Occupational exposure in MR facilities due to movements in the static magnetic ﬁeld

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Purpose: The exposure of operators moving in the static field of magnetic resonance (MR) facilities was assessed through measurements of the magnetic flux density, which is experienced as variable in time because of the movement. Collected data were processed to allow the comparison with most recent and authoritative safety standards.

Methods: Measurements of the experienced magnetic flux density B were performed using a probe worn by volunteers moving in MR environments. A total of 55 datasets were acquired nearby a 1.5 T, 3 T, and 7 T whole body scanners. Three different metrics were applied: the maximum intensity of B, to be compared with 2013/35/EU Directive exposure limit values for static fields; the maximum variation of the vector B on every 3s-interval, for comparison with the ICNIRP-2014 basic restriction

aimed at preventing vertigo effects; two weighted-peak indices (for “sensory” and “health” effects: SENS-WP, HLTH-WP), assessing compliance with ICNIRP-2014 and EU Directive recommenda-

tions intended to prevent stimulation effects.

Results: Peak values of |B| were greater than 2 T in nine of the 55 datasets. All the datasets at 1.5 T and 3 T were compliant with the limit for vertigo effects, whereas six datasets at 7 T turned out to be noncompliant. At 7 T, all 36 datasets were noncompliant for the SENS-WP index and 26 datasets even for the HLTH-WP one.

Conclusions: Results demonstrate that compliance with EU Directive limits for static fields does not guarantee compliance with ICNIRP-2014 reference levels and clearly show that movements in the sta- tic field could be the key component of the occupational exposure to EMF in MR facilities.

Key words: experienced magnetic field, magnetic resonance, movements in a static magnetic field, occupational exposure to EMF, weighted-peak index

1. INTRODUCTION

Magnetic resonance imaging (MRI) has gained more and more importance as a diagnostic tool, thanks to technical advances. Nowadays, 1.5 T and 3 T scanners are routinely applied in clinical diagnostics, whereas systems with higher field strengths (7 T and beyond) are used for research pur- poses. In this framework, safety issues for healthcare workers need to be carefully considered and managed.

In this paper, the assessment of exposure of operators moving in the static magnetic field of magnetic resonance (MR) facilities was investigated. The purpose was to quantify the exposure levels and compare them with the safety stan- dards intended to prevent the biological effects that may arise.

In the last decade, several studies have focused on charac- terizing work-related exposure to static magnetic fields and motion-induced time-varying magnetic fields from MRI scanners, in order to identify possible related transient and long-term effects[1–3](#_bookmark18) and to assess the actual exposure levels during MRI examinations.[4–7](#_bookmark10)

The mechanism for the magnetic field induced vertigo has been identified and the threshold values, for the external magnetic flux density B or its variation, able to induce such effect have been predicted,[8](#_bookmark10)disclosing a link between the dis- comfort sensation and the intensity of the static magnetic field.

Computational techniques have been used to investigate the exposure to movement-induced electric fields,[6,9,10](#_bookmark10)reveal- ing that in some cases and for some of the considered move- ments in the simulated MR environment, the basic restrictions set by international guidelines[11](#_bookmark10) can be exceeded in proximity of both 3 T scanners[6](#_bookmark10) and 7 T scanners.[10](#_bookmark10)

* 1. Biological effects of static magnetic ﬁelds

Various biological effects have been associated with the exposure to static magnetic fields.[12](#_bookmark11) Some of them have been attributed to the electric field appearing in the tissues, accord- ing to Faraday’s law, in case of translations in a nonhomoge- neous magnetic field as well as rotations in a homogeneous

or nonhomogeneous field. These effects have been classified into two groups.[13](#_bookmark12)

* “Sensory” effects, considered annoying and disturbing, but not dangerous for the health, yet to be avoided in

ordinary (*uncontrolled*) working conditions, because they can impair working ability and possibly affect

*controlled* conditions, where access is restricted to workers trained to understand the possible biological effects of the exposure and able to control their move- ments in order to minimize them. Perception of phos- phenes and feeling of nausea or vertigo are the main effects of this group.

* “Health” effects, to be avoided even in *controlled* expo- sure conditions, as they might constitute a health risk.

These effects involve the stimulation of nerves and mus- cles throughout the body, which might cause painful sensations, involuntary muscle contractions and possi- bly cardiac extra systoles.

* 1. The regulatory framework

In the European Union, occupational exposures to static magnetic fields are governed by the 2013/35 European Direc- tive[14](#_bookmark13); the 2014 guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP),[13](#_bookmark12)although not mandatory, should also be taken into account.

For what concerns the static magnetic field, the Directive specified only exposure limit values (ELVs) in terms of maxi- mum field intensity. These ELVs, which were taken from the ICNIRP-2009 guidelines,[12](#_bookmark11)are summarized in Table [I](#_bookmark0).

The 2 T value for *normal* conditions took into account both the sensory effects due to the magnetic flux density B in itself and those attributable to movements. The 8 T value for *controlled* conditions was set to prevent any possible (albeit not established) health effect of the static field, with no expli- cit mention to movements. The prevention of movement-

induced sensory effects was entrusted to the workers’ ability to appropriately limit their movements. Moreover, the Direc-

tive referred to the expected publication of ICNIRP specific guidelines for a comprehensive assessment of the movement- related effects; these guidelines were actually published in 2014,[13](#_bookmark12) but they have not (yet) been transposed into the

Directive text. However, the 2015 “Nonbinding guide to good practice for implementing Directive 2013/35/EU” [15](#_bookmark14) makes explicit reference to the 2014 ICNIRP guidelines, e.g., in

TABLE I. Directive 2013/35/EU exposure limit values (ELVs) for the external magnetic flux density B from 0 to 1 Hz.

Sensory effects ELVs Health effects ELVs

Normal working conditions 2 T

Controlled working conditions 8 T

workers’ safety. These effects can be tolerated in

Appendix D.4 “Assessment of exposure to static magnetic fields” and Appendix F “Guidance on MRI”.

The Directive introduced also two sets of ELVs (“Health effects ELVs” and “Sensory effects ELVs”) and of action levels (“High ALs” and “Low ALs”) for the protection against stimulation effects of excitable tissues in the 1 Hz– 10 MHz frequency range. With the exception of “High ALs”,

these limits were taken from the occupational basic restric-

tions (BRs) and reference levels (RLs) specified in the ICNIRP-2010 guidelines for the same frequency range.[11](#_bookmark10) The ELVs were specified in terms of peak induced electric field, the ALs as root-mean-square (rms) of the magnetic flux density.

The ICNIRP-2014 guidelines[13](#_bookmark12) explicitly addressed the problem of the effects arising from motion-induced electric fields below a few Hz. They provided:

* a BR of 2 T (as DB variation of the magnetic flux den- sity over any 3 s period) for preventing transient sen-

sory effects such as vertigo and nausea in *uncontrolled*

exposure conditions;

* BRs and RLs for preventing effects due to the stimula- tion of the central nervous system (“sensory” effects, in particular the perception of so-called “phosphenes”) in *uncontrolled* exposure conditions;
* BRs and RLs for preventing the “health” effects due to the stimulation of the peripheral nervous system (PNS)

in *controlled* exposure conditions.

The stimulation BRs (as peak induced electric field) and RLs (as peak time derivative of B) varied with the frequency in the range from > 0 to 1 Hz. At the frequency of 1 Hz, the BRs for *controlled* and *uncontrolled* exposure conditions matched respectively the health and sensory effects ELVs required under the 2013/35/EU Directive. Similarly, the ICNIRP-2014 RLs for *controlled* and *uncontrolled* exposure conditions matched at 1 Hz respectively the Directive High and Low ALs. Table [II](#_bookmark2) summarizes the limits for stimulation effects which arise from the combined provisions of these two regulations; in the table, the values are expressed as rms averaged quantities.

1. MATERIALS AND METHODS
	1. General approach

The exposure due to movements in the static magnetic field of an MR site was assessed through the measurement of

the “experienced” magnetic flux density in the reference sys- tem of the exposed worker, by means of a probe worn by health professional volunteers and kept in fixed positions on

their bodies while acting in the MR environments.

In most cases, the measurement point was chosen on the head, which is one of the parts of the body of greatest physio- logical interest and which possibly experiences fast and fre-

quent movements, combining its own with those of the whole body. The probe was fixed to the volunteer’s head by means of a special support (Fig. [1](#_bookmark1)).

In a few cases, the measuring point was placed at the hip. The choice of these measurement points is in line with simi- lar studies in literature.[2,5,6](#_bookmark20) In principle, regulatory limits should be checked everywhere in the body, while measure- ments can obviously be taken in just a few points. The com- parison among results relating to the same person and movements, but taken in different body positions should allow to gather information on both the spatial distribution of the field, and on the reproducibility of the pertinent radiation protection parameters when varying the position of the probe.

* 1. Instrumentation and measurement procedure

Measurements were taken using the THM1176 Three-axis Hall Magnetometers (Metrolab Instruments SA, Geneva,



FIG. 1. Position of the probe on the volunteer’s head. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE II. Directive 2013/35/EU action levels (ALs) and ICNIRP-2014 reference levels (RLs) (for preventing stimulation effects).

|  |  |  |  |
| --- | --- | --- | --- |
| Effects | Conditions and parameters | Frequency range (Hz) | Magnetic flux density (Brms) (T) |
| Sensory effects (phosphenes) | Uncontrolled exposure conditions RLs/Low ALs | 0–0.660.66–8 | 0.3/(f/Hz)0.2/(f/Hz)2 |
| Health effects (peripheral nerve stimulation) | Controlled exposure conditions RLs/High ALs | 0–8 | 0.3/(f/Hz) |

Switzerland). It is a handheld probe with a dynamic range from a few hundred microtesla up to 3 T (MF type) or 20 T (HF type) in four spans, bandwidth DC to 1 kHz and 1% uncertainty. It detects the three field components simultane- ously and sends them separately to a PC, through an USB link, for storage and processing. A control software allows to set the sampling rate and the averaging factor, and to manage the data transfer.

All measurements reported here were made with a sam- pling speed of 100 samples/second and an averaging factor of 10, giving an effective output rate of 10 vector samples per second, which was the maximum allowed by the control soft- ware. This rate limited to 5 Hz the bandwidth of the signal being analyzed; however, postprocessing showed that the spectral contents of the experienced magnetic flux density B were always within 2 Hz.

The health professional volunteers were chosen among the personnel of the MR wards, therefore they were aware of the operations carried out during normal work procedures. They were asked to execute sequences of movements, called “ac-

tions” hereinafter, in order to mimic the actual behavior of

health workers (Fig. [2](#_bookmark3)). During each action, the sampled

components of B were sent to the PC and stored in a text file, creating what was called a “dataset”.

All the actions were previously agreed with the health pro-

fessionals, annotated and filmed. A total of 25 actions (A1,

.. ., A25) and 55 datasets were acquired in the course of three measurement surveys:

* Eight actions (one dataset each) in the 1.5 T survey (scanner Philips Achieva — Philips Healthcare, Best,

the Netherlands — at the IRCCS Bambino Ges`u Chil- dren’s Hospital, Palidoro, Rome);

* Eleven actions (one dataset each) in the 3 T survey

(scanner Siemens Magnetom Skyra — Siemens Health-

care, Erlangen, Germany — at the IRCCS Bambino Ges`u Children’s Hospital, Rome);

* Six actions (36 datasets in all) in the 7 T survey at the

Imago 7 Foundation, Pisa, Italy, using a passively



FIG. 2. Executing an “action” close to a 3 T MR scanner. [Color figure can be viewed at wileyonlinelibrary.com]

shielded GE MR950 7 T scanner (GE HealthCare, Mil- waukee, WI, USA).

All scanners were whole body systems. Table [III](#_bookmark4) shows a summary of the examined actions: detailed descriptions of these actions have been reported in the supplemental mate- rial (Chapter 1 “Description of the actions”) available online.

Since the aim of the study was to provide information concerning the actual exposure of the MRI personnel in their regular activity, measurements were performed by try- ing to reproduce realistic and spontaneous movements. More schematic and standardized movements could have been more suitable for numerical investigation or compar- ison with other studies, but this approach would have missed the chance to show, observe, and quantify the actual exposure.

7 T actions were almost all related to engineering and sys- tem set-up activities and thus not to be performed on daily basis, except for action A24, which was very similar to those performed at lower fields, and action A25, which was clearly an emergency action.

* 1. Measurement repeatability and reproducibility

Each of the six 7 T actions was repeated a few times (gen- erating 36 datasets in all) in order to check the repeatability and the reproducibility of the measurements, either in unchanged conditions or changing the volunteer or the probe

position on the volunteer’s body. Three health professional volunteers (A,B,C) were involved in these actions. “A” was a 40 yr old male, 1.80 m tall, weighing 74 kg; “B” was a 39 yr old female, 1.65 m, 63 kg; “C” was a 35 yr old male,

1.88 m, 90 kg. There were four options for the position of

the probe on the body: the left or the right side of the head, and the left or the right hip. For a few 7 T actions up to four different repetitions (called “runs”) with the same subject and probe position were also executed.

Each action of the 1.5 T and 3 T surveys was repeated just once, with the probe in the head-right position.

* 1. Data processing

The stored datasets were postprocessed in order to derive values to be compared with the appropriate regulations. For each dataset, compliance was assessed:

* with EU Directive for static magnetic fields, by compar- ing the dataset peak value with limits specified in

Table [I](#_bookmark0);

* with the vertigo limit as for ICNIRP-2014, by compar- ing the maximum value of the modulus of the variation of the vector B on every 3 s-interval with the basic

restriction of 2 T;

* with the stimulation limits (Table [II](#_bookmark2)), by resorting to the “weighted-peak” (WP) approach in time- domain.[11,16](#_bookmark10)

TABLE III. Summary of actions.

Nominal MR field strength/number of actions

Number (code)

of actions Type of actions

Number of datasets

|  |  |  |  |
| --- | --- | --- | --- |
| 1.5 T/8 actions | 3 (A1.. .A3) | Anesthesiologist involved in cardiological examinations on pediatric patients, three different | 3 |
|  |  | operations |  |
|  | 5 (A4 .. . A8) | Technical staff preparing pediatric patients for cardiological examinations, five different operations | 5 |
| 3 T/11 actions | 2 (A9, A10) | Technical staff with cooperative patient, two cases with different movements | 2 |
|  | 1 (A11) | Technical staff with noncooperative patient | 1 |
|  | 2 (A12, A13) | Nurse with cooperative patient, two cases with different movements | 2 |
|  | 2 (A14, A15) | Nurse with noncooperative patient, two cases with different movements | 2 |
|  | 3 (A16, A17, A18) | Anesthesiologist with noncooperative patient, three cases with slightly different movements | 3 |
|  | 1 (A19) | Generic MRI operator | 1 |
| 7 T/6 actions | 1 (A20) | Technical staff: preparation of the RF coil | 6 |
|  | 1 (A21) | Technical staff: hardware maintenance on the back of the scanner | 7 |
|  | 1 (A22) | Technical staff: cable insertion and connection of the RF coil at the bore | 7 |
|  | 1 (A23) | Technical staff: preparation for functional examination | 8 |
|  | 1 (A24) | Nurse: preparation of a patient | 5 |
|  | 1 (A25) | Nurse: emergency management for a patient’s call | 3 |

Since parameters such as peak or rms values are inappro- priate when dealing with complex waveforms, both ICNIRP- 2014 and the EU Directive recommended the weighted-peak method for assessing compliance of nonsinusoidal low fre- quency fields. According to it, waveform frequency contents must be weighted taking both the frequency behavior of the limit and the relative phases of the spectral components into account; then, the maximum absolute value of the weighted waveform must be calculated. This approach leads to the cal- culation of the WP index, whose value must be lower than 1 to ensure compliance. Actually, two WP indices were consid- ered: HLTH-WP, related to health effects and based on the ICNIRP RLs for *controlled* exposure conditions and on the EU Directive High ALs, and SENS-WP, related to sensory effects and based on the ICNIRP RLs for *uncontrolled* condi- tions and the Directive Low ALs. The *weighted-peak* index is defined through Eq.(1):

*WPx y z*ð*t*Þ¼ X ﬃﬃﬃ cos 2p*fit* þh*x y z*ð*fi*Þþ uð*fi*Þ

*B* ð*f* Þ*x*;*y*;*z i*

; ;

*i B* ð*f* Þp2

; ;

(1)

*L*

*i*

*Impulse Response* type and were developed on the basis of the so-called *pole-zero matching method*.[16](#_bookmark16)

A minimum sampling rate is required for the proper func- tioning of the WP filters. For the B waveforms, a rate of 100 samples/s turned out to be a good compromise between accuracy, stability, speed, and memory requirements; thus, the datasets had to be over-sampled by a factor of 10. Re-sam- pling had to be carried out without modifying the spectra of B, so as not to alter the WP indices: the spectrum of each dataset was first determined applying a Discrete Fourier Transform and then the calculated spectral components were re-sampled with the necessary sampling rate.

Validation tests were performed on the filters, comparing the actual filter transfer function (inverse of the normalized amplitudes, and phases) with the ALs/RLs values and the phase additive terms provided by the applicable regulations. The differences were within the tolerated margins.[11](#_bookmark10) The details and results of the validation tests have been reported

in the online supplemental material (Chapter 2 “Validation of

WP Index ¼ *Max*qﬃ*W*ﬃﬃﬃ*P*ﬃﬃﬃ2ﬃﬃðﬃﬃ*t*ﬃﬃÞﬃﬃþﬃﬃﬃﬃ*W*ﬃﬃﬃﬃ*P*ﬃﬃﬃ2ﬃﬃðﬃﬃ*t*ﬃÞﬃﬃﬃþﬃﬃﬃﬃ*W*ﬃﬃﬃﬃ*P*ﬃﬃﬃ2ﬃﬃðﬃﬃ*t*ﬃÞﬃﬃ

the WP filters”).

*x*

*y*

*z*

where *B*

*x,y,z*

*(fi)* and h

*x,y,z*

*(fi)* are the spectral peak amplitudes

1. RESULTS

and phases of the three Cartesian components of the mag- netic flux density B at frequencies *fi*; *BL(fi)* are the rms limits from Table [II](#_bookmark2) and φ*(fi)* are proper phase additive terms whose values were specified in[11](#_bookmark10) (together with tolerances for *BL* and φ), in order to make it possible to implement the WP method in *hardware*, by means of a chain of first-order RC analog filters. Using a *software* approach instead, the WP index can be calculated in the frequency-domain, by applying Eq. (1), or in the time-domain, by applying well established digital signal processing techniques[17](#_bookmark15) aimed to emulate that chain of RC filters. In our implementation of the time-domain WP approach, the emulated filters were of the *Infinite*

Results are summarized in Table [IV](#_bookmark5) (1.5 T and 3 T sur- veys) and Table [V](#_bookmark6) (7 T survey). The maximum values of B, of its variation in 3 s and of the SENS-WP and HLTH-WP indices are reported for each action. The peak values of the time derivative of B are also shown: as a consequence of the formulations of the ICNIRP *controlled* RLs and EU2013/35 High ALs, these values are directly proportional to the HLTH-WP indices.

Only the minimum and maximum values attained by each quantity across the datasets of each 7 T action are reported in Table [V](#_bookmark6); full data are available in the online supplemental material (Chapter 3 “Full 7 T data”).

TABLE IV. Summary of results — 1.5 T and 3 T surveys.

EU-2013/35 + ICNIRP-2014

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Survey | Action | Duration (s) | B peak (T) | Max DB (T) over 3 s | SENS-WP | HLTH-WP | dB/dt peak (T/s) |
| 1.5 T | A1 | 24.4 | 0.06 | 0.08 | 0.1 | 0.1 | 0.1 |
|  | A2 | 58.4 | 0.12 | 0.12 | 0.2 | 0.1 | 0.2 |
|  | A3 | 27.8 | 1.43 | 1.43 | 2.1 | 1.0 | 2.4 |
|  | A4 | 68.3 | 0.06 | 0.07 | 0.1 | 0.0 | 0.1 |
|  | A5 | 43.8 | 0.05 | 0.05 | 0.1 | 0.0 | 0.1 |
|  | A6 | 53.0 | 0.04 | 0.03 | 0.1 | 0.0 | 0.1 |
|  | A7 | 52.5 | 0.06 | 0.04 | 0.1 | 0.0 | 0.1 |
|  | A8 | 84.0 | 0.17 | 0.17 | 0.2 | 0.1 | 0.2 |
| 3 T | A9 | 70.0 | 0.45 | 0.41 | 0.6 | 0.3 | 0.8 |
|  | A10 | 49.0 | 0.37 | 0.38 | 0.6 | 0.3 | 0.8 |
|  | A11 | 57.0 | 0.42 | 0.45 | 0.7 | 0.4 | 1.1 |
|  | A12 | 31.0 | 0.09 | 0.10 | 0.1 | 0.1 | 0.2 |
|  | A13 | 28.0 | 0.06 | 0.07 | 0.2 | 0.1 | 0.2 |
|  | A14 | 66.0 | 0.05 | 0.06 | 0.1 | 0.0 | 0.1 |
|  | A15 | 61.0 | 0.04 | 0.04 | 0.0 | 0.0 | 0.1 |
|  | A16 | 53.0 | 0.24 | 0.25 | 0.4 | 0.2 | 0.5 |
|  | A17 | 47.0 | 0.31 | 0.26 | 0.3 | 0.1 | 0.4 |
|  | A18 | 40.0 | 0.34 | 0.28 | 0.4 | 0.2 | 0.6 |
|  | A19 | 27.0 | 0.43 | 0.46 | 0.8 | 0.4 | 1.1 |

DB stands for the module of the variation of the experienced magnetic flux density; SENS-WP and HLTH-WP stand for the weighted-peak indices for “sensory” and

“health” effects respectively. Underlined values indicate noncompliance with the corresponding regulatory limits.

TABLE V. Summary of results — 7 T survey.

EU-2013/35 + ICNIRP-2014

dB/dt peak

Action Number of datasets Duration (s) B peak (T) Max DB (T) over 3 s SENS-WP HLTH-WP (T/s)

A20 6 86.0 ÷ 111.0 1.11 ÷ 1.55 0.92 ÷ 1.96 2.6 ÷ 7.7 1.0 ÷ 2.2 2.2 ÷ 5.6

A21 7 88.0 ÷ 131.1 0.77 ÷ 1.20 0.97 ÷ 1.33 1.4 ÷ 5.1 0.8 ÷ 1.6 1.9 ÷ 3.8

A22 7 86.0 ÷ 103.0 1.38 ÷ 3.02 1.37 ÷ 3.34 2.2 ÷ 7.3 1.2 ÷ 2.8 2.8 ÷ 7.1

A23 8 177.1 ÷ 231.1 0.77 ÷ 1.67 0.85 ÷ 1.93 1.8 ÷ 5.1 0.8 ÷ 2.1 2.0 ÷ 5.2

A24 5 142.1 ÷ 234.1 1.41 ÷ 2.01 1.53 ÷ 2.35 1.3 ÷ 3.4 0.6 ÷ 1.2 1.6 ÷ 2.9

A25 3 67.0 ÷ 76.0 1.68 ÷ 2.06 1.54 ÷ 2.06 9.9 ÷ 13.1 2.8 ÷ 3.7 6.4 ÷ 8.5

DB stands for the module of the variation of the experienced magnetic flux density; SENS-WP and HLTH-WP stand for the weighted-peak indices for “sensory” and “health” effects respectively. For each action and each quantity, minimum and maximum values attained across the various datasets were reported. Underlined values indi- cate noncompliance with the corresponding regulatory limits.

Underlined values indicate noncompliance with the corre- sponding regulatory limits.

1. DISCUSSION
	1. Compliance with EU Directive ELVs for static

ﬁelds

All measurements were compliant with the 8 T EU limit for exposures in *controlled* working conditions (Table [I](#_bookmark0));

1.5 T and 3 T measurements were also compliant with the 2 T limit for exposures in *normal* working conditions.

Peak values greater than 2 T were detected in nine data- sets, belonging to three 7 T actions (A22, A24, and A25).

These datasets were all taken at the volunteers’ heads (eight on the right and one on the left side). Action A24 was non-

compliant when measured on the left, while it was compliant when measured on the right: however, the difference was within the measurement reproducibility (i.e., 20–30%).

* 1. Compliance with ICNIRP-2014 basic restriction for preventing vertigo effects

All the 1.5 T and 3 T actions were compliant with the ICNIRP BR of 2 T for DB-over-3 s. Six 7 T datasets exceeded this limit; these datasets belong to the same actions for which the 2 T peak value was exceeded. In three datasets of the action A22, the peak limit was exceeded, but the limit

on |DB| was not; this result depended on how quickly the vol- unteer entered the zone where Bpeak > 2 T. Since exceeding the 2 T ELV involves *controlled* exposure conditions, the identification of ICNIRP noncompliances on |DB| may help to formulate useful advices for controlling movements, if necessary.

* 1. Compliance with ICNIRP-2014 and EU Directive recommendations for preventing movement- induced stimulation effects

1.5 T and 3 T actions were compliant with *sensory* RLs and ALs (SENS-WP<1, limits in Table [II](#_bookmark2)), with the exception of one 1.5 T action (A3). During this action, the volunteer introduced rapidly the head inside the bore to check a prob- lem raised by the patient. At 7 T, all datasets were noncom- pliant with these limits.

All 1.5 T and 3 T actions were also compliant with *health* RLs and ALs (HLTH-WP < 1). At 7 T, 26 datasets (dis- tributed among all six actions) were noncompliant; 7 T mea- surements carried out with the probe at the hip provided index values usually lower than those at the head, probably because movements of the hip tend to be slower than the head ones.

The SENS-WP indices resulted always greater than the HLTH-WP ones. This difference underlines the presence of frequencies higher than 0.66 Hz in the dataset spectral con- tents, since the RLs for sensory and health effects are the same up to that frequency.

during the initial phase of the action, involving a fast approaching to the patient.

Since workers at the 7 T facility were exposed under *con- trolled* conditions, further attention had to be given to the HLTH-WP index. Some useful operating indications can be drawn from Figs. [4](#_bookmark7) and [5](#_bookmark9), referring to two datasets of the 7 T survey. In these figures, the moduli of the vector B detected by the probe (dotted lines) and of the DB/Dt incremental ratio corresponding to each pair of successive samples of B (verti- cal bars) were reported (the DB/Dt ratio should be regarded as an estimate of the time derivative dB/dt of the experienced magnetic flux density).

Figure [4](#_bookmark7) presents a situation in which the maximum value of the derivative was achieved probably because of a rapid shift in an area of strong spatial gradient of the magnetic flux density. Figure [5](#_bookmark9) shows a high |dB/dt| due to a rapid rotation in a relatively homogenous field zone.

* 1. Repeatability and reproducibility issues

The detected B values and their time and frequency pat- terns showed a certain spread, depending on the operator



Extremely high values of both WP indices were reached in the action A25, simulating a situation where the health pro- fessional had to respond quickly to an urgent patient request;

note that an action of this kind, involving an “emergency” sit- uation, was performed only in the 7 T survey. On the con-

trary, action A24, which was more similar to clinical activity at 1.5 T and 3 T, presented very lower values of indices.

For the action A25 (in particular, the dataset correspond-

ing to subject B, position head-right, 2nd run), the moduli of the magnetic flux density B and of its time derivative were reported in Fig. [3](#_bookmark8). The highest |dB/dt| values were reached

FIG. 4. Action A22 (detail), subject A, position head-right, 3rd run. Dotted line: modulus of B; vertical bars: modulus of the time derivative (|DB/Dt|). [Color figure can be viewed at wileyonlinelibrary.com]

**(a)**

**(b)**

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| --- | --- | --- | --- | --- |
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FIG. 3. Action A25 (full length; description: the operator moved from the door of the control room, walked quickly to the door of the magnet room, opened it and entered; in the meantime, the scan sequence was turned off; then the operator went toward the patient (feet side), looked at him and talked with him; finally, he decided to get him out and went with him out of the magnet room, closing the door), subject B, probe position head-right, 2nd run. (a): modulus |B|(t) of the experienced magnetic flux density B as a function of time; (b): modulus |dB/dt|(t) of the experienced magnetic flux density B time derivative (calculated as the incremental ratio between any two adjacent samples). [Color figure can be viewed at wileyonlinelibrary.com]



 

FIG. 5. Action A22 (detail), subject A, position head-right, 4th run. Dotted line: modulus of B; vertical bars: modulus of the time derivative (|DB/Dt|). [Color figure can be viewed at wileyonlinelibrary.com]

involved or on the position of the probe above his/her body; differences were detected even when the same operator repeated the same action in the same conditions. In order to investigate this issue, the six actions of the 7 T survey were repeated several times, hence some statistical elaborations were performed on the resulting datasets.

Concerning repeatability of the same action by the same subject, the relative standard deviation (RSD) of the WP index values varied between 4% and 59%: however, there were not actions more critical than others. Data from different actions repeated by the same volunteer exhibited a mean RSD between 20% and 30%.

The Mann–Whitney nonparametric test (with a signifi- cance level of 0.05) applied on same action data simulated by different subjects showed no significant differences between any pair of datasets. This test was chosen considering the small number of repetitions and because it is a good indicator of reproducibility when changing the operator.

In most cases, data taken changing the probe position on the body, lay within one standard deviation of the mean.

* 1. Comparison with literature data

Comparison with data from literature cannot be rigorous, because values of |B| and |dB/dt| depend more on the posi- tioning of the probe within the magnet room and on body movements than on the magnet strength. However, consider- ing different approaches is useful for a thorough exposure assessment.

The peak values of |dB/dt| at 3 T were lower than the val- ues reported in similar measurements,[5,6](#_bookmark10) but during the actions A9–A19 the volunteer never introduced the head inside the bore, differently from the cited literature cases. The levels at 7 T were almost always higher than the values in a previous study,[18](#_bookmark17) where only the mean peak rates of change were reported, ranging from 1.3 to 4.1 T/s. All these evalua- tions were conducted with the probe in the same position as in the present study on the head of the subject. In the case of

the 1.5 T survey, the comparison with peak |dB/dt| values from other studies[4,7](#_bookmark10) is made difficult by the different posi- tion of the probe on the body, which affects the nature and the speed of the movements.

As for peak B measurements, the influence of the probe position on results is less relevant. The peak |B| values reported at 1.5 T and 7 T were slightly higher than literature data[4,7,19](#_bookmark10) only in the case of actions implying the passage of the probe through the bore (A3 and A22, respectively), while the ones at 3 T, not related to movements inside the bore, were lower than those of previous studies.[4,19,20](#_bookmark10)

Since the values found were — in many cases — higher not only than the regulatory limits, but also than the threshold val- ues for vertigo effects identified in[8](#_bookmark10) volunteers and workers involved in the study were asked if they had experienced dizzi- ness or other disturbing effects when operating in the MR unit. No sensory effects due to the static magnetic field were observed on any workers and volunteers in the 1.5 T and 3 T facilities, except one of the workers who experienced dizzi- ness during his daily activity at 3 T. The symptoms disap- peared 30 min after the exposure, with minimal residual

tiredness.

None of the 7 T health professional volunteers reported any effect after their actions.

Nevertheless, patient tolerability of 7 T field was investi- gated as reported in[21](#_bookmark19) a tolerability test was administered to 180 subjects that underwent brain MR examination at 7 T, in order to monitor their discomfort. A total of 51% of subjects reported at least one side effect but all were mild in intensity and did not require examination interruption. The discomfort was similar to that experienced at lower field strengths and was not related to gender or health status; it was reduced with time after system installation with increasing operator experi- ence in performing 7 T MR examinations. No serious adverse event was reported.

1. CONCLUSIONS

Metrics to quantify exposure levels experienced by opera- tors moving in the static magnetic field of MR facilities were presented and applied in the course of three surveys per- formed nearby a 1.5 T, a 3 T, and a 7 T whole body scanners. The experienced magnetic flux density B was detected by means of a probe worn by health professional volunteers in fixed positions while moving in the MR environments. A total of 55 datasets were acquired, considering different sub- jects, measurement points and actions. Datasets were post- processed and calculated data compared with limits in.[13,14](#_bookmark12) The *weighted-peak* approach in time-domain was imple- mented for compliance assessment with the sensory and health stimulation limits.

Peak values of |B| greater than the 2 T EU Directive ELV for static fields were detected in nine out of the 36 examined datasets of the 7 T survey, with the probe placed on the volun- teer’s head. All the actions at 1.5 T and 3 T were compliant

with the ICNIRP BR for DB-over-3 s, while six datasets at 7 T

were noncompliant with this BR. For three datasets at 7 T, the

limit on |DB| was not exceeded, whereas the peak limit on |B| was. Compliance with the EU ELV is obviously not sufficient to ensure compliance with the ICNIRP BR and vice versa.

1.5 T and 3 T actions were compliant with limits for the SENS-WP index, with the exception of one 1.5 T action. At 7 T, all 36 datasets resulted noncompliant for this index and 26 datasets also for the HLTH-WP one. Particularly high val- ues of the WP indices were reached in the 7 T action simulat- ing a situation where the health professional responded quickly to an emergency. A deeper analysis led to the conclu- sion that the control of movements is more effective in reduc- ing exposure if it is combined with the knowledge of the spatial distribution of the magnetic field.

Finally, results confirm that compliance with EU Directive ELVs for static fields is not sufficient to guarantee compli- ance with ICNIRP-2014 RLs for movement-induced stimula- tion effects, when the waveforms are processed according to the weighted-peak approach.

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CONFLICTS OF INTEREST

The authors have no relevant conflicts of interest to disclose.

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