Weighted-peak assessment of occupational exposure due to MRI gradient fields and movements in a nonhomogeneous static magnetic field

D. Andreuccetti[a)]
IFAC-CNR, "Nello Carrara" Institute for Applied Physics of the Italian National Research Council, via Madonna del Piano 10, 50019 Sesto Fiorentino, Florence, Italy

G. M. Contessa and R. Falsaperla
INAIL, Italian Workers' Compensation Authority, Via di Fontana Candida 1, 00040 Monte Porzio Catone, Rome, Italy

R. Lodato and R. Pinto
ENEA, Italian Agency for New Technologies, Energy and Sustainable Economic Development, Unit of Radiation Biology and Human Health, Casaccia Research Centre, via Anguillarese 301, 00123 Rome, Italy

N. Zoppetti
IFAC-CNR, "Nello Carrara" Institute for Applied Physics of the Italian National Research Council, via Madonna del Piano 10, 50019 Sesto Fiorentino, Florence, Italy

P. Rossi
INAIL, Italian Workers' Compensation Authority, Via di Fontana Candida 1, 00040 Monte Porzio Catone, Rome, Italy

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Purpose: A procedure for assessing occupational exposure due to magnetic resonance imaging (MRI) gradient magnetic fields and movement-induced effects in the static magnetic field is proposed and tested.
Methods: The procedure was based on the application of the *weighted-peak* method in time domain. It was tested in two 1.5 T total-body and one 3 T head-only scanner MRI facilities in Rome (Italy). Exposure due to switched gradient fields was evaluated in locations inside the magnet room where operators usually stay during particular medical procedures (e.g., cardiac examinations of anesthetized patients); MRI sequences were selected to approach as far as possible a representative worst case exposure scenario. Movement-induced effects were evaluated considering the actual movements of volunteer operators during work activity, by measuring the perceived time-varying magnetic field by a head-worn probe. The analysis of results was based on ICNIRP 1998 and 2010 guidelines, following a *weighted-peak* approach and including an *ad hoc* extension to the latter ones, needed to verify compliance in the frequency range 0–1 Hz.
Results: Exposures due to switched gradient fields in 1.5 T MRI scanners mostly resulted noncompliant with ICNIRP 1998 occupational reference levels, being, at the same time, always compliant with ICNIRP 2010 ones. Gradient field levels and ICNIRP indexes were significantly lower for the 3 T unit, due to its small dimensions, as that unit was a head-only scanner. Movement-induced effects resulted potentially noncompliant only in the case the operator moved the head inside the bore of a 1.5 T scanner.
Conclusions: The procedure had proven to be a sound approach to exposure assessment in MRI. Its testing allowed to draw some general considerations about exposures to gradient magnetic fields and movement-induced effects. [http://dx.doi.org/10.1118/1.4771933]

Key words: occupational exposure, magnetic fields, magnetic resonance imaging, gradient fields, movement in static field, weighted peak

I. INTRODUCTION

Occupational exposure in magnetic resonance imaging (MRI) facilities raised concern after the publication of Directive 2004/40/EC "on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields),"[1] which was based on the 1998 International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines.[2] The implementation of the Directive by Member States was initially planned by April 2008, being this term postponed to April 2012 by the Directive 2008/46/EC, since "the potential impact of the implementation of Directive 2004/40/EC on the use of medical procedures based on medical imaging and certain industrial activities should be reconsidered thoroughly."[3] A further postponement to October 2013 was decided with the Directive 2012/11/EU, "given the technical complexity of the subject matter."[4]

After the publication of the Directive 2004/40, ICNIRP provided new recommendations for static magnetic fields.[5] New guidelines, with revised reference levels for low-frequency fields (1–100 kHz), were published in 2010.[6] In this latter guidelines, no indication was provided for frequencies up to 1 Hz; recently, ICNIRP released a specific draft on this issue, in public consultation from February 23rd to May 24th, 2012.

In the MRI environment, the static magnetic field (SMF), the low-frequency switched gradient magnetic field (GMF), and the radio-frequency field should be considered. As far as the static field is concerned, two issues have to be investigated: the SMF itself and the movements through its spatial gradients, which induce electric fields and currents in the tissues of the exposed body.

A first study on occupational exposure in MRI was funded by European Commission in 2008, indicating that more than 90% of the procedures taken into account were compliant with the provisions of Directive 2004/40/EC, with the exception of interventional MRI and fast movements in positions close to the scanner.

Recent studies on occupational exposures in MRI units with 1–3 T scanners reported that exposures induced by movements in SMF may be above threshold values derived from both ICNIRP and the Institute of Electrical and Electronics Engineers (IEEE) for the 0–7 Hz frequency range.[7–9] Moreover, in positions close to the bore, where personnel may have access, measured values of switched gradient fields during clinical sequences may exceed both Directive action values (i.e., ICNIRP 1998 reference levels) and dB/dt derived limits.[10,11]

Nevertheless, no standardized assessment procedures are yet available in the literature dealing with GMF signals and movements in SMF. The matter is how to perform and process measurements in order to assess exposures according to frequency-dependent limits issued by standardization organizations.

In the study presented here, a procedure for assessing exposure in MRI was developed and tested. The procedure considered exposures to low-frequency switched GMF and movement-induced effects in the SMF; radio frequency fields were not taken into consideration.

II. MATERIALS AND METHODS: GENERAL ASPECTS

The assessment procedure was tested in the MRI units of three health care facilities in Rome (Italy): "Ospedale San Giovanni Calibita Fatebenefratelli" (H1 in the following), where a Philips Achieva Nova 1.5 T whole-body MRI scanner is used for routine clinical examinations; "Fondazione Santa Lucia" (H2), where a Siemens Magnetom Allegra 3 T system is installed: it is a small head-only scanner, mainly used for research on brain functionality; "Ospedale Pediatrico Bambino Gesù" (H3), equipped with a Philips Achieva 1.5 T whole-body scanner. This last facility is a paediatric hospital, where cardiac examinations on sedated children are often run and require the presence of an anesthesiologist close to the patient during scanning. In the Italian contest, this seems to be the only case in which the staff must be present inside the magnet room during an examination.

No fixed-point measurements of the SMF were made, because a 2D field map was already available. Moreover, staff exposure inside the scanning room of any 1.5 T scanner (like in H1 and H3) is well below the limits for SMF proposed by latest ICNIRP guidelines.[5] In the case of the 3 T H2 scanner, which is a research unit, the magnet room can be considered a controlled environment, where exposures are allowed up to 8 T, according to the same guidelines.

Switched GMF generated by gradient coils were measured in all the three facilities. Exposure due to motion in the nonhomogeneous SMF could be studied at H3 only, due to site or instrumentation difficulties elsewhere.

A simple "worst-case" approach to risk assessment was adopted: for each campaign, the magnetic flux density was measured in specific points, selected on a worst-case basis, thus characterizing *time* rather than *space* variation of the field.

In particular, GMF was measured in one or two points of interest, chosen at each site as representative of maximum exposure; for the same reason, MRI scanning sequences with fast-switching gradient signals (e.g., EPI sequences) were chosen as far as possible.

Exposure due to motion in the SMF was evaluated through a magnetic field probe worn by volunteers, who were asked to perform "actions," i.e., to mime some typical movements of the operators during their working activities. During each action, the probe remained in a fixed position on the volunteer's body, so that the measurement point was close to his/her head, considered to be the main target organ with respect to effects of low frequency magnetic fields.

III. MATERIALS AND METHODS: GRADIENT FIELDS

III.A. Measurement setup

MRI gradient coils produce complex-waveform magnetic fields with spectra in the kHz range, and consequently particular care is required in developing a procedure to measure and analyze these fields in order to correctly assess the exposure of personnel assigned to MRI wards.

The measurement set-up used in this study was made up of four basic subsystems: a Narda ELT-400 Exposure Level Tester (Narda Safety Test Solutions, Pfullingen, Germany) equipped with a three-axial 100 cm^2 probe; an Agilent U2531A Data Acquisition (DAQ) device (Agilent Technologies, Santa Clara, CA); a standard notebook (PC) and a LabVIEW software application (LabVIEW 2009, National Instruments Corp., Austin, TX).

The ELT-400 Exposure Level Tester has two operating modes: the *field strength* (FS) mode and the *shaped time domain* (STD) mode. In the FS mode, the probe allows root-mean-square (rms) and peak measurements with a flat frequency response from a low-cut frequency (1 Hz, 10 Hz, or 30 Hz user-selectable) up to the maximum operating frequency

TABLE I. Summary of GMF measurement campaigns.

Facility and scanner	Set code	MRI sequence examined	ELT-400 mode	Notes
Ospedale San Giovanni Calibita	H1S1	EPI axial	FS	21 slices
Fatebenefratelli—Rome	H1S2	EPI axial	FS	Single slice
Philips Achieva Nova 1.5T	H1S3	EPI coronal	FS	Single slice
Whole body scanner	H1S4	EPI sagittal	FS & STD	Single slice
Routine clinical examinations				
Fondazione Santa Lucia—Rome	H2S1	DTI 6 directions	FS & STD	TP
Siemens Magnetom Allegra 3T	H2S2	DTI 6 directions	FS	OP
Head scanner	H2S3	Double Echo DPT2	FS & STD	OP
Research on brain functionality				
Ospedale pediatrico	H3S1	Cardiac black blood	FS	
Bambino Gesù—Palidoro (Rome)	H3S2	EFF	FS	
Philips Achieva 1.5T	H3S3	Q-flow	FS	
Whole body scanner	H3S4	Cardiac short axis	FS	
Cardiac examinations on children				

(400 kHz @ −3 dB). The STD mode is designed to implement the *weighted-peak* (WP) approach, according to the ICNIRP 2003 statement on complex waveforms[12] and the ICNIRP 1998 reference levels. The meter can be remotely controlled through an RS-232 link; moreover, three voltage signals—which, in the FS mode, are instantaneously proportional to the three components of the magnetic flux density—are available through an analog output port. The overall probe uncertainty is ±4%. In these measurement campaigns, the probe was maintained fixed in selected measurement points, with the proper inclination necessary to align its three axes with predefined horizontal and vertical directions, with Y axis directed vertically upwards. The larger 100 cm^2 probe was preferred (although the smaller 3 cm^2 one would have provided a better spatial resolution) mainly to avoid sensitivity problems, also considering that exact positioning and high spatial resolution were not primary key features for the test of the procedure presented here.

The three (x,y,z) ELT-400 analog outputs were wired to the Agilent U2531A DAQ, a high speed USB 2.0 data acquisition device, featuring four differential input channels with 14 bit resolution and allowing a truly synchronous sampling rate up to 2×10^6 samples per second per channel. The PC was connected to the magnetic field probe through the RS-232 link and to the DAQ through the USB link. A LabVIEW application, specifically developed for this study, gave this PC the ability to manage the whole system and acquire and store the measured data.

III.B. Measurement campaigns and procedures

A total of 9 MRI scanning sequences in 11 measurement sets were analyzed in the course of the three GMF campaigns in the facilities H1, H2, and H3 (Table I). In each facility, one or two measurement points were selected, aimed at representing the maximum possible staff exposure.

At the H1 facility, three sequences commonly used in diagnostic practice were examined: *EPI Axial*, *Coronal,* and *Sagittal*, all with a slice thickness of 0.5 mm and a repetition time of 3 s. The first of them (*Axial*) was examined both in case of continuous repetition of a series of 21 slices (this set is identified as H1S1 in the following) and in case of continuous repetition of a single slice, with remaining time filled by silence (set H1S2 in the following); sequences relative to the *Coronal* and *Sagittal* orientations were examined in the single slice case only; their measurement sets are identified as H1S3 and H1S4, respectively. The probe was placed in front of the bore opening, 1 m from the ground and 0.2 m from the gantry front plane (a plane perpendicular to the axis of the bore). This point was chosen, after a preliminary survey, as representative of the maximum possible staff exposure. The GMF was measured for 20 s for each set, with a sampling rate of 50 kS/s/ch (kilosamples per second per channel), both in ELT-400 FS mode/320 μT full scale range (all the sets) and in STD mode for occupational exposures/1600% full scale range[14] (set H1S4 only); the selected low-cut frequency was 1 Hz for all the sets.

At the H2 facility, two sequences used in brain examinations were considered: *DTI 6 directions* and *Double Echo DPT2*. Two measurement points were also chosen: the *operator point* (OP), suitable to exemplify a typical operator position in actual examinations, and the *test point* (TP), chosen to represent the maximum possible exposure outside the bore. At the OP, the probe centre was 1 m from the ground, 0.4 m from the gantry front plane, and 0.73 m from the stretcher axis; at the TP, the probe was fixed on the stretcher along its axis, just in front of the bore opening, 0.25 m from the stretcher horizontal plane and 0.25 m from the gantry front plane. Three combinations of measurement point and scanning sequence were analyzed: set H2S1 (point TP, MRI sequence *DTI 6 directions*), set H2S2 (point OP, MRI sequence *DTI 6 directions*), and set H2S3 (point OP, MRI sequence *Double Echo DPT2*). The GMF was measured for 20 s for each set, using a sample rate of 50 kS/s/ch, both in ELT-400 FS mode/32 μT full scale range (all the sets) and in STD mode for occupational exposures/160% full scale range[14] (all sets but H2S2); in order to reduce noise, a low-cut frequency of 30 Hz was selected for all H2 sets.

At the H3 facility, four sequences used in paediatric cardiac examinations were considered: *Cardiac Black Blood*, *EFF*, *Q-flow*, and *Cardiac Short Axis*, identified as sets H3S1, H3S2, H3S3, and H3S4 in the following. The probe was placed at 1.10 m from the ground and 0.45 m from the gantry front plane, where an anesthesiologist usually stays during certain types of cardiac examinations on children. The GMF was measured for 5 s (sets H3S1, H3S2, and H3S3) or 20 s (set H3S4) with a sampling rate of 50 kS/s/ch, only in ELT-400 FS mode/320 μT full scale range, with a low-cut frequency of 30 Hz.

III.C. Postprocessing

Parameters such as peak or RMS values are poorly descriptive when dealing with complex waveforms, considering that ICNIRP reference levels vary with frequency. For this reason, ICNIRP is recommending a particular method, called the "weighted-peak" approach, for assessing compliance of non-sinusoidal low frequency fields.[12] According to it, the waveform frequency contents must be weighted taking both the frequency behavior of the reference levels and the relative phases of the spectral components into account; then, the maximum absolute value of the weighted waveform must be extracted. This approach leads to the calculation of the *weighted-peak* index, whose value must be lower than 1 to express compliance with the guidelines.

For practical purposes, this approach could be implemented in at least three different ways.

1. In hardware, by means of a chain of proper analog filters able to provide a gain function exhibiting the required amplitude and phase frequency responses.
2. In software in the frequency domain, sampling the waveform, executing a discrete Fourier transform on the samples, applying the proper weighting factor and phase shift to each spectral component and finally rebuilding the waveform in the time domain.
3. Using well-established digital signal processing (DSP) techniques[13] to implement—in software in the time domain—a transfer function able to emulate the gain (amplitude and phase) of the required filter chain.

An approach based on the third way was adopted in our study to compute the *weighted-peak* indexes according to both the 1998 and 2010 ICNIRP guidelines. The GMF waveforms, measured by the ELT-400 in FS mode, sampled and digitized by the DAQ, were processed through software weighting functions having proper amplitudes and phases; this way, it was possible to measure the field just once and apply different weighting functions, in line with different exposure standards. Each weighting function was designed with the aim to numerically emulate, in time domain, a chain of first-order analog filters whose amplitude frequency response approximated the inverse of the desired reference levels, scaled to peak values. Validation tests were also performed on these digital filters, in order to check their implementations *versus* their analog correspondents (see supplementary material).[15]

IV. MATERIALS AND METHODS: MOTION IN THE STATIC FIELD

Assessment of exposure to SMF should just require to measure the field strength with a suitable probe and compare the measured values with the exposure limits for static fields established in international guidelines.[5] Nevertheless, it is interesting to investigate how motion-induced current densities and electric fields compare with time-varying related basic restrictions. Thus a simple approach was developed, able to trace the exposure back to that of a person standing still in a time-varying, spatially homogeneous magnetic field. This approach was based on analyzing the exposure in a reference system integral with the subject and moving with him/her. In this reference system, the exposed subject experienced a time-varying magnetic flux density that has been called "perceived magnetic flux density" (pMFD); this field was measured in a single point and fully characterized in time in a few actual exposure situations. Once again, the *weighted-peak* approach was used to process in time domain the pMFD sampled waveforms.

IV.A. Measurement setup

The pMFD was measured by means of a probe worn by a volunteer and kept in a fixed position on his/her body. The measurement point was purposely chosen close to the head which, in addition to being a region of maximum interest, possibly experiences the fastest movements during usual practises, due, e.g., to fast rotations.

Measurements were taken with a Metrolab THM-1176 Three-axis Hall Magnetometer (Metrolab Instruments SA, Geneva, Switzerland), a handheld probe with a dynamic range from a few microtesla up to 20 T in four spans, frequency bandwidth from DC to 1 kHz and $\pm1\%$ uncertainty. This probe measures the three components of the magnetic field simultaneously and separately; it can be connected to a notebook PC through an USB link for data acquisition and storage.

The probe sensing element was kept fixed to the volunteer's head by means of a special support, so that it could follow both the overall movements of the whole body (translation, bending of the torso) and those of just the head (rotation, inclination). This way, it was established not just a measuring position, but also a reference system for the pMFD measures, whose axes were aligned with the three main reference directions of the head: vertical (Y axis, positive upward), frontal (Z axis, positive forward), and lateral (X axis, positive leftward).

The volunteer was asked to execute one or more sequences of standard movements, called "actions" hereafter, which were considered typical for personnel (nurses, anesthesiologists) assigned to MRI wards: walking along paths that the staff would usually be expected to cover, standing still while moving the trunk (bending) or the head (rotating) at the positions they would be expected to occupy during clinical procedures and so on.

IV.B. Measurement campaign

The pMFD measurement campaign took place at the H3 facility only. Eight actions (labelled A1–A8) were executed,

TABLE II. Summary of results of the GMF measurements (WP indexes are given as absolute, not percent, values: i.e., 1 means 100%).

Set code	ELT-400 mode-range	|B| peak [μT]	WP-1998 occupational	WP-1998 population	WP-2010 occupational	WP-2010 population
H1S1	FS-320 μT	114	2.44	12.0	0.415	1.57
H1S2	FS-320 μT	110	2.41	11.9	0.409	1.55
H1S3	FS-320 μT	65.3	1.13	5.56	0.210	0.786
H1S4	FS-320 μT	102	1.26	6.23	0.234	0.902
	STD-1600%		1.30			
H2S1	FS-32 μT	2.50	0.318	1.58	0.046	0.179
	STD-160%		0.321			
H2S2	FS-32 μT	3.31	0.039	0.194	0.006	0.025
H2S3	FS-32 μT	1.10	0.017	0.085	0.003	0.013
	STD-160%		0.019			
H3S1	FS-320 μT	64.0	0.91	4.50	0.143	0.570
H3S2	FS-320 μT	110	1.58	7.85	0.212	0.860
H3S3	FS-320 μT	118	1.56	7.72	0.235	0.916
H3S4	FS-320 μT	113	1.45	7.26	0.191	0.789

designed to represent the routine movements of MRI personnel. Five of them (A4–A8) were aimed at simulating technical staff while preparing paediatric patients for cardiac examinations and the remaining three (A1–A3) were related to standard behavior of the anesthesiologists, when involved in the same examinations. All movements of the volunteers during the eight actions were also filmed. During these movements, the three pMFD components were sampled and stored in the USB-connected notebook, using the control software supplied with the probe, which was set for an averaging factor of 10 and a sampling rate of 10 S/s/ch (samples per second per channel). This rate, which was the maximum value allowed by the control software, limited the acquired frequency spectrum to 5 Hz: however, data processing showed that the spectral contents of the pMFD was always within 2 Hz.

IV.C. Postprocessing

Data acquired during the SMF-pMFD measurement campaign were processed in a way similar to the one described for GMF measures, using the same numerical filters. A minimum sampling rate is required for the proper functioning of these filters: the sampling rate has to be high enough that the highest filter corner frequency falls sufficiently below the sampling Nyquist frequency (which is half the sampling rate). Since this highest corner frequency was 3 kHz in the GMF filters, a sampling rate exceeding 6 kS/s was required; actually, a sampling rate of 10 kS/s turned out to be a good choice. So pMFD waveforms had to be resampled by a factor of 1000 in order to apply the *weighted-peak* algorithm and this resampling had of course to be accomplished without introducing new harmonic contents, which would have seriously altered the WP indexes. Hence, the spectral contents of the actions were first determined applying a discrete Fourier transform to the whole set of its samples and then the calculated spectral components were resampled with the necessary sampling rate.

Moreover, ICNIRP-2010 guidelines do not specify reference levels for frequencies below 1 Hz.[6] While it was possible to ignore this problem in processing the GMF measurements (since there were no significant spectral contents below 1 Hz in them), it had to be fully addressed in the case of the SMF-pMFD measurements, whose spectra contained important contributions at these frequencies. This issue was resolved by extrapolating down to any frequency >0 Hz the trend proportional to $1/f^2$ exhibited by the 2010 guidelines for frequencies between 1 and 8 Hz, so creating new "2010-extended" reference levels. No other extrapolation function was considered, because the $1/f^2$ behavior had a solid scientific basis (being the continuation of the behavior above 1 Hz and being also adopted by the ICNIRP draft cited above), while any other function (apart a constant value) would have been largely arbitrary. If one considers that the ICNIRP 1998 and 2010 occupational reference levels for magnetic flux density have identical $1/f^2$ behavior above 1 Hz and that the 1998 ones are constant below 1 Hz (so representing the truly "worst case"), then our choice allows us to state that any other reasonable (albeit groundless) extension, as for example the $1/f$ behavior, will be positioned between these two extremes.

V. RESULTS AND DISCUSSION: GRADIENT FIELDS

In Table II, a summary of the results obtained for the 11 examined measurement sets (summarized in Table I) is reported. The sets are identified by means of the conventional "HnSn" codes introduced above. Results are expressed in terms of peak field strengths and maximum *weighted-peak* indexes, both for general population and occupational exposures, according to previous (WP-1998) and current (WP-2010) ICNIRP guidelines.

The measured magnetic flux density peak values ranged from 1 μT up to more than 110 μT. Measurements related to 1.5 T scanners (H1 and H3 series) resulted noncompliant with ICNIRP-1998 reference levels for general population and most of them even with occupational ones. All measurements were compliant with ICNIRP-2010 occupational reference levels and all but H1S1 and H1S2 also with reference levels for general public. Measurements related to the 3 T scanner (H2 series) resulted somewhat noisier than the others and exhibited very much lower peak values and WP indexes, almost always below any reference level. In our opinion, this could be due to the small dimensions of the scanner (which was a head-only unit) and, in particular, of its GMF coils; in fact, the magnetic field outside a source decays with distance, the more compact the source, the more rapid the decay. For this reason, and considering they add nothing to the general conclusions we can draw from the other ones, the measurements of this series have not been further reported here.

Sequences showing similar peak field strengths can exhibit quite different WP indexes; this aspect is discussed in the following, where one set at the H1 site and one set at the H3 site are analyzed more in depth.

V.A. GMF set H1S1

Measured and processed data for set H1S1 are reported in Figs. 1 and 2. In Fig. 1, a 50 ms [graph (a)] and 5 ms [graph (b)] time frame around the measured maximum peak value are shown. Since the three Cartesian components of the field were almost sinusoidal and synchronous, an approximately linear polarization resulted probably due to the fact that, in the selected sequence, the current was flowing in one of the three gradient coils only.

The quasisinusoidal nature of the waveform emerges also from the spectrum [Fig. 1(c)] that refers to the *Z* field component (the most intense of the three). The spectral contents were concentrated close to the main component at frequency around 1200 Hz; a third harmonic around 3500 Hz is also visible.

In Fig. 2, the trends of the *weighted-peak* indexes WP-1998 and WP-2010 for occupational exposure are shown. The maximum values of the indexes in both cases were reached by the "spike" that can be observed also in Figs. 1(a) and 1(b) and that was responsible of increasing the peak field level from almost 100 μT to 114 μT, the WP-1998 index from almost 2.0 to more than 2.4 and the WP-2010 index from 0.3 to more than 0.4. This spike was probably an artifact due to an interference or a small movement (e.g., a vibration) of the probe.

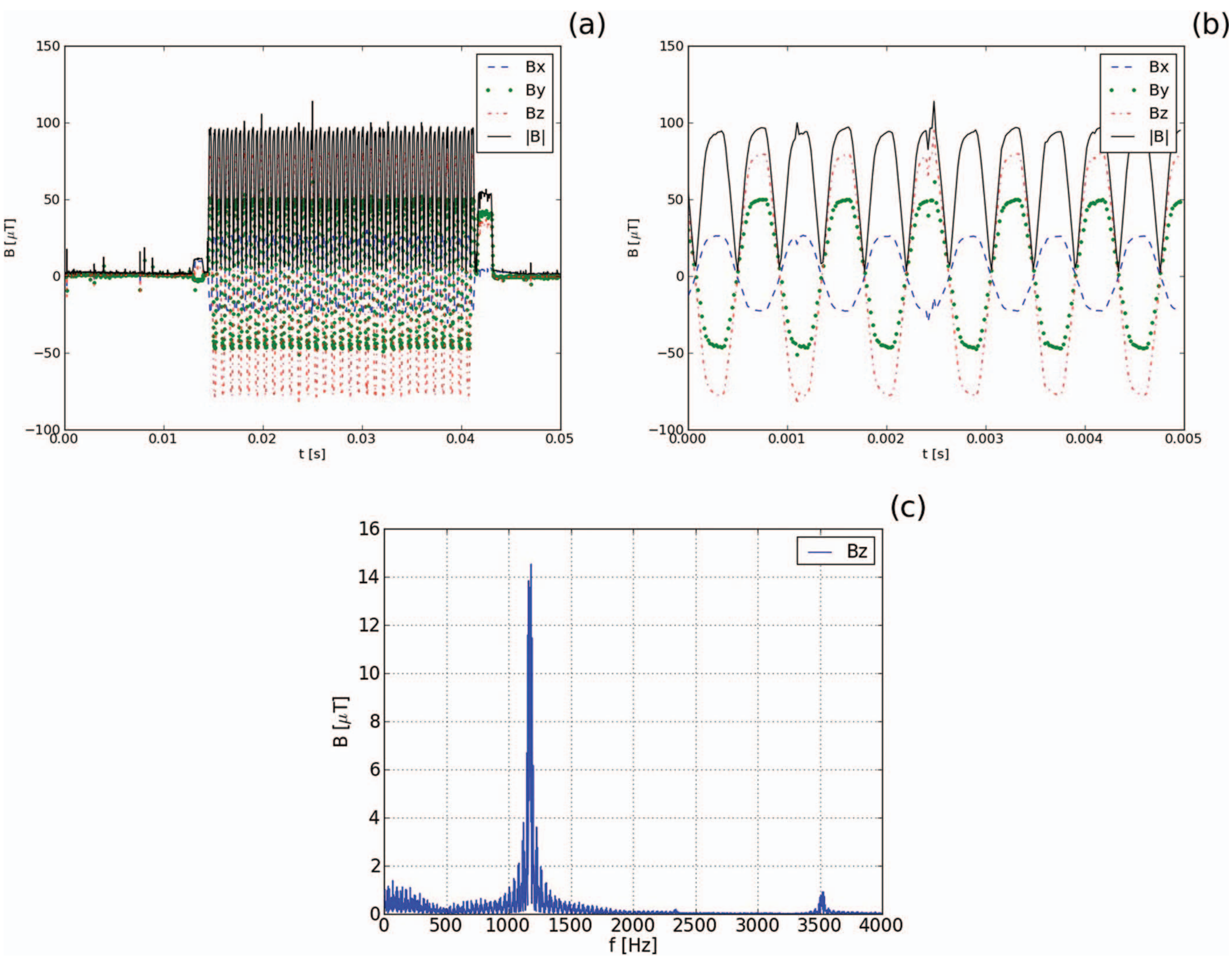

FIG. 1. GMF measurements, set H1S1: (a) in time domain; (b) in time domain with faster time base; (c) frequency spectrum (Z component).

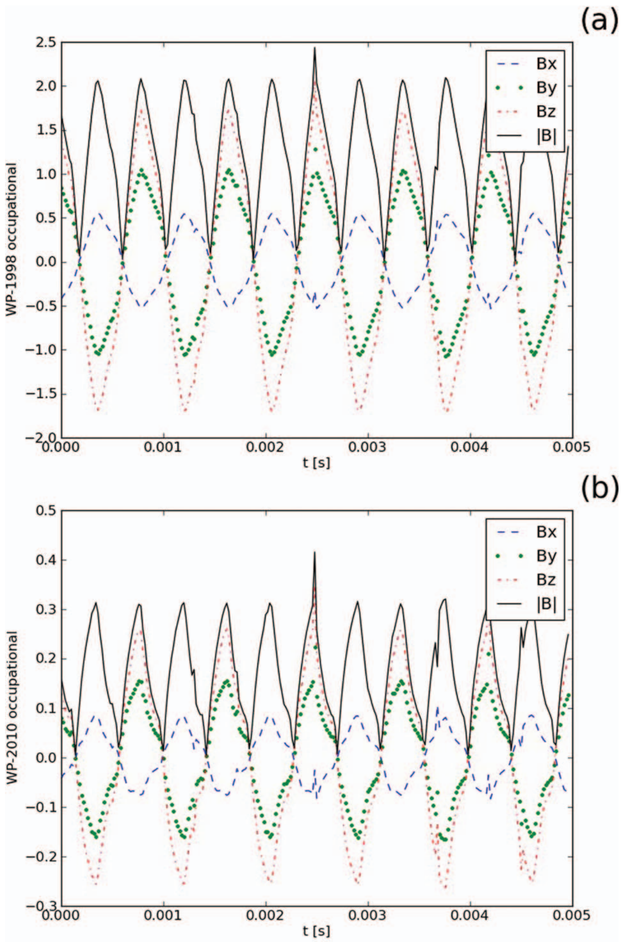

FIG. 2. GMF measurements, set H1S1: WP indexes for occupational exposures according to (a) ICNIRP-1998 and (b) ICNIRP-2010 guidelines.

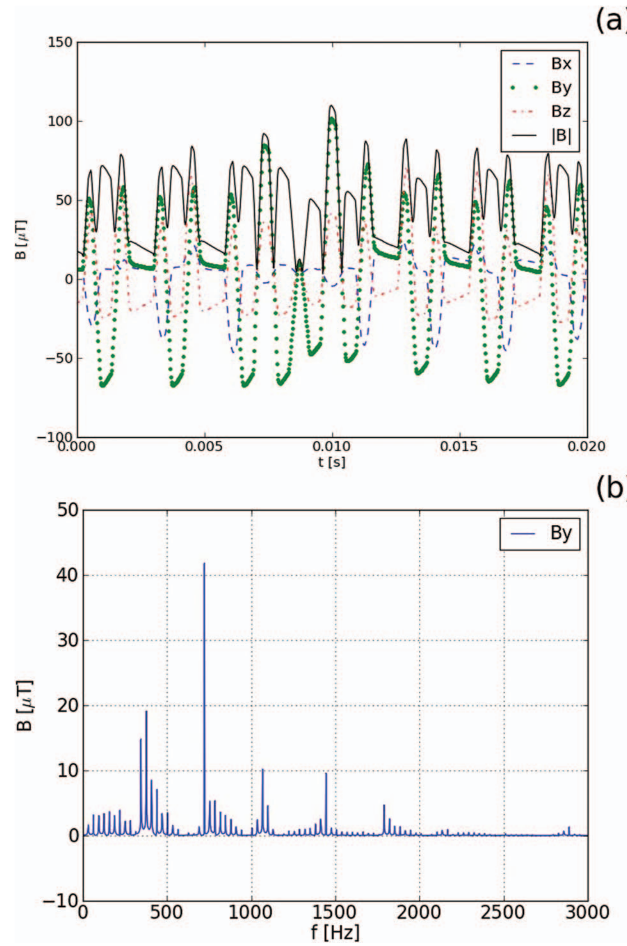

FIG. 3. GMF measurements, set H3S2: (a) in time domain; (b) frequency spectrum (Y component).

V.B. GMF set H3S2

Measured and processed data for set H3S2 are reported in Fig. 3. In this case, the Cartesian components of the field were far from being sinusoidal [Fig. 3(a)] and synchronous: therefore, the polarization was not linear. The spectrum [Fig. 3(b)] was much more spread than that of H1S1; in particular, the lower frequency spectral components of H3S2 were responsible of the fact that, while the peak value of the field was close to that of H1S1, its *weighted-peak* indexes were much lower than those of H1S1. This happened because the ICNIRP reference levels decrease with increasing frequency and consequently lower frequency components of the spectrum are weighted with lighter weighting factors.

VI. RESULTS AND DISCUSSION: MOTION IN THE STATIC FIELD

In Table III, a summary of the results obtained for the eight examined actions is reported. The actions are identified by means of the conventional A1–A8 codes introduced above. Results are expressed in terms of peak field strengths and maximum *weighted-peak* indexes, both for general population and occupational exposures, according to previous (WP-1998) and current (WP-2010-extended) ICNIRP guidelines.[2,6]

Results for action A3 demonstrate that compliance with ICNIRP limits for static fields is not sufficient to guarantee compliance with reference levels for movement-generated perceived time-varying fields, when the waveforms are processed according to the *weighted-peak* approach, even when applying the more permissive 2010-extended guidelines.

Action A3 is an extreme case, because the volunteer had put the head inside the bore (miming an inspection to the patient), thus approaching the 1.5 T nominal value of the scanner. In all the other actions, exposures resulted always compliant with ICNIRP 1998 occupational (but not general population) reference levels and with both ICNIRP 2010-extended ones. WP-1998 indexes resulted always higher than WP-2010-extended ones, even if 1998 and 2010 guidelines are identical in the 1–25 Hz frequency range. This feature is particularly evident in the action A8 and it is easily understood considering that the former guidelines recommended a constant limit value below 1 Hz, while for the latter one a $1/f^2$ behavior was assumed. Actually, the differences between WP-1998 and WP-2010-extended indexes should be entirely attributed to the spectra of the actions, which had important contents below 1 Hz, as it is clearly shown in Fig. 4 for action A8.

TABLE III. Summary of results of the SMF-pMFD measurements, executed around a 1.5T whole body MRI scanner used mainly for cardiac examinations on children (H3 site). Actions A1–A3 mimed standard movements of anesthesiologists involved with sedated paediatric patients. Actions A4–A8 mimed typical technical staff movements while preparing paediatric patients for examinations. WP indexes are given as absolute, not percent, values: i.e., 1 means 100%.

Action code	Duration [s]	|B| peak [mT]	WP-1998 occupational	WP-1998 population	WP 2010 extended occupational	WP 2010 extended population
A1	24.3	61.0	0.230	1.16	0.104	0.518
A2	58.3	116	0.448	2.26	0.151	0.747
A3	27.7	1430	6.130	30.9	1.67	8.24
A4	68.2	59.4	0.247	1.24	0.058	0.286
A5	43.7	49.4	0.179	0.904	0.046	0.228
A6	52.9	36.3	0.139	0.703	0.065	0.324
A7	52.4	56.6	0.266	1.340	0.065	0.325
A8	83.9	171	0.684	3.45	0.083	0.410

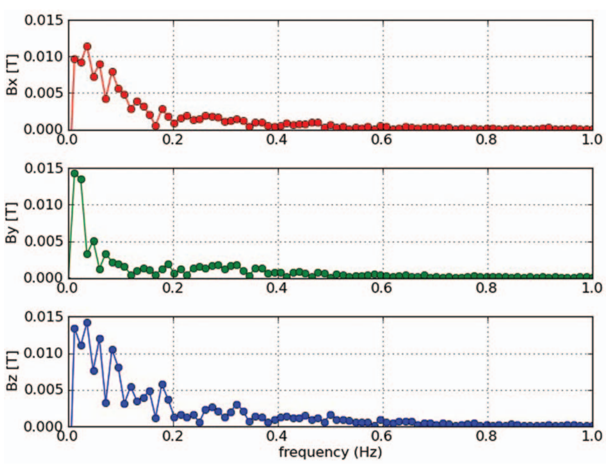

FIG. 4. SMF measurements, action A8: pMFD frequency spectrum.

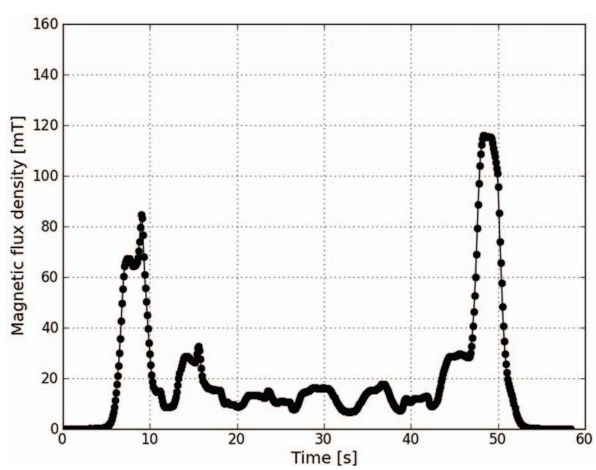

FIG. 5. SMF measurements, action A2: perceived magnetic flux density as a function of time. Description of the movement: The volunteer (miming an anesthesiologists) left the control room, entered the magnet room, approached the stretcher with the patient, did what it should be done, then reached her standard work position, remained there some moments doing various movements while maneuvering a respirator (rotation of the torso and of the head), including leaning over the stretcher to try to read the display placed on the other side, then took a step back to better positioning herself and repeated many of the above operations, bend her torso to check the patient, then exited the magnet room.

Once again, to higher pMFD peak values did not necessarily correspond higher values for the WP indexes, thus confirming the usefulness of the *weighted-peak* approach.

Values of pMFD vs time for some of the actions (A2, A3, and A8) are reported in Figs. 5–7, respectively. Actions are briefly described in the figure captions. It is worth spending a word about reproducibility and repeatability of these results. Similar actions performed by different volunteers should be expected to give raise to rather different index values, especially if the different volunteers have very different statures. In fact, the field probe is fixed to the volunteer's head and the field strength detected along the movement path would be strongly affected by the probe height. On the other side, different index values should also be expected even if the same action is repeated by the same volunteer: it is possible to get an idea of this repeatability just comparing different actions involving not so different movements (for instance, A5 was very similar to A6, while A8 was pretty much a repetition of A7). Actually, turning the head or bending the torso with a

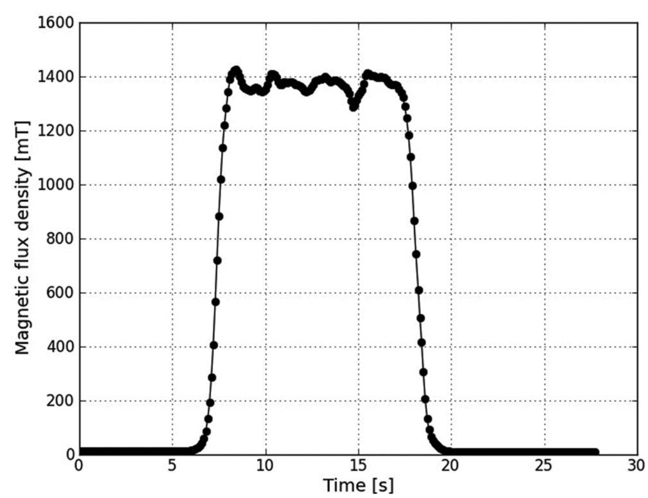

FIG. 6. SMF measurements, action A3: perceived magnetic flux density as a function of time. Description of the movement: The volunteer (miming an anesthesiologist) entered the magnet room, moved behind the gantry passing on its left, performed various movements at the rear opening of the bore (backed off, bend her torso several times, put her head inside the bore), then exited the magnet room.

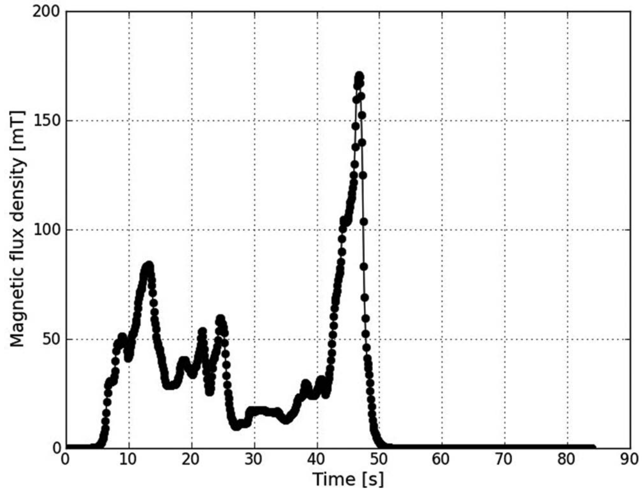

FIG. 7. SMF measurements, action A8: perceived magnetic flux density as a function of time. Description of the movement: The volunteer (miming a technician) left the control room, entered the magnet room, reached the stretcher, performed various preparations on the patient and placed the RF coil on him, raised the stretcher, and pushed it into the bore, checked the patient, then left the magnet room and returned in the control room.

slight different speed and/or amplitude will give raise to very different perceived dB/dt (hence WP index) values.

VII. CONCLUSIONS

A procedure for assessment of occupational exposures in MRI was developed and tested in three different facilities, with a selection of representative scanning sequences. The procedure was based on the application of the *weighted-peak* method in time domain, assuming a worst-case scenario for the spatial distribution of the fields.

The implementation of the WP method was based on an offline software application, developed at the purpose, in order to process raw data acquired by the instrumental set-up.

A specific software filter—which included an *ad hoc* extension of the ICNIRP-2010 reference levels below 1 Hz—was developed, allowing a comprehensive verification of compliance of effects induced by movements in the static magnetic field.

Measurements were accomplished through commercial instrumentation and hardware, allowing reproducibility in any MRI facility and in similar low frequency, complex waveform exposure conditions.

In agreement with previously published data, for the two 1.5 T MRI here investigated, exposures to switched gradient fields exceeded the ICNIRP 1998 reference levels, being at the same time compliant with ICNIRP 2010 ones (maximum exposure was around 50% of limit).

Exposures to GMF were significantly lower (more than an order of magnitude) for the 3 T unit, probably thanks to its small dimensions, as that unit was a head-only scanner.

Results for movement-induced effects showed that exposure was always compliant with ICNIRP 1998 and 2010 "extended" reference levels, with the exception of fast movement of the head inside the bore of 1.5 T unit (respectively, around 600% and 170% of limit). It is crucial to note that compliance with ICNIRP 2009 limits for static magnetic fields is not sufficient to guarantee compliance with movement-induced effect reference levels, even applying the less-restrictive 2010-extended ones, when the waveforms are processed according to the *weighted-peak* approach.

The results from this study are currently being used as input for dosimetric assessment of internal E fields and current densities, which will be the subject of a specific publication.

Further steps of the study will include a more detailed spatial assessment of exposure levels and a measurement campaign of gradient fields and movement-generated fields on a 3 T total body MRI scanner.

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[a]Author to whom correspondence should be addressed. Electronic mail: D.Andreuccetti@ifac.cnr.it

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[15]See supplementary material at http://dx.doi.org/10.1118/1.4771933 for details on implementation and testing of ICNIRP filters.