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RESEARCH ARTICLE

A Standard Protocol Proposal for Reliable and Time-Saving Shielding Effectiveness Measurements for MRI Faraday Cages

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Abstract:

Background:

An inadequate shielding of radio-frequency cabins for magnetic resonance imaging devices can affect clinical images with artifacts. For this reason, periodic measurements of shielding effectiveness are recommended. However, a wide gap exists between the international reference standard currently available for shielding effectiveness measurement (IEEE-Std 299/2006) and the practical approach, mainly because of the poor applicability of the standard to any situation.

Objective:

The aim of this work is to suggest a novel procedure for the measurement of the shielding effectiveness of radiofrequency cabins for clinical magnetic resonance imaging devices. The application of the cabin door measurements for shielding effectiveness assessment is proposed.

Methods:

Based on the only international standard currently available, some critical aspects of shielding effectiveness measurements are highlighted. Taking into account theoretical considerations, a novel approach is suggested in order to simplify the applicability of the standard. Frequency ranges and measurement points were reduced by considering the specific device inside the shield.

Results:

Results obtained by the application of the proposed protocol were compared with the results obtained by the application of the standard procedure IEEE-Std 299/2006. No significant discrepancies between measurements have been found. It was observed that the time to perform measurements reduced by almost three times.

Conclusion:

A time-saving method for measurement of shielding effectiveness in a narrow range of frequencies is proposed.

Keywords: MRI, MRI RF artifacts, Faraday cage, Shielding effectiveness, Radio-frequency cabin, RF shield, Standard protocol.

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1. INTRODUCTION

Magnetic Resonance Imaging (MRI) is nowadays a powerful diagnostic method; its application is increasing because of its known advantages in terms of high-quality images, non-ionizing radiations and relatively low risks. The main healthcare companies are continuously improving their MR devices, developing innovative solutions about MR scanners, Radiofrequency (RF) coils, hardware components and magnets. All MR scanners are recognized as medical devices.

However, artifacts are a very common issue in MRI clinical utilization, they can affect the diagnostic quality or, may be confused with pathology. Multiple causes of artifacts might not only be patient-related but, above all, machine-related and shielding-related [1 - 3]. One of the most common

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artifacts is RF noise. Stray RF signals, if not attenuated by an efficient shield, can lead to the following (Fig. **1**): narrow-band noise is projected perpendicularly to the frequency-encoding direction; and broadband noise affects the image over a large area due to the application of the Fourier transform, needed to reconstruct the image. However, reduction or elimination of stray RF interferences can be achieved with appropriate site planning and proper installation but overall with RF shielding realized by means of so-called 'Faraday cages'.

All MR scanners, regardless of their magnetic induction intensity, need this particular hosting enclosure, the design of which is strictly based on the MR scanner parameters. Different from the design and installation of MR systems, the design and setup of the shielding enclosures are rather simple. In fact, an RF shielding cabin is quite simple from a structural point of view and the consolidated techniques for design and installation are, in most cases, sufficient to guarantee good performances in terms of RF attenuation. However, this relative simplicity often leads to underestimate some important aspects that, instead, would deserve more attention, as they can have critical consequences.

The efficacy of the RF shielding is measured by a parameter called Shielding Effectiveness (SE). The isolation effect of shielded enclosures is only as good as its ability to prevent EM fields from extending inward or outward beyond their walled boundaries. MRI professionals cannot take that for granted because no enclosure is perfect. Unavoidable aspects of enclosure construction can become a source of RF field breaches.

The access door to this kind of enclosure – the RF Cabin - is equipped with beryllium copper finger-contacts along the perimeter to ensure perfect and constant contact between the door and its frame.

Over the time, particularly in facilities that may undergo significant vibration or with frequent use of the door, this perimetrical contact may be damaged, collect dust and get loose, thus creating weak points in shielding effectiveness.

Shielded enclosures incorporate surface discontinuities, such as pipes or conduits passing through, feed-through filters, which allow cables inside the cage to connect to cables outside, and these are other points compromising the shielding integrity. For all these reasons, it is the best technical practice to periodically measure and verify SE values. With the door being the main part that can loose shielding, we concentrated our efforts on SE evaluation of the door.

The objective of this work was to highlight some critical aspects of SE measurements of MRI Faraday cages, on the basis of our experience, due to a wide gap existing between the reference standard currently available (IEEE-Std 299/2006 [4]) and the practical approach. Our aim is to analyze the most commonly used procedures, in order to organize current knowledge and to introduce an innovative way of performing the measurements. Thus, as a result of this work, we suggest a new protocol for SE measurements of the door in MRI shielded rooms.

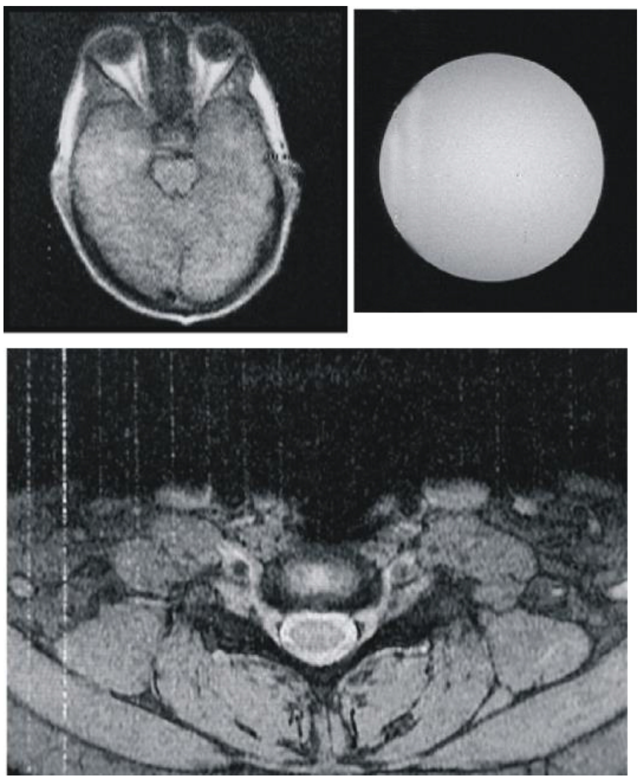

Fig. (1). Examples of RF Artifacts in MRI imaging.

2. MATERIALS & METHODS

In the following sections, a short description of the electromagnetic scenario is reported, as well as the critical points in designing RF enclosures. Among the quality and safety aspects, the SE measurements are focused and the IEEE Std 299/2006 is presented. Then, the poor applicability of the standard in the case of SE evaluation of MRI Faraday cages doors is underlined and a novel approach is suggested in order to obtain uniform door SE measurements in MRI environments by means of the application of a time-saving measurement method.

2.1. Mri Electromagnetic Scenario

Despite the complexity of current MRI scanners, the hardware of an MRI system is comprised of four main elements:

[1] **Main magnet**: Its function is to generate a static and mostly homogeneous magnetic induction field (**B**) for the nuclei magnetization;
[2] **Gradient coils**: It is responsible for magnetic induction fields linearly varying in space, necessary for images generation;
[3] **Ancillary coils**: It is useful to compensate non-homogeneities and to modify the shapes of main fields;
[4] **RF coils**: They generate the magnetic oscillating field at the desired Larmor frequency.

Worldwide, more than 60 million clinical MRI scans are performed annually on over 25,000 MRI systems. Most of these systems are used purely for clinical purposes and operate at field strength 3 T or below 3 T. Nevertheless, major neuroimaging centers of hospitals and universities use or are planning to use even higher field strength systems (7 T, 9.4 T, 10.4 T, 11 T) primarily for research applications [5]. In the case of hydrogen proton, the Larmor frequency is 42.57 MHz/T. Thus, for clinical purposes, RF transmitting and receiving systems operate at frequencies equal to 8.514 MHz, 63.85 MHz and 127 MHz for 0.2 T, 1.5 T and 3 T field strengths, respectively. Therefore, the widest range of frequencies in MRI applications is estimated approximately around [8 MHz-150 MHz] whereas, for very high field MRI scanners (7 T and higher), higher frequencies of RF signals (*i.e*. 300 MHz and higher) are utilized. The above-mentioned frequency range is the same as that used by common sources in the environment. Thus, the need for an RF shielded enclosure to prevent radio waves to enter the scanner room. Such enclosure is usually called “Faraday cage” even though Faraday Cages have been traditionally referred to as enclosure. “Faraday cages” usually indicate enclosures protecting from electrostatic fields. However, in this paper, both Faraday cage and RF cabin are the terms to indicate the shielding enclosure surrounding an MRI device. They are realized by means of aluminum self-supporting panels, bolted together with steel screws and a conductive scrim, or copper sheets, fixed on wooden panels. The RF cabin is provided with a grounding system, whose resistance should not exceed 1 Ω (connections between RF-shield and the equipotential hub), and an electrically insulating carpet (about 2 mm thick).

Very high levels of attenuation, about 70-130 dB, are expected accordingly to the specifications required for a given MRI scanner, and generally specified at the time cabins are designed and built. To improve the shielding effectiveness, the cage must have the minimum number of conveniently designed apertures. Moreover, electrical continuity has to be guaranteed using specific gaskets, conductive scrims, metallic fingers and so on. The most critical points in designing RF enclosures are:

- The **access door**, must guarantees perfect adherence to the structure if closed. The necessary electrical continuity is achieved through creeping contacts, called fingers (usually made of copper/beryllium) and through the minimization of mechanical stresses;
- The **view-window**, made in double glass or polycarbonate, with a metal grid inside;
- The **apertures for air-vent**, comprised of particular honeycomb filters or waveguides;
- The **filter panel** connecting the electronic systems, in the adjacent technical area, to the magnet room;
- The **waveguides** used to introduce in the MRI room medical gases or liquids.

Despite the wide availability of international technical standards regarding medical devices, electromedical equipment and magnetic resonance, there is a lack of a specific standard for the SE measurement and verification, suitable for MRI locations. For this reason, the manufacturers of MRI Faraday cages, or the responsible for the maintenance service, have to refer to more general documents concerning this particular measurement. A key role is played by the standard IEEE 299-2006 [4], presented in the next section.

2.2. The Ieee 299-2006 Standard

As defined in a study [6], we define SE as: *“The ratio of the signal received (from a transmitter) without the shield, to the signal received inside the shield; it’s the insertion loss when the shield is placed between the transmitting antenna and the receiving antenna”*.

The IEEE Std 299-2006 is nowadays the only reference for SE measurements of large enclosures (smallest linear dimension greater than or equal to 2.0 m) and it incorporates the basic concepts of MIL-STD 285 [7] now withdrawn. Specific measurement procedures are suggested for frequencies ranging from 9 kHz up to 18 GHz, this range may be extended down to 50 Hz and up to 100 GHz. As discussed in the next section, although MRI shielded rooms fully fall under the domain of applicability of the standard, it is often impossible (or redundant) to follow all the procedures described and this is a relevant issue for producers, testing companies, clinical engineers or MRI professionals involved in the acceptance process, installation or maintenance management of MRI cabins.

Briefly [4], before the SE evaluation, preliminary procedures are recommended that are as follows: preparation of a test plan, calibration of any piece of instrument equipment, evaluation of an appropriate reference level, preliminary shield check, and removal of objects not belonging to the usual electromagnetic scenario. Therefore, for each test point, two measurements are required: the first one in the absence of the shield (H_1 (E_1) indicates the magnetic (electric) field measured with antennas in the absence of the enclosure (reference reading); the second one, with the interposition of the shield between the transmitting and the receiving antennas, (H_2 (E_2) is the magnetic (electric) field measured with the receiving antenna inside the enclosure. The whole frequency range (9 kHz-18 GHz) is divided into the following types: i) low range (9 kHz-20 MHz), ii) resonant range (20 MHz-300 MHz) and, iii) high range (300 MHz-18 GHz), for which different procedures, antennas and formulas are required. Specific values of test frequencies are not indicated, but some sub-intervals are recommended for each range. In the low range, the definition of SE takes into account the magnetic component of the EM field, in the resonant range, the electrical one, while in the high range, power is considered. Measured quantities, related units and SE definitions are redefined in Table **1**, where they are expressed also in nonlinear units.

In case of MRI scanners (0.2 T-7 T), the frequency range involved is 8 MHz -300 MHz, thus the attention is focused on low and resonant ranges. For low range measurements, the use of a small electrostatically shielded loop antenna (0.3 m diameter) is suggested. The measurement setup is composed of: 1) a signal generator (plus amplifier) connected by a shielded cable to the transmitting loop; 2) the receiving loop and, 3) a field detector (preferably a spectrum analyzer although selective receivers are often utilized). Hence, in the low-range, a magnetic field shall be generated by a current in the small loop antenna, driven by a continuous wave (CW) signal. The transmit loop is placed outside the shield, whereas the receiving loop is inside the enclosure and the distance between them shall be 0.60 m (edge to edge) plus the thickness of the shielding barrier. The antennas shall be coplanar in a plane perpendicular to the wall, as sketched in Fig. (**2**).

Accordingly to IEEE Std 299-2006, around single-panel entry doors, tests should be conducted for 14 loop positions. In areas where shielding enclosure construction is electrically non-uniform (for example air vent, or connector panel, panel-to-panel seams), measurements shall be conducted in a similar manner.

As far as the resonant range is concerned, in the case of 20 MHz-100 MHz frequency range, the use of biconical antennas is suggested, whereas λ/2 dipoles are recommended for frequencies at or above 100 MHz. Once again, the basic measurement procedure consists of positioning the transmitting antenna outside the shield and the receiving one inside the shield and measuring the magnitude of the largest received signal. Measurements must be repeated with antennas in both horizontal and vertical polarization. For both dipole and loop antenna, the same method is proposed. The reference reading is the maximum reading among different position readings of both transmitting and receiving antennas. When the shield is inserted, the receiving antenna must be swept in position (throughout the interior shield) and in polarization to obtain the largest detector response, that is recorded for determining the worst SE. Besides a series of transmit antenna positions shall be selected to cover the overall surfaces. This second set of measurements is schematically represented in Fig. (**3A**) and (**3B**), for horizontal and vertical transmitting antenna configuration, respectively.

The calculation of the lowest resonant frequency of the shielded enclosure is also suggested.

2.3. Novel Protocol Proposed

The poor applicability of the standard was observed in our surveys on SE measurements in several MRI sites. A strong gap between the approaches suggested by the standard and the practical execution emerged, and in no case was the IEEE Std 299-2006 rigorously applied.

As a matter of fact, even if the suggested procedures are detailed and rigorous, a lot of liberty is given to the testing organization. In particular, the following issues emerged from a survey we carried out among MRI professionals:

Table 1. Measured and calculated quantities as a function of frequency ranges (adapted from IEEE Std 299™-2006).

–	**Frequency Range**		
	9 kHz-20 MHz (Low range)	**20 MHz -300 MHz (Resonant range)**	**300 MHz - 18 GHz (High range)**
Measured Quantities	$\lvert H_1\rvert$, $\lvert H_2\rvert$ (or $\lvert V_1\rvert$, $\lvert V_2\rvert$)	$\lvert E_1\rvert$, $\lvert E_2\rvert$	P_1, P_2
Linear Units	µA/m, µT (or µV)	µV/m	W
Shielding Effectiveness (dB)	$SE = 20\log_{10}\frac{H_1}{H_2}$ $SE = 20\log_{10}\frac{V_1}{V_2}$	$SE = 20\log_{10}\frac{E_1}{E_2}$	$SE = 10\log_{10}\frac{P_1}{P_2}$
Logarithmic Units (All Frequencies)	SE=$\lvert E_1\rvert$(dB)-$\lvert E_2\rvert$(dB); SE=$\lvert H_1\rvert$(dB)-$\lvert H_2\rvert$(dB) SE=$\lvert V_1\rvert$(dB)-$\lvert V_2\rvert$(dB); SE=P_1 (dB) - P_2 (dB)		

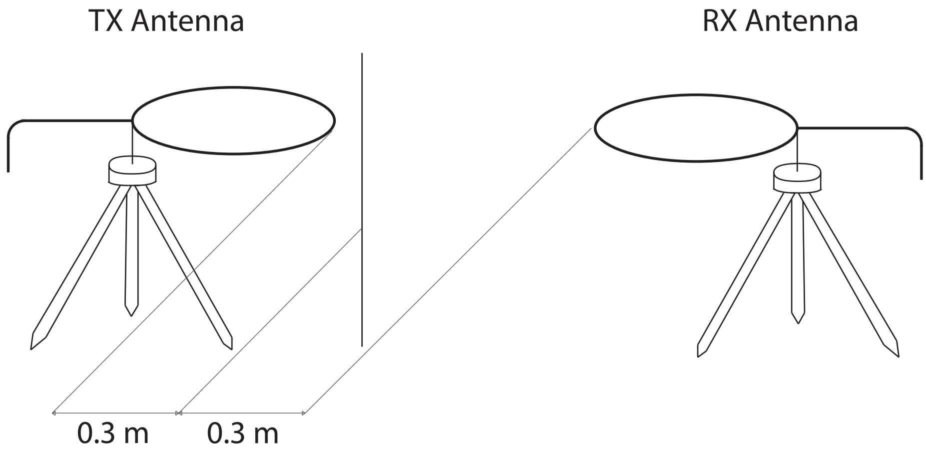

Fig. (2). Coplanar horizontal loop antennas (with or without shield).

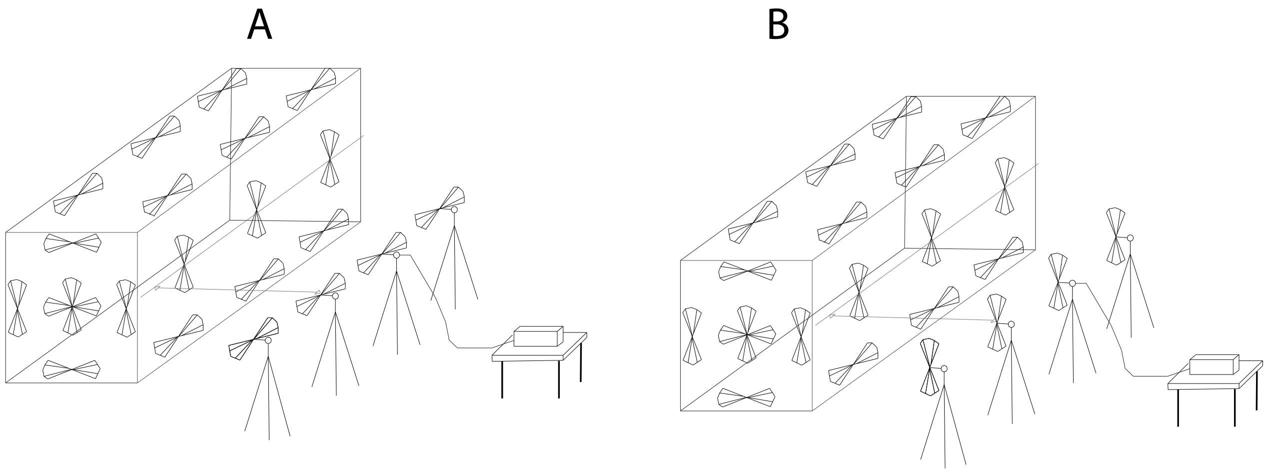

Fig. (3). Measurement set up antenna configuration in the resonant range (20-100 MHz):
A) horizontal transmitting; **B**) vertical transmitting (adapted from ref.4).

[1] The standard is too general (wide frequency ranges, since it refers to a wide kind of shielding necessities);
[2] It suggests very time-consuming procedures going in conflict with the time-machine availability;
[3] The set up shown in Fig. (**3A** and **3B**) must be repeated for each position of the transmitting antenna, with a waste of time to collect often non-relevant information;
[4] In many cases, the use of dipole and biconical antenna is impossible/useless to apply in MR environments because of space and logistic limitations;
[5] The resonant frequency calculation should be mandatory in this case because it is very often close to the operating frequency of the machine.

In this section we propose a protocol, partially adapting the IEEE Std-299 (2006), more suitable for MRI RF cabins, highlighting only the procedures that we found adequate. We hereby describe the protocol for a typical measurement around 63.86MHz typical for 1.5T magnets, the most commonly used system.

Before starting the test, preliminary activities and prerequisites are required. They can be summarized as follows:

[1] Preparation of a test plan which shall include: dimensions of the cage, test frequencies, test locations, limits of SE to pass/fail the test, brand and model of the MR device, including the static B field value, a detailed description of the instrument set up and other notes;
[2] Removal of metallic equipment that is not a normal part of the enclosure. Ancillary equipment (blower fans, carts, coils) normally present inside the enclosure shall remain in place during the test;
[3] Limitations to the number of people within the shielded enclosure (if possible, a maximum of two persons should be allowed);
[4] Visual check, inside and outside the MR room, in order to identify inaccessible surfaces and areas of

leakage and repair them before measurements take place (cleaning of door contacts, replacement of damaged fingers);

[5] An "electromagnetic check" should be performed both inside and outside the magnet room in order to evaluate whether possible radiofrequency interferences sources are present due to medical devices (RX tomography, Marconi therapy devices), light systems, electronic devices (switching power suppliers, digital thermometers *etc*.);

[6] The frequency range of interest shall be reduced to a restricted RF interval which is strictly linked to the MR apparatus. Thus, for the selection of test frequencies, it is necessary to know the operating frequencies of the MR device and the bandwidth of receivers. The widest range that we can currently consider is about 8 MHz - 300 MHz.

Given the B strength, the corresponding Larmor frequency (f_{test}) is known (*e.g*. for a 1.5 T device f_{test} = 63.86 MHz) and measurements at this frequency are mandatory. However, other frequencies, around the operating f_{test}, can be established. Actually, we can reasonably believe that the shielding behavior of a surface is quite similar in a narrow frequency range, so it is up to the tester and testing conditions, the decision to verify further frequencies. In addition, the variability of data can occur due to cavity resonance effects. Indeed, the operating frequency often belongs to the interval $0.8\ f_{ijk}<f_{test}< 3\ f_{ijk}$, where f_{ijk} is the cavity resonance frequency; hence, we suggest the following calculation of the fundamental resonant frequency (according to the formula reported in [3], eq. (1).

$$f_{ijk} = \frac{1}{2\sqrt{\varepsilon\mu}}\sqrt{\left(\frac{i}{a}\right)^2 + \left(\frac{j}{b}\right)^2 + \left(\frac{k}{c}\right)^2} \qquad \textbf{(1)}$$

where:

μ, and ε are the permeability and permittivity inside the enclosure;

a, b and c indicate the three dimensions of the enclosure in meters (*i.e*. length, height and width respectively);

i, j, and k, are positive integers 0,1,2,3… (and not more than one of i,j,k can be zero at the same time). Under ideal conditions, the resonant frequency in megahertz is given by eq. (2).

$$f_{ijk} = 150\sqrt{\left(\frac{i}{a}\right)^2 + \left(\frac{j}{b}\right)^2 + \left(\frac{k}{c}\right)^2} \qquad \textbf{(2)}$$

and the lowest resonant frequency for the shielding enclosure, being c the smallest dimension, is eq. (3).

$$f_r = f_{110} = 150\sqrt{\left(\frac{1}{a}\right)^2 + \left(\frac{1}{b}\right)^2} \qquad \textbf{(3)}$$

Once the frequencies of interest have been established, the test points must be selected. Among the most critical locations in an MR Faraday cage, as already discussed, we suggest testing the door and specific test points as described below. Measurements around the door already give a meaningful idea of the shielding behavior of the enclosure, with the door being the most critical point because of its movement and frequent utilization. Then, if further analyses are required, additional testing surfaces can be identified such as the view-window, filter panels, blind panels and other surfaces containing visible penetrations. Consultation of technical documents of the structure is strongly recommended before selecting test locations since penetrations are often not visible and all surfaces under test must be mentioned in the final report.

As far as the selection of test points is concerned, there is another important consideration. Currently, the standard defines an accessible test location as a location that can be reached by a test antenna or probe without modifying a parent structure; in MRI units, it often happens that it is not possible to position the transmit and the receiving antennas over a surface, or it is not possible to position them at the same height, or at a given distance. The instrumentation setup suggested by the IEEE standard of course remains valid (signal generator plus amplifier, Tx and Rx antennas, spectrum analyzer plus attenuator) however, all instruments and auxiliary equipment (other probes, cables, tripods) must be nonmagnetic to access the magnet room. The spectrum analyzer, whose operation directly affects the numerical value of the SE, must be regularly calibrated before any measurement. Since all measurements are relative and not absolute measurements, it is not necessary to calibrate every piece of equipment (each antenna), but it can be sufficient to rely on the spectrum analyzer calibration.

The Dynamic Range (DR) of the spectrum analyzer must be adequate. DR is the difference between the reference level and the minimum discernable signal above the noise floor (3 dB or more above the noise floor). A wide DR is not strictly required because, if the spectrum analyzer is calibrated, it is sufficient to reduce the maximum readable level on its display ("Reference Level"), in combination with an appropriate RBW selection when executing the closed-door measurement. Due to the reduction of noise floor, the visibility of even a small peak is guaranteed despite the lack of high-preforming instruments. The measurement procedure requires two different stages: in the first one, the reference level shall be evaluated (*i.e*. the measurement acquired with transmitting and receiving antennas placed opposite each other, without the shielding surface). After that, the measurement of the signal received with RX over a shielding surface is performed. The measurement of the reference level should be carried out in the same conditions as the other measurement to guarantee a more accurate SE evaluation. Besides, the reference level should not be less than -10 dB.

It must be noticed that the setting parameters do not affect significantly the peak value, but can only have an influence on noise level, which is why a small RBW is suitable, especially for low-level signals.

For measurements in the radiofrequency range, we tend to prefer dipole antennas to biconical ones since they are more appropriate for this kind of measurements (since test frequencies are fixed, a broadband analysis is not required). The possibility of using custom magnetic loop antennas as probes for SE measurement purpose also in the resonant range is currently under study. The potential substitution of the biconical (or dipoles) antenna would produce numerous advantages for MRI SE measurements, which was the objective of this work.

The EM fields should be generated by power applied to TX antenna, and received from a similar RX antenna. A continuous wave signal shall be used to drive the TX antenna with power adequate to maintain a suitable DR.

With regard to the position 'over the door', we retain that 6 points are sufficient (instead of 14 as indicated by the standard, Fig. (**4A** and **4B**). These positions allow the evaluation of shielding behavior at the center of the door and along the weakest lines. The same configuration could be adopted for the view-window.

About the distance between TX and RX antennas, we suggest collecting the measurements at distance 0.60 m plus the thickness of the shield, for a better characterization of the enclosure. The antennas shall be in the same configuration (*i.e.* the same polarization and position) over the shielding surface. For the calculation of the SE, we can use the following equation: $SE=P_{ref}-P_{shield}$ [dB]. P_{ref} and P_{shield} are the values obtained in the absence and in the presence of the screen, respectively.

However, we would also like to highlight the maximum value found on the spectrum analyzer ($P_{shield,MAX}$), which corresponds to minimum SE (SE_{MIN}), which can be obtained by varying the receiver antenna position and polarization: $SE_{MIN}=P_{ref}-P_{shield,MAX}$ [dB]. In this way, for each point, we shall have two Shielding Effectiveness values, which shall be noted in the final report. Finally, when all data are collected, one can average all the results obtained at a specific frequency and distance if a unique value of SE is desired for each shielding surface.

At the end of each measurement, a test report shall be fully-formed. The information to be reported is almost the same as that indicated in the standard [4]. Conclusions about the test data (pass/fail) shall also be included in the final report, according to specific attenuation performances required by the MR producers. Typically required values are higher than 80 dB.

3. RESULTS

We tested several RF cabins using the IEEE-Std 299/2006. Here, in the following, we report the results obtained by testing the door of a RF cabin following the requirements detailed in IEEE-Std 299/2006 (Table **2**) for measurements carried out at 10 MHz, (Table **3**) for measurements carried out at 64 MHz) along with the results obtained following our proposed protocol (Table **4**) for measurements carried out at 10 MHz, Table **5** for measurements carried out at 64 MHz).A vertical (V) or horizontal (H) coplanar couple of loops measured the magnetic field (M) for measurements carried out at 10 MHz. On the other hand, a vertical (V) or horizontal (H) coplanar couple of dipoles measured the Electric field (E) for measurements carried out at 64 MHz.

First, the application of IEEE Std 299-2006 to the SE measurement of the door required 14 measurements at four different frequencies (10 MHz. 30 MHz. 64 MHz and 100 MHz). Thus, we had a total number of 56 measurements. Here, for the sake of brevity, we reported only two tables summarizing results at 10 MHz and 64 MHz, but values obtained at other frequencies are comparable. Our protocol required 6 measurements at two frequencies, and therefore, comprised a total number of 12 measurements. The time needed for the application of IEEE Std 299-2006 for evaluating SE of the door is on average about 4 hours, whereas our protocol required 1.5 hours.

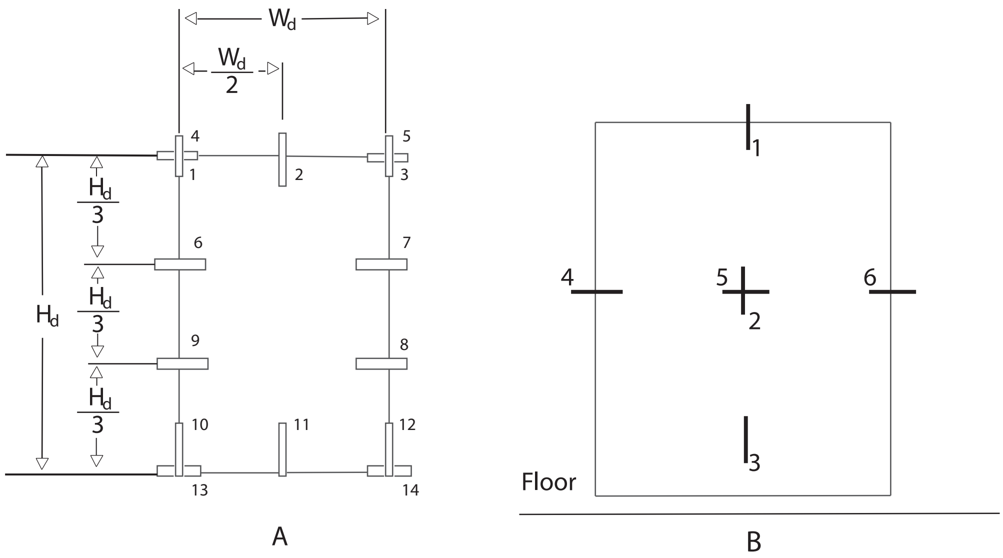

Fig. (4). Single panel entry door. Measurement points and antenna orientations suggested in reference [4] (sizes of the door Hd x Wd) (**A**), in this study (**B**).

Table 2. Measured values obtained applying IEEE Std 299-2006 for the evaluation of SE at 10 MHz of a door in a RF cabin housing a 1.5 T MRI system. A vertical (V) or horizontal (H) coplanar couple of loops measured the magnetic field (M).

Point no.	Polariz.	Field	Reference [dB]	Reading [dB]	Measured RF Cabin SE[dB]	Requested RF Cabin SE[dB]
1	V	M	-10.40	-86.50	76.10	80.00
2	V	M	-10.40	-83.40	73.00	80.00
3	V	M	-10.40	-84.50	74.10	80.00
4	H	M	-10.40	-81.20	70.80	80.00
5	H	M	-10.40	-93.00	82.60	80.00
6	H	M	-10.40	-84.00	73.60	80.00
7	H	M	-10.40	-91.00	80.60	80.00
8	H	M	-10.40	-93.40	83.00	80.00
9	H	M	-10.40	-90.00	79.60	80.00
10	V	M	-10.40	-82.00	71.60	80.00
11	V	M	-10.40	-89.50	79.10	80.00
12	V	M	-10.40	-92.00	81.60	80.00
13	H	M	-10.40	-94.00	83.60	80.00
14	H	M	-10.40	-83.50	73.10	80.00

Table 3. The measured value obtained by applying IEEE Std 299™-2006 for the evaluation of SE at 64 MHz of a door in an RF cabin housing a 1.5 T MRI system. A vertical (V) or horizontal (H) coplanar couple of dipoles measured the electric field (E).

Point no.	Polariz.	Field	Reference [dB]	Reading [dB]	Measured RF Cabin SE[dB]	Requested RF Cabin SE [dB]
1	V	E	-1.00	-85.40	84.40	80.00
2	V	E	-1.00	-70.50	69.50	80.00
3	V	E	-1.00	-78.50	77.50	80.00
4	H	E	-1.00	-74.00	73.00	80.00
5	H	E	-1.00	-87.00	86.00	80.00
6	H	E	-1.00	-74.00	73.00	80.00
7	H	E	-1.00	-88.00	87.00	80.00
8	H	E	-1.00	-94.20	93.20	80.00
9	H	E	-1.00	-80.00	79.00	80.00
10	V	E	-1.00	-72.00	71.00	80.00
11	V	E	-1.00	-76.00	75.00	80.00
12	V	E	-1.00	-86.50	85.50	80.00
13	H	E	-1.00	-88.00	87.00	80.00
14	H	E	-1.00	-79.00	78.00	80.00

Table 4. Measured value obtained applying the proposed protocol for the evaluation of SE at 10 MHz of a door (same door and same equipment utilized for results reported in Table 3) in an RF cabin housing a 1.5 T MRI system.

Point no.	Polariz.	Field	Reference [dB]	Reading [dB]	Measured RF Cabin SE[dB]	Requested RF Cabin SE [dB]
1	V	M	-4.00	-78.00	74.00	80.00
2	V	M	-4.00	-80.50	76.50	80.00
3	V	M	-4.00	-79.00	75.00	80.00
4	H	M	-3.30	-78.50	75.20	80.00
5	H	M	-3.30	-79.00	75.70	80.00
6	H	M	-3.30	-85.20	81.90	80.00

Table 5. The measured value obtained by applying the proposed protocol for the evaluation of SE at 64 MHz of a door (same door and same equipment utilized for results reported in Table 4) in an RF cabin housing a 1.5 T MRI system.

Point no.	Polariz.	Field	Reference [dB]	Reading [dB]	Measured RF Cabin SE[dB]	Requested RF Cabin SE [dB]
1	H	E	9.80	-69.00	78.80	80.00
2	H	E	9.80	-60.50	70.30	80.00
3	H	E	9.80	-70.00	79.80	80.00
4	V	E	0.40	-75.40	75.80	80.00
5	V	E	0.40	-79.20	79.60	80.00
6	V	E	0.40	-82.50	82.90	80.00

By considering the measurements carried out at 10 MHz, a mean SE of 77 dB was obtained by applying IEEE Std 299-2006, along with a standard deviation of about 5 dB. By applying the hereby proposed protocol, an average SE of 76 dB was obtained, with a standard deviation of about 3 dB. As it can be easily seen, the results are very similar. The SE measured in both cases is consistent with the required attenuation of 80 dB.

4. DISCUSSION

Moreover, by considering the evaluation carried out at 64 MHz, an average SE of 80 dB was obtained by applying IEEE Std 299-2006, along with a standard deviation of about 7 dB. By applying the hereby proposed protocol, an average SE of 78 dB was obtained with a standard deviation of about 4 dB. In addition, in this case, there is no discrepancy in measurements and in both cases, the measured SE is consistent with the required attenuation of 80 dB.

Therefore, the present proposal suggests a novel, rigorous but time-saving approach to SE measurements in MRI environments in a narrow range of frequencies of interest. We can summarize it with the following steps:

[1] Preliminary check procedures;
[2] Test plan;
[3] Set up of instruments.

Then: For each selected frequency:

[1] Measurement of the reference level (in each antenna configuration and for each selected distance).

For each point on the surface:

[1] Measurement of the minimum SE (by varying the position and the orientation of the receiving antenna);
[2] Measurement of effective SE (with antennas aligned and in the same polarization).

Then:

[1] Analysis of collected data (to establish the test results);
[2] Calculation of average SE as a qualitative indicator of the global shield performance;
[3] Test Report.

About SE measurement methods, we believe that important goals have been achieved in this work since we highlighted the inadequacy of current standard references and attempted to draw a possible path towards effective standardization. In our view, this is an urgent task because it is associated with quality and safety.

CONCLUSION

Although the design and building of MRI shielding enclosures are generally performed in a professional manner, there are still many aspects that cannot be taken for granted.

We hope that our contribution can help in adopting a time saving and practical approach for SE assessments of MRI cabin, which could allow increasing the repeatability and reproducibility of measurement results, thus allowing quantitative comparisons and performance assessments.

LIST OF ABBREVIATIONS

DR	=	Dynamic Range
EM	=	Electro-Magnetic
MR	=	Magnetic Resonance
MRI	=	Magnetic Resonance Imaging
RF	=	Radio Frequency
SE	=	Shielding Effectiveness

ETHICAL APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

HUMAN AND ANIMAL RIGHTS

No animals/humans were used in the studies that is the basis of this research.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

The authors confirm that the data supporting the findings of this research are available within the article.

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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