

## Analysis of magnetic and electromagnetic field emissions produced by a MRI device

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**Abstract**—The results of a magnetic and electromagnetic measurement survey are presented, which was carried out around a Magnetic Resonance Imaging device. The investigation is performed with the twofold aim of characterising the field source under the different operating sequences and evaluating the exposure of workers both to the static and time-varying magnetic field. The exposure levels are estimated, as a function of the position of the workers and the field characteristics, and their compliance with the existing and possible new limits is discussed. Critical situations are put in evidence in relation to both the exposure limits and the performance of the available measuring instruments.

### I. Introduction

Magnetic Resonance Imaging (MRI) is a non-invasive technique that allows the acquisition of images of slices/planes from inside the body. To obtain this goal the technique exploits the interaction between body tissues and an electromagnetic field, the latter composed of radio-frequency pulses and a strong background DC field. The patient is exposed to a high static magnetic field and a radiofrequency (RF) pulse, whose frequency is proportional to the strength of the DC field, which is applied to “disturb” the alignment of the hydrogen nuclei in the living tissues. The image-constructing signal is generated during the re-alignment of the nuclei after such a RF pulse. These devices are sources of magnetic and electromagnetic fields over a large fraction of the electromagnetic spectrum from DC to several hundreds of megahertz. Thus, the use of Magnetic Resonance Imaging devices both as a diagnostic tool or as a surgical intervention support is a critical issue when compliance with the prescription concerning the exposure of workers has to be assessed.

MRI equipment essentially consists of a source of static magnetic field, gradient coils which work in the frequency range from tens to several hundreds of hertz and a series of coils excited through a radio-frequency (RF) signal whose fundamental frequency is around 63.87 MHz. For the smaller devices, the static field is generated by a circuit of hard magnetic materials and permanent magnets, for the larger ones it is produced by a superconducting magnet. The higher the static magnetic field, the higher the definition of the reconstructed images; so a MRI scanner is characterized by its level of static magnetic field. MRI scanners for diagnostics work with static fields from 0.5 T up to 7 T with manufacturers geared towards devices with increasing static field. Moreover, the levels of time-varying magnetic fields cannot be disregarded, taking into account that the medical staff might stay close to the patient as in the case of children or newborns or in the prospect of the MRI use during surgical interventions.

The complexity of the MRI exposure situation, and the great number of people involved are among the reasons that have led to investigate the field emissions of such kind of equipment [1, 2]. Moreover, because of the thorny subject, the implementation of the Directive 2004/EC concerning the exposure of workers to electromagnetic fields has been postponed.

In the framework of an Italian national research project, which aims at developing MRI shielding solutions implemented by superconductive and traditional elements, a magnetic and electromagnetic measurement survey has been carried out around a 1.5 T Magnetic Resonance Imaging scanner. The investigation has been performed with the manifold aim of characterising the field source under different operating conditions and identifying critical aspects as concerns the exposure of workers both to the static and time-varying field.

After a brief review of the exposure evaluation methods, the adopted measurement procedures and the results obtained are presented. Starting from the measured values, the compliance with the exposure limits is assessed, by considering the reference levels presently recommended by the Guidelines issued by the International Commission on Non-Ionising Radiation Protection (ICNIRP) [3, 4] and, for the relevant frequencies, the recently proposed limits [5].

### II. Exposure evaluation

According to the ICNIRP Guidelines, the conformity to the exposure prescriptions to the static magnetic fields can be directly verified by comparing the measurements with the limits, expressed as magnetic flux density, which are shown in Table I for occupational exposure. The evaluation of the compliance in the case of time-varying fields has to be verified in terms of basic restrictions (e.g. induced current densities up to 10 MHz and

Specific Absorption Rate from 100 kHz to 300 GHz). However, for practical reasons, the first on-site assessment can be performed by comparing the electric and magnetic field measurement values with the proper reference levels. If compliance with the reference level is found, then compliance with the basic restriction is ensured [4]. In case of exposure to multi-frequency fields, an evaluation method based on a frequency domain analysis can be adopted according to the procedure described in the following. An exposure index  $T_0$  is computed by summing the amplitudes  $B(f_i)$  of the spectral components at the frequency  $f_i$ , each one weighted by the inverse of the corresponding reference level  $B_{RL}(f_i)$ . Compliance is found if the obtained index  $T_0$  is less than unity [4, 6]. This approach gives a realistic evaluation for simultaneous exposure to fields produced by sources with not-coherent phase. However, for exposure to distorted field produced by only one source or by phase coherent sources, the above technique becomes unnecessarily conservative. Moreover, different sampling frequencies and time windows of the recorded signal can modify the spectrum and consequently the estimated  $T_0$  [7]. Thus, ICNIRP suggests alternative methods to verify the compliance to the reference levels and basic restrictions. In particular, for distorted waveforms in the low and intermediate frequency range (from 8 Hz to 65 kHz for the workers) a specific approach is recommended in [6]. According to the latter, the recorded magnetic field is weighted by a complex function whose magnitude is given by the ratio of the reference level  $B_{RL}(f_{ARB})$  at the arbitrarily chosen frequency  $f_{ARB}$  (e.g.  $f_{ARB} = 10$  kHz) to the reference level  $B_{RL}(f_i)$  at the frequency  $f_i$ .

Table I – ICNIRP occupational exposure limits for static field

	Former limit (issued in 1994)	Current limit (issued in 2009)
Whole working day	200 mT	Not defined
Exposure of head and of trunk	2 T	2 T
Exposure of limbs	5 T	8 T

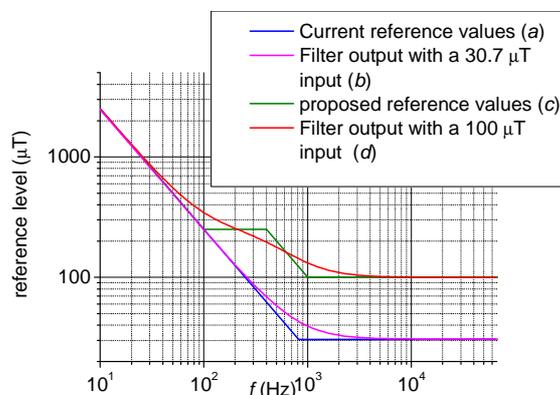


Figure 1. Comparison between in-force and revised reference level from 8 Hz to 65 kHz

The exposure index  $T_W$  is then computed as ratio of the weighted signal peak value  $B_{W|peak}$  to  $B_{RL}(f_{ARB})$ . An immediate evaluation of compliance is obtained if  $T_W \leq 1$ .

Taking into account the behaviour of the reference levels versus frequency, this weighting approach is conveniently implemented by making use of an analog or digital first order high-pass filter [6, 7]. Fig. 1 compares the current reference levels for the workers (curve (a)) with the corresponding filter output to sinusoidal fields of rms amplitude equal to  $B_{RL}(f_{ARB})=30.7$   $\mu$ T (curve (b)). A deviation of the filter output up to 3 dB is clearly found around the cut-off frequency (820 Hz). The recently proposed ICNIRP draft guidelines [5], which reconsider the basic restrictions and reference levels, do not give any indication about the possible architecture of a filter which approximates the corresponding new piece-wise curve (Fig. 1, curve (c)). The only constraint suggested is to keep a maximum deviation of 3 dB between the limit piecewise curve and the filter response.

According to this requirement; the following gain magnitude is suggested:

$$|W(f)| = \gamma \cdot \frac{f \cdot \sqrt{1 + \left(\frac{f}{z_2}\right)^2}}{\sqrt{1 + \left(\frac{f}{p_1}\right)^2} \cdot \sqrt{1 + \left(\frac{f}{p_2}\right)^2}} \cdot \frac{k}{B_{RL}(f_{ARB})}$$

where  $\gamma = 4 \cdot 10^{-3}$  s, the two zeros are  $z_1 = 0$  Hz and  $z_2 = 400$  Hz, the two poles are  $p_1 = 100$  Hz  $p_2 = 1000$  Hz and  $k$  is a constant related to the filter gain expressed in  $\mu$ T. The output of the filter with a 100  $\mu$ T ( $k = 100$   $\mu$ T) input is shown in Fig. 1 (curve (d)).

The MRI device generates magnetic fields in three different bands of the frequency spectrum. Thanks to the fact that the three bands are very distant and the interactions with the human body are governed by different mechanisms, the assessment of the compliance with the reference value can be separately carried out [4]. In the next section, the analysis for the time varying fields is performed by comparing the exposure indexes obtained with the less conservative approach, considering the existing reference levels and the proposed new ones.

### III. Measurement procedures and results

Different instruments and procedures were adopted to measure the magnetic flux density generated by the three field sources contemporary acting: the superconducting magnet, the gradient coils and the RF coils. All the instruments were previously calibrated over the range of amplitudes and frequencies of interest by making use of the INRIM systems for the generation of reference DC and AC magnetic field and RF electromagnetic fields. Measurement points were selected after having verified the paths and possible standings of the involved medical staff in proximity to the machine bore.

#### A. Field generated by the superconducting magnet

Taking into account the value of the static field generated by the superconducting magnet, the DC field was measured by a meter equipped with a tri-axial Hall probe, having measurement range from 10  $\mu$ T to 3 mT. The investigation was performed on the outside of the device, in the area facing its front. Field values were recorded in correspondence of a grid with 0.25 m square mesh up to 3 m distant along the device axis (Y) and up to 2 m laterally (X-axis). Further measurements were performed on a plane surface on one side of the device, one meter above the floor. Fig. 2a shows a sketch of the 1.5 T MRI machine and the two areas investigated. A colour map of the measured field values is shown in Fig. 2b and Fig. 3c for the lateral and front areas respectively. The maximum magnetic flux density (860 mT) was measured in correspondence of the bore. This value can be directly compared with the exposure limit for workers, which has been recently set by ICNIRP to 2 T.

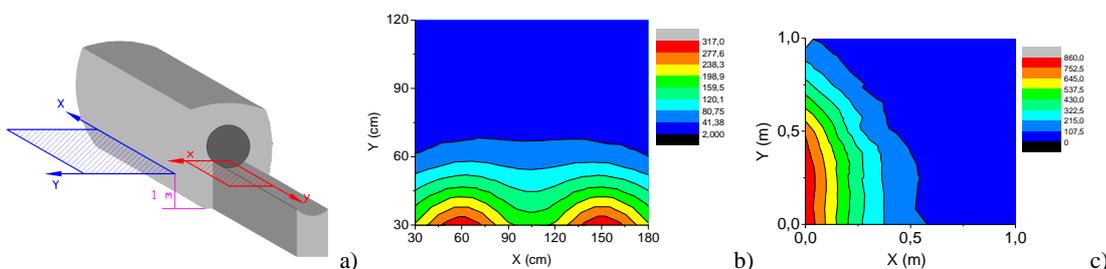


Figure. 2 a) Sketch of the MRI device; colour map of magnetic flux density ( $\mu$ T) on the blue layer (b) and on the red layer (c).

#### B. Field generated by the gradient coils

The task of the gradient coils is the generation of a controlled spatial gradient in the distribution of the static magnetic field along the X, Y and Z directions, with respect to the constant value  $B_0$  in the volume surrounding the MRI isocenter. The set up for each axis is generally made of two anti-Helmholtz coil pairs supplied by square-wave currents. The three anti-Helmholtz systems can be fed at the same time with different currents; consequently, the wave-shape of the detected magnetic field varies with the measurement point.

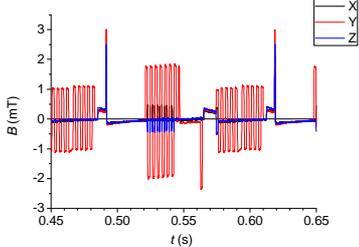
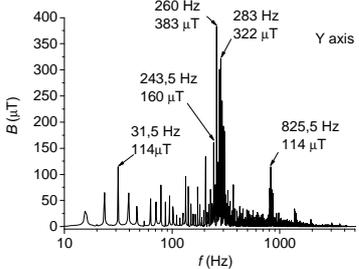
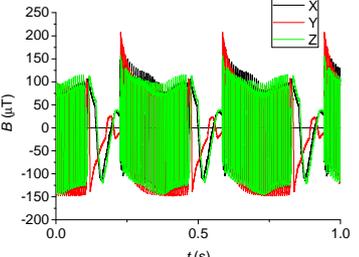
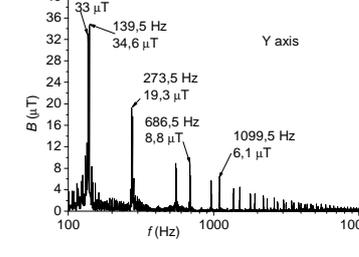
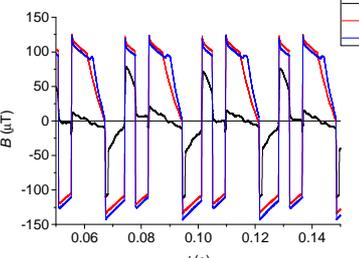
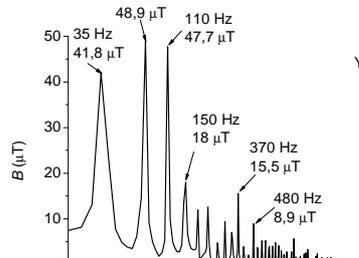
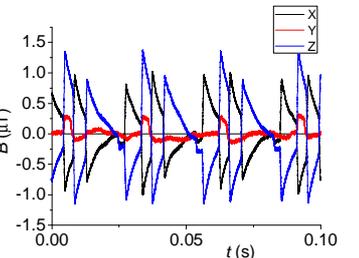
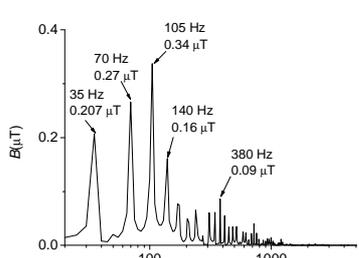
The field generated by the gradient coils was measured by a time-varying magnetic flux density meter equipped with a tri-axis concentric coil probe, with bandwidth 1 Hz to 400 kHz and measurement range from 60 nT to 80 mT. In addition to the rms value of the measured field, the chosen meter allows the recording of the time-behaviour of the three orthogonal field components through an analog to digital converter. The probe was positioned on the patient cot, in the position of the patient head at about 1 m from the floor. The time-behaviours of the field components were recorded at two points along Y axis in correspondence of the bore and 1.35 m far from it. Table II shows the time behaviours of the field components measured close to the bore and the related resultant frequency spectrum for three MRI sequences (Echo planar, Turbo Spin Echo, Spin Echo), together with the exposure index evaluated by using the less conservative approach and considering the current limits ( $T_{W1}$ ) and the proposed one ( $T_{W2}$ ). As can be seen, the exposure indexes are always higher than unity, for both the approaches. A strong dependence on the MRI sequence is found. Compliance with reference levels is always verified when the probe is 1.35 m from the bore. One can note that for the same sequence (Spin-Echo), detected both close to the bore and 1.35 m far from it, different time waveforms have been measured; this is due to the combination of the spatial field components.

It must be remarked that the recorded field behaviours do not reproduce accurately the “square” pulse generated by the gradient coils, because of the instrument step response. In fact, the field meter is fitted out with a high-pass filter, which behaves like a second order high-pass filter with a non-linear inductance and whose cut-off frequency can be selected. In presence of a field waveform with a time behaviour characterised by intervals with a constant value, the measurement system response is affected by the filter, the latter giving rise to a dumped

oscillation. As an example, in presence of a generated magnetic field with a square waveform, the measured signal can tend to a saw-tooth, depending on the time constant of the filter. This decay effect is particularly evident for the Spin-Echo sequence recorded behaviour (Table II sequence *d*).

Comparative tests, performed on simulated square pulses, show that the error introduced in the evaluation of the exposure index is quite negligible, since the filter does not modify the highest frequency components, which give the most significant contribution to the exposure index.

Table II Summary of the gradient field measurements

Sequence		Time behavior	Frequency spectrum
Echo Planar (a)	$T_{W1}$ 48	 <p>Close to the bore</p>	
	$T_{W2}$ 17		
Turbo Spin Echo (b)	$T_{W1}$ 8.6	 <p>Close to the bore</p>	
	$T_{W2}$ 2.5		
Spin Echo (c)	$T_{W1}$ 4.4	 <p>Close to the bore</p>	
	$T_{W2}$ 1.5		
Spin Echo (d)	$T_{W1}$ 0.2	 <p>1.35 m far from the bore</p>	
	$T_{W2}$ 0.1		

### C. Field generated by the radio-frequency coils

As in the previous cases, measurements were performed in the area facing the machine, by keeping the antennas and probes at a safety distance from the device to avoid the “missile” effect. A wide-band (100 kHz to 1 GHz) measuring instrument optically connected to isotropic electric and magnetic field probes was used. In addition, a spectrum analyser (100 kHz to 13 GHz) connected to a loop antenna and a biconical antenna was employed for narrow-band measurements. Spot measurements were carried out along a semi-circular path centred at the bore with a radius of 1.5 m for the isotropic probes, 1.2 m for the loop antenna and 0.7 m for the biconical one. The

radio-frequency and the gradient coil fields were measured simultaneously. As regards the wide-band measurements, a maximum power density value of  $1 \text{ W/m}^2$  was measured with the Turbo Spin Echo sequence (1.5 m from the bore), which approximately corresponds to an electric field of 20 V/m and a magnetic field of 50 mA/m, under the hypothesis of plane wave propagation. These figures should be compared to the ICNIRP reference values of 61 V/m and 160 mA/m respectively ( $10 \text{ W/m}^2$ ), in the considered frequency range. In addition, many narrow-band measurements were performed with different MRI sequences. Fig. 4 shows the first results obtained by processing the values recorded by the spectrum analyser connected to a loop antenna (Fig. 3a) or a biconical antenna (Fig. 3b). The maximum magnetic field-strength (about 100 mA/m) was measured with an Echo-Planar sequence at a frequency of 63.8 MHz when the field probe is 1.2 m distant from the bore. The same frequency gives the maximum electric field-strength (about 40 V/m) with a Turbo Spin-Echo at a distance of 70 cm from the bore. Several harmonic frequencies are also present in the radiated emission spectrum (up to 700 MHz) but their level is at least 40 dB lower than the field level of the fundamental.

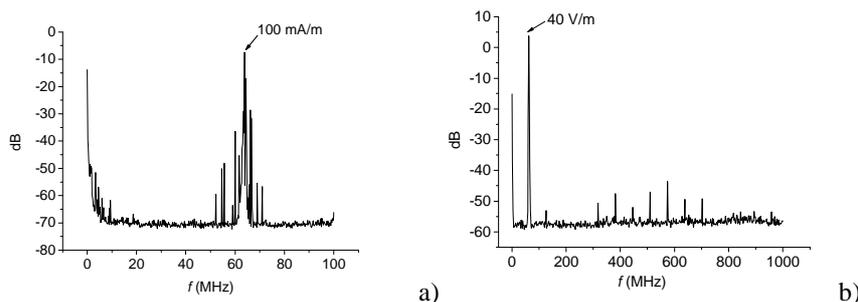


Fig. 3 RF narrow band measurements: a) magnetic field-strength, b) electric field-strength

#### IV. Conclusions

A measurement survey on the magnetic and electromagnetic fields generated by a 1.5 T MRI scanner has been carried out. The analysis of the recorded data has allowed the assessment, in terms of reference level, of the compliance with the occupational exposure prescriptions, stated by the ICNIRP. With reference to the considered operating sequences, the exposure constraints are not exceeded as far as the static and RF fields are considered. In the case of gradient fields, critical situations are identified in the area close to the bore, even if the evaluation is performed with the less conservative approach. A strong dependence of the exposure levels on the MRI sequence is also found. It is worth noticing that the measured time waveforms do not faithfully reproduce the generated signal in the case of gradient fields because of the filtering performed by the meter. Nevertheless, the exposure index is not significantly influenced by this effect, which is actually under further investigation.

#### V. Acknowledgments

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