields is not presented due to the low levels found during measurement campaigns. It is noteworthy that, owing to the complex waveform of the GMF, a specific method for compliance assessment, called the "weighted peak- WP", was introduced by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) 2003 Statement [1] and recommended by the European Directive 2013/35/EU [2]. According to this method, the frequency content of an Impulsive signal is processed by weighing the amplitudes of the spectral components against the relevant limits (workers/population) at the corresponding frequencies, also considering the phases of the components. The maximum absolute value of the waveform weighed constitutes the index required (I_{WP}), whose value must be less than 1 (or 100% depending on the chosen normalization criterion) to ensure compliance with the exposure condition.
To obtain the WP index, the GMF waveforms and SMF movement data were measured and post-processed through a software weighting function with appropriate amplitudes and phases. The measurement chain was homemade and developed for these purposes.

2. Materials and Methods

2.1 Setup for measurements of the gradient fields

In order to accurately assess the exposure of personnel assigned to MRI units, special care must be taken to measure and analyze the complex-waveform magnetic fields produced by MRI gradient coils, which have spectra in the kHz range.
Four main subsystems compose the measurement setup used in this study: a three-axial, 100 cm^2 probe-equipped Narda ELT-400 Exposure Level Tester (Narda Safety Test Solutions, Pfullingen, Germany); an Agilent U2531A Data Acquisition (DAQ) device (Agilent Technologies, Santa Clara, CA); a standard notebook (PC) and a suite of Python3 and LabVIEW applications used to manage the measurement chain and to elaborate the results. This configuration is characterized by great flexibility and provides total control of the measured data, which is not always possible with the most modern integrated systems.
Even if the ELT400 instrument implements the weighted peak method in hardware, the measurements were carried out in plain field strength mode and the weighted peak indices were calculated via software in the post-processing phase. This approach has the advantage of being able to determine multiple exposure indices for the

same measurement and possibly being able to evaluate the exposure indices according to standards published after the measurements. The Agilent U2531A DAQ, a high-speed USB 2.0 data acquisition device, was connected to the three (x, y, and z) ELT-400 (used in Field strength- FS mode) analog outputs. It has four differential input channels with 14-bit resolution and supports a truly synchronous sampling rate of up to 2 Msamples per second per channel. These samples were used to determine the WP indices with a software implementation of the hardware filters developed with the finite impulse response (FIR) technique.
The measurement campaigns were carried out for the following scanners:

- 1.5 T Philips Achieva Nova survey, for routine clinical examination,
- 1.5 T Philips Achieva survey, for cardiac examination on children
- 1.5 T Achieva survey, a second model of the device
- 3 T Siemens Magnetom Skyra survey
- 7T GE HealthCare MR950 research scanner (investigational device)

The Python applications created for this purpose were subsequently made available on the Webnir platform, at the website link:
https://www.webnir.eu/launcher.php?id=18&area=CEM.

2.2 Setup for measurements of movement in the static magnetic field

In this case, the chosen reference quantity to be measured is the magnetic flux density in a (moving) reference system linked to the exposed worker.
The chosen instrument was the THM1176 Three-axis Hall Magnetometers (Metrolab Instruments SA, Geneva, Switzerland), which has a DC bandwidth up to 1 kHz, a dynamic range from several hundred microtesla up to 3 T (MF type) or 20 T (HF type) in four spans, and 1% uncertainty. It simultaneously detects the three field components and sends them via a USB link to a PC. The control software permitted an effective output rate of 10 vector samples per second, which was achieved by taking all measurements with a sampling speed of 100 samples/second and an averaging factor of 10. The bandwidth of the signal under analysis was limited by this rate to 5 Hz.
Several parameters have been calculated starting from the acquired samples and in particular: the peak values of the magnetic flux density and of its time derivative, the change of the magnetic flux density during any 3 second period of the acquired sequence, the weighted peak indexes referred to controlled and uncontrolled exposures [5]. For the calculation of the WP indices, the approach was the same used for the evaluation of gradient field exposure where, in this case, the frequency response of the filters is the composition of the limits defined by the ICNIRP 2014 Guidelines (Reference Levels-RLs, below 1 Hz) [3] and those defined by Directive 2013/35/EU (Low and High ALs, over 1 Hz) (Figure 1).

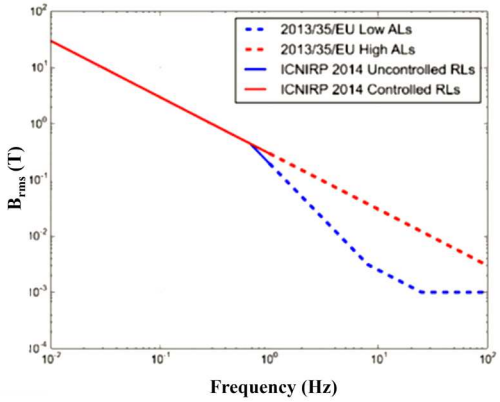

Figure 1: Limits used for the calculation of the WP indices in the case of movement in the SMF.

The software procedure that calculates all these parameters, starting from the measured field samples, has been made available through a web interface on the Webnir platform:
https://www.webnir.eu/launcher.php?id=3&area=CEM.
Health professional volunteers, selected from MR wards staff, mimicked real health workers' actions in pre-approved and filmed sequences. Realistic and spontaneous movements, rather than schematic ones, were performed to capture authentic exposure scenarios. Each action generated a dataset with the B field's sampled components sent to a PC and stored in a text file. A total of 25 actions (A1 to A25) and 55 datasets were collected across three surveys:

- 1.5 T survey: Eight actions (one dataset each) using a Philips Achieva scanner,
- 3 T survey: Eleven actions (one dataset each) using a Siemens Magnetom Skyra scanner,
- 7 T survey: Six actions (36 datasets) using a GE HealthCare MR950 scanner.

This “experienced” field has been measured through the use of a probe worn by volunteers while acting in MR environments. As the head is one of the body parts most physiologically interesting and may move quickly and frequently, combining its independent movements with those of the entire body, it was most often selected as the measurement point, and a special helmet has been used to fix the probe in place (right side of the head).
In the case of the six 7 T actions, the 36 datasets (instead of one for each action, as done for 1.5 and 3 T) are needed to deeply verify the aspects related to repeatability and reproducibility of the results, maintaining or altering the following conditions: volunteer, probe type (MF/HF) or probe position (left/right side of the head or hip). Therefore, two health professionals (A and B) were involved: A (1.80 m, 74 kg) and B (1.65 m, 63 kg).

3. Results

In the regulatory framework, the Directive 2013/35/EU establishes comprehensive criteria for the assessment of occupational exposure to EMF. Concerning limit values, it integrates the recommendations of the guidelines

issued by ICNIRP 1998 on high-frequency fields [4], in 2009 on static fields [5] and in 2010 on low-frequency fields [6]. The ICNIRP 1998 Guidelines are also the scientific reference for the European Recommendation 1999/519 [7] for limiting population exposure to both low and high frequencies. For various reasons, regulatory aspects relevant to the protection of the population are also of interest to those dealing with occupational exposures [8]. In what follows, we will therefore refer to the Directive 2013/35/EU and to the set of ICNIRP guidelines [3], [4], [5], and [6] to compare and discuss exposure levels encountered in MRI.
Following are the results of the measurements, divided into two different sections, to consider separately those related to the GMF and to the movement in SMF.

3.1 Gradient fields

Table 1. Measurement results of GMF

Scanner	Sequences	Measurement points	WP 2010occ.	WP 1998pop.
Philips Achieva Nova 1.5 T *Routine clinical examination*	EPI axial	[20,0,100]	0.41	12.00
	EPI coronal	[20,0,100]	0.21	5.56
	EPI sagittal	[20,0,100]	0.23	6.23
Philips Achieva 1.5 T *Cardiac examination on children*	Cardiac black blood	[45,70,110]	0.14	4.50
	EFF	[45,70,110]	0.21	7.85
	Q-flow	[45,70,110]	0.24	7.72
	Cardiac short axis	[45,70,110]	0.19	7.26
Philips Achieva 1.5 T *second device*	EPI 200µs	[50,67,70]	0.11	/
		[50,67,120]	0.14	/
Siemens Magnetom Skyra 3 T	EPI 270 µs	[50,67,120]	0.14	/
		[50,67,170]	0.11	/

In Table 1 the measurement points coordinate, reported in brackets, are the distance from the frontal axis and the longitudinal axis of the bore, and the height from the ground, respectively.
For the 7 T device, at point A, the probe centre was positioned at different heights from the ground, 50 cm from the gantry front plane, and 70 cm from the stretcher axis. Table 2, reports the WP indices referred to the Directive Low AL_S and also the ICNIRP 1998 population exposure, for a point named A, at a different height (x_i) from the ground (A_x_i).

Table 2. Measurement results for the 7 T scanner for point A

Sequences	Point	WP AL_Low	WP 1998 pop
EPI axial	A_120	0.6	18.4
EPI coronal	A_120	0.6	18.2
DWI02 b_value 1000	A_120	0.8	30.5
DWI03 b_value 1400	A_120	0.8	29.2
DWI04 b_value 2200	A_120	0.6	20
EPI axial	A_170	0.6	17.9
EPI coronal	A_170	0.7	18.5
DWI02 b_value 1000	A_170	0.6	19
DWI03 b_value 1400	A_170	0.7	20.3
DWI04 b_value 2200	A_170	0.6	21.3
EPI axial	A_050	0.7	18.2
EPI coronal	A_050	0.7	17.9
DWI02 b_value 1000	A_050	0.7	19
DWI03 b_value 1400	A_050	0.6	16.3
DWI04 b_value 2200	A_050	0.6	17.7
FSE-IR	A_050	0.5	9.8
FSE	A_050	0.5	9.3

As can be seen in Table 1, the WP index for occupational refers to the ICNIRP 2010 RLs, while in Table 2 it refers to the Low ALs of Directive 2013/35/EU. The reason is that the calculations reported in Table 1 were carried out when the directive had not yet been published. In any case, the RLs of the ICNIRP 2010 LG are the same as the Low LAs (frequency range from 0 Hz to 10 MHz) of the directive and thus the results are fully comparable.

3.2 Movement in the static magnetic field

In Table 3 the results of the measurement campaigns are presented only in the cases where exceeding the weighted-peak indices for "sensory" (sensory-WP) and "health" (health-WP) effects were reported. All of them are related to actions performed in situations of emergency from the different subjects. In addition, all measurements were performed with the probe MF type, with the exception of those marked in blue (probe HF type).

Table 3. Measurement results for the movement in the SMF

Action	Subject	B peak [T]	Max ΔB over 3 s [T]	EU-2013/35+ICNIRP-2014	
				sensory-WP	health-WP
1.5 T					
A3	/	1.43	1.43	2.1	1.0
7 T					
A20	A (HR)*	1.16	1.39	4.9	2.2
A20	A (HR)	1.55	1.84	7.7	2.1
A20	B (HR)	1.46	1.96	3.0	1.7
A21	A (HR)	0.92	1.07	5.1	1.2
A21	A (HR)	1.20	1.33	3.7	1.6
A22	A (HR)	2.58	2.24	6.9	2.8
A22	B (HR)	2.94	3.34	3.0	1.6
A22	B (HR)	3.02	3.16	7.3	2.8
A23	B (HiL)$^{+}$	1.67	1.86	2.7	1.4
A23	B (HR)	1.40	1.93	5.1	2.1
A24	B (HR)	1.70	1.70	3.4	1.1
A24	B (HL)°	2.01	2.35	2.2	1.2
A25	B (HR)	2.05	2.06	9.9	2.8
A25	B (HR)	2.06	2.04	13.1	3.7

Note: * Head Right; $^{+}$ Hip Left; ° Head Left

4. Discussion and conclusion

With regard to switched Gradient Fields, the results of the measurements carried out showed that exposures may violate the ICNIRP 1998 RLs for the population, while compliance with ICNIRP 2010 is verified. As mentioned before RLs are equivalent to Low ALs of the Directive 2013/35/EU.

It is important to note that the nomenclature of the various scanners examined through static magnetic field values (1.5T, 3T, 7T) is only functional for their identification. Exposures to switched gradient fields depend solely on the technical characteristics of the gradient coils, data is not available at the moment. However, it is expected to acquire such data in future planned campaigns.

In the case of movement in the SMF, 1.5 T and 3 T actions were compliant with all the limits, with the exception of one 1.5 T action for the sensory-WP index, when the volunteer quickly inserted his head into the bore to check the patient's condition.

At 7 T, all the 6 actions resulted in noncompliant for sensory-WP (36 datasets) and also for the health-WP (26 datasets) indices, and 2 actions (6 datasets) for the ICNIRP-2014 ΔB limit and EU Directive 2 T limit.

In general, the exceedances of these last two and the SENS-WP limits confirm that workers should be instructed to control their movements, as usually done in any high-field MRI sites ($\geq$ 3 T).

Particularly high values of the WP indices were reached in the 7 T action simulating a situation where the health professional responded quickly to an emergency. However, these actions were not performed at the 1.5 T and 3 T scanners. The exceedances of the indices occur in areas where the magnetic field value is lower than 1.5 T, and in one case even lower than 1 T and therefore should be evaluated also in 1.5 T and 3 T scanner environments. More measurements are needed to understand if these high values are related to the type of action performed within a certain value of static magnetic field inside different field MR rooms taking into account also of the specific gradient of the specific magnet.

Results show that compliance with EU Directive sensory effects Exposure Limit Values (ELVs) for static fields (2T) is not sufficient to guarantee compliance with ICNIRP-2014 RLs for movement-induced stimulation effects, even those recommended to prevent health effects.

Acknowledgments

The authors want to thank the staff of medical facility involved in Rome: Hospital *San Giovanni Calibita Fatebenefratelli* and Pediatric Hospital *Bambino Gesù*, for the friendly hospitality and support provided. A special thanks also to D. Andreuccetti, G. Burriesci, V. Cannatà, E. Genovese, R. Lodato, V. Lopresto, C. Merla, A. Napolitano, R. Pinto, P. Rossi, G. Tiberi for the valuable assistance during the measurement's campaigns [9][10].

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