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RESEARCH ARTICLE

A novel tool for estimation of magnetic resonance occupational exposure to spatially varying magnetic fields

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Abstract
Object Staff operating in the environment of magnetic resonance imaging (MRI) scanners are exposed daily to static magnetic fields (MFs). To protect workers several guidelines are present in literature reporting exposure limits values expressed in terms of magnetic flux density or induced current density. We present here a novel tool for estimating the induced current density due to worker movement in the MR environment.
Materials and methods A Matlab script was created to estimate the induced current density J due to operator movements along a chosen walking path.
Results The induced current density associated with any worker's movements during MR procedures is dependent on the walking speed and on the spatial gradient fields associated with a specific path. Some examples of possible worker paths were considered here for a 3 T MR scanner and a maximum value of 160 cm/s walking speed.
Conclusion This tool permits one to find exposure level for specific worker walking path and speed; it can be used as assessment tool in any MRI centre and for workers safety education. It is valid for any kind of commercial scanner because it requires only the knowledge of the MR scanner room map with isogauss lines.

Keywords MRI safety · Magnetic resonance · Induced current density · Occupational exposure

Introduction

Magnetic resonance imaging (MRI) and spectroscopy (MRS) are diagnostic techniques widely used in medicine and are having a growing impact on neurology, cardiology and many other diagnostic areas. These techniques are considered safe, since instead of ionizing radiation they use three electromagnetic fields at three different frequency ranges: a static magnetic field, time-varying magnetic fields (gradients) and radiofrequency (RF) fields. However, as in any healthcare intervention, there are intrinsic hazards that must be understood and taken into consideration. These hazards are relative to all three types of field that can affect patients, staff and other persons in the MR environment [1–4] (radiology technicians, radiologists, anesthetists, interventionalists, nurses, researchers, maintenance staff and cleaners). Workers operating MRI and MRS are repetitively and lengthily exposed to large static magnetic fields always present in the scanner room during their daily work shift since their job involves patient preparation and assistance before and after each clinical exam. This implies that they move inside the MR scanner room: their movements in significant spatial heterogeneous static magnetic fields cause exposure to low frequency (<1Hz) time-varying magnetic fields [5], inducing electrical current in the worker's body. Recent advances in MRI have resulted in an increase in static (up to 4 T clinically and up to 7 T in research) and time-varying magnetic fields as well as in occupational exposures [6,7]. A 2008 review summarized studies on health effects of occupational exposure to static MFs [8]: no firm conclusions can be drawn from the available data about these effects. Moreover, a recent

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World Health Organization (WHO) monograph concluded that there is insufficient scientific data for establishing health risks of exposure to static magnetic fields [9]. In 2004, the European Union adopted the Physical Agents (Electromagnetic Fields) Directive 2004/40/EC [10] on health and safety requirements for exposure to electromagnetic fields in the workplace. This directive contains exposure limits values expressed in terms of current density in the head and trunk (e.g. induced by the operator movements in significant spatial heterogeneous static magnetic fields that cause an exposure to low frequency time varying magnetic fields) and of specific absorption rate (SAR) at radiofrequency. The directive sets limits and creates concern on the implication in the use of clinical MRI [11], so the European Parliament decided to postpone the deadline for its implementation by all member states from 2008 to 2012. Experimental measurement of exposure levels in terms of induced current density is very complex and thus cannot be used in daily routine assessment. Using numerical simulations of tissue-equivalent body models it is possible to accurately estimate the induced current density, but this method requires long computational times and complex body models [12]. This paper presents a novel tool for estimating the induced current density due to worker movements in the static magnetic field of a MR scanner that is based on a simplified model used in guidelines referred to in the European Directive (that is ICNIRP guidelines). Thanks to an user-friendly graphical interface the presented assessment tool is very easy-to-use and can be used while workers safety education.

Materials and methods

Theory

Electromagnetic field theory is based on the classic set of Maxwell's equations: the third equation expresses the concept that an electric conductor, such as the human body, which moves in spatial heterogeneous static magnetic fields B, induces an electrical field E [13]:

$$\nabla \times \bar{E} = -\frac{\mathrm{d}\bar{B}}{\mathrm{d}t}, \tag{1}$$

Equation 1 in its integral form is known as Faraday's law:

$$\oint_{\Gamma} \bar{E} \bullet \mathrm{d}\bar{l} = -\frac{\mathrm{d}\Phi_B}{\mathrm{d}t}, \tag{2}$$

where Φ_B is the magnetic flux and the integral of electric field $\bar{E}$ is calculated over a path $\bar{l}$ on the surface Γ.

According to the ICNIRP model for calculating induced current density [14], we can resolve Eq. 2 for a circular loop in the human body with a radius r:

$$\oint_{\Gamma} \bar{E} \bullet \mathrm{d}\bar{l} \rightarrow \oint_{\Gamma} E \cdot \mathrm{d}l \cdot \cos(0) = E \oint_{\Gamma} \mathrm{d}l = E 2\pi r$$
$$= -\frac{\partial(\pi r^2 B)}{\partial t} \rightarrow E = -\frac{r}{2}\frac{\mathrm{d}B}{\mathrm{d}t} = k\frac{\mathrm{d}B}{\mathrm{d}t}, \tag{3}$$

where k is a geometry factor for a given subject. A radius of 0.64 m is assumed here for a typical current loop in the body [14,15], while for the calculation of induced current density in the head a radius of 0.07 m can be chosen [15].

Finally, Eq. 3 can be simplified as follow:

$$E = k\frac{\mathrm{d}B}{\mathrm{d}t} = k\left(\frac{\partial B}{\partial x} \cdot v_x + \frac{\partial B}{\partial y} \cdot v_y + \frac{\partial B}{\partial z} \cdot v_z\right) \quad [\mathrm{V/m}]. \tag{4}$$

Thus, starting from the knowledge of worker walking speed components (v_x, v_y, v_z) and the magnetic field gradients in all three directions, it is possible to calculate the induced electric field in the operator's body.

However, the parameters that mostly express human exposure to a low frequency spatial varying magnetic field is the induced electrical current density that can be calculated as follows:

$$J = \sigma \cdot E \quad [\mathrm{A/m^2}], \tag{5}$$

where σ is the mean electrical conductivity of human tissues chosen here equal to 0.2 s/m according to ICNIRP guidelines [14].

International guidelines and regulations on static magnetic field occupational exposure limits

A recent document of the ICNIRP [16] reports the new guidelines on limits of exposure to static magnetic fields applied to the occupational and general public and not to patients undergoing medical diagnosis or treatment. In this document the limits of the exposure are separate for occupational exposure, that is for "individuals who are exposed to static magnetic fields as a result of performing their regular or assigned job activities", and general public exposure, that "refers to the entire population" (Table 1). Contrary to the previous ICNIRP document [17] the new "guidance is not

Table 1 Static magnetic field exposure limits

Exposure characteristics	Magnetic flux density (B)
Occupational	
Head and trunk	2 T
Limbs	8 T
General public	
Any part of the body	400 mT

based on time-averaged exposure, because in addition to the experience gained with the use of MR and other static field sources world-wide over the last 20 years, mechanistic considerations indicate that any effects are likely to be acute". For this reason the new guidance sets the exposure limits in terms of spatial peak magnetic flux density.

The ICNIRP document "recommended that occupational exposure of the head and trunk should not exceed a spatial peak magnetic flux density of 2 T except for the following circumstance: for work applications for which exposures above 2 T are deemed necessary, exposure up to 8 T can be permitted if the environment is controlled and appropriate work practices are implemented to control movement-induced effects". MRI certainly qualifies as such as environment, but it is evident the importance to an adequate workers safety education.

The European Parliament Directive 2004/40/EC w [10] reports the exposure limit values for current density for time-varying fields up to 1 Hz, according to the basic restrictions on the effects of exposure based on established health effects [14]. This limit is 40 mA/m^2 (root means square value which should be multiplied by $\sqrt{2}$ to obtain peak current density value) for the head and trunk and should be respected to prevent effects on the cardiovascular and central nervous system. Afterwards, the Directive 2008/46/EC [18] postponed the deadline for implementation of the previous Directive by all member states from 2008 to 2012. A proposal for the new EU Directive has been available since June 2011 [19]: the proposal explains that the limit values in the previous directive are too low and based on too conservative assumption so would limit to a disproportionate extent the use and development of MRI. Hence, to guarantee both high level of safety protection for workers and the continuation and development of MRI, the limit values has to be reviewed. In particular, in the Article 3 of proposed directive a new paragraph has been added that "provides an exemption from the exposure limits for the medical MRI sector and related activities". Annex IV in the proposal is specific to MRI and sets objectives will be followed and tasks carried out but, at the moment, does not set any specific safety limit value. The draft of the new directive is currently evaluating, but the legislative process will take many months so it is not possible to speculate today final decisions.

Last ICNIRP guidelines relative to limiting exposure to time varying electric and magnetic fields (1 Hz to 100 kHz) [20] was published at the end of 2010: contrary to the previous ICNIRP document [14], in this document the exposure limits are given in terms of internal induced electric field (V m^{-1}). The guidelines recommend that "exposure in controlled environments, where workers are informed about the possible transient effects of such exposure, should be limited to fields that induced electric fields in the head and body of less than 800 mV m^{-1} in order to avoid peripheral and central myelinated nerve stimulation". However, the last ICNIRP document doesn't include guidelines applicable to movement induced electric fields or time varying magnetic fields up to 1 Hz, which will be published separately.

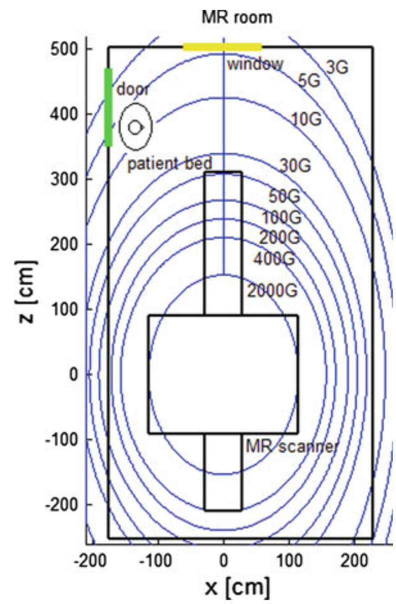

Fig. 1 MR scanner room and isogauss line map with magnetic field levels (G = Gauss)

Methods

Starting from the knowledge of the isogauss line map of our MR scanner (GE Signa HDx 3.0T), provided by the manufacturer, a Matlab script was created to calculate the static magnetic field value (B) at each point of the MR room (in the ground plane, that is the xz plane). Figure 1 shows the map of our MR scanner room and isogauss lines, which have been approximated to ellipses. The isogauss lines are at the height of the isocenter of the MR scanner.

The B value at each point in the room is calculated by fitting the data of the isogauss lines using a piecewise exponential interpolation: the maximum error between interpolated data and isogauss lines data is 5%. Figure 2a shows the fitting results for the static magnetic field value in the MR room relative to the ground plane. In Fig. 2b the B profiles along the x (red) and z (blue) directions starting from the isocenter ($z = 0$, $x = 0$) with the relative B value obtained from the isogauss lines (B_x map and B_z map respectively).

By means of a graphical user interface (GUI), which shows the MR scanner room (see Fig. 3), it is possible to simulate any movements of a worker on the ground plane (xz plane) choosing the start and stop points and one or more direction change points (for example, using the mouse and clicking on each point). The simulator draws the chosen path with a red line on the MR scanner room map (see Fig. 3).

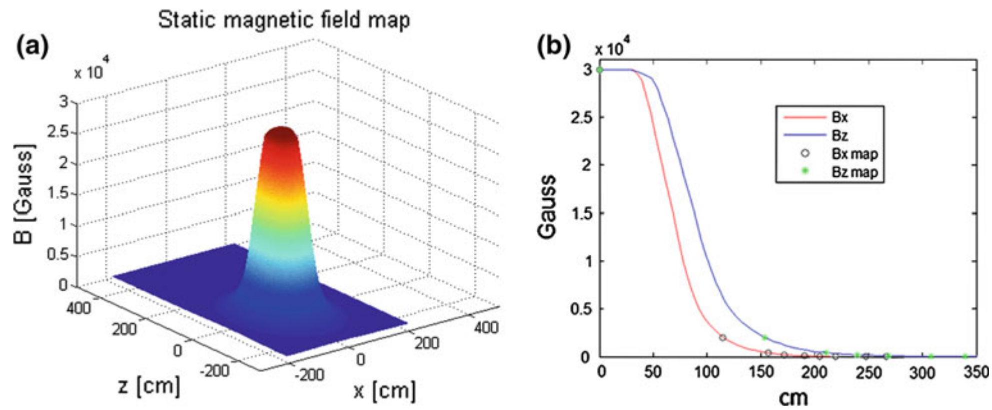

Fig. 2 3D map (**a**) and profile along x and z directions (**b**) of static magnetic field

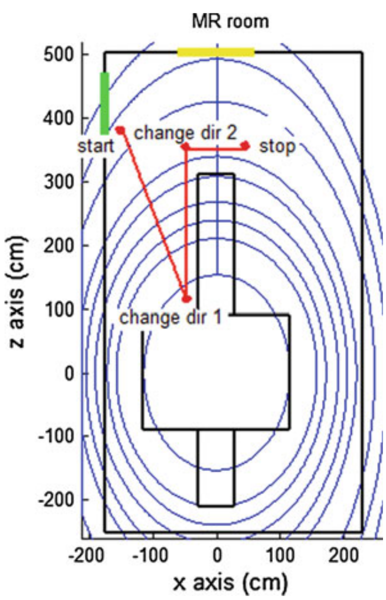

Fig. 3 Example of a chosen worker walking path

Finally, the operator walking speed along the chosen path can be easily set. Once the walking path and speed are chosen, the tool estimates induced electric field E and current density J using Eqs. 4 and 5 with spatial gradients calculated for each point on the path [15], and the average dielectric conductivity of human tissue σ (in this paper we chose $\sigma = 0.2$ S/m [14]). The maximum value J along the path, expressed in mA/m^2, is reported.

We chose three possible paths for a worker in MR scanner room, shown in Fig 4. Path number 1 is along the z direction: starting from point A close to the MR bore entrance the worker walks along the patient bed axis up to point B (total path length = 1.80 m). Path number 2 is along the x direction: starting from point A close to the bore entrance the worker walks away perpendicular to the patient bed up to point B (total path length = 1 m). For both cases we chose a walking speed that increases linearly in the first part of the path, then remains constant and equal to the maximum value (vmax) in the central part of the path, and finally decreases linearly up to the stop point. Some maximum values of the walking speed were chosen for each cases: 140 cm/s, that is the average walking speed for an adult man, 160 cm/s to simulate quick movements of the operators in the room and 120 cm/s for slower movements. The chosen paths are both possible during the routine daily work shift of an MR worker.

Finally, we tested a complete path (path number 3) which simulates worker movements during patient preparation for a typical cardiac MR exam (Fig. 4b). Starting from the room door (A) the operator walks up to the patient bed (B) and stops to prepare the patient, then walks up to the bore entrance (C) and stops to start the procedure; finally he/she walks towards the door (D) to exit from the MR scanner room. The total path length is about 7 meters. For the first (AB, 250 cm long) and second (BC, 100 cm long) way in the path we chose a walking speed that increases linearly, then remains constant and equal to the maximum value and finally decreases linearly up to the stop point. For the last way (CD, 325 cm long) the walking speed increases linearly and then remains constant and to the maximum value to permit the worker to go out of the scanner room. Three maximum values of the walking speed were chosen for all ways: 160, 140 and 120 cm/s.

Experimental measurements

In order to validate the fitting model used in this work, we measured the real static magnetic field values in the room to validate. Once the goodness of our magnetic field map is demonstrate, the accuracy of induced current density estimation only depends on the effectiveness of previous equations (Eqs. 4, 5). Using a magnetic field meter we measured the actual static magnetic field value relative to the isogauss line position indicated on the manufacturer map. Then, the actual values were used in our fitting model and the maximum

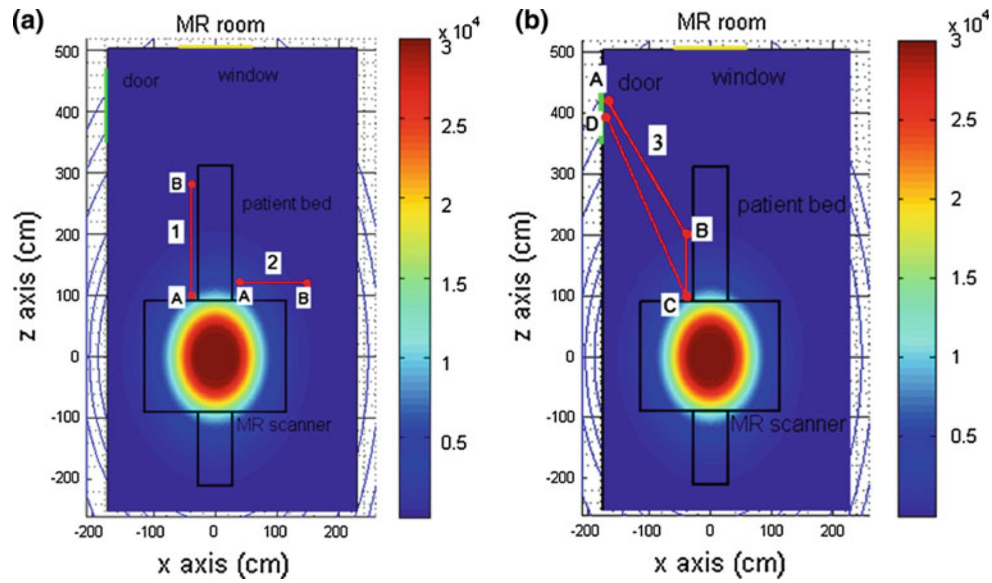

Fig. 4 Chosen worker paths: **a** path no. 1 along z direction and path no. 2 along x direction, **b** path no. 3: example of a possible path during patient preparation

Table 2 Static magnetic field measurement and estimation

	Path no. 3 point A	Path no. 3 point D	Path no. 1 point B	Path no. 2 point B	Path no. 3 point B	Path no. 2 point A	Path no. 3 point C	Path no. 1 point A
Measured magnetic field (Gauss)	3.8	4.2	70	265	441	3700	6560	6560
Estimated magnetic field (Gauss)	4.05	4.42	74.2	280	448.83	3830	6618	6618

relative error was calculated between the magnetic field map obtained from actual and manufacturer data. This maximum error was lower than 10% for static magnetic field values in the entire MR scanner room. As further verification the actual static magnetic field values were measured in the start and stop points of each tested worker path (Table 2) and in some others important points in the room, for example at the patient bed extremities. Also in this case the error between the measurements and the estimated magnetic field values was calculated and remains under 10%.

Results

For each of the three worker paths our simulator calculated the static magnetic field and the induced current density due to the magnetic field gradient along the path; finally, the J maximum value along the path, expressed in mA/m^2, is reported.

Figure 5 shows the results for path number 1; in this case, with a maximum walking speed value equal to 160 cm/s the maximum current density is equal to 41.30 mA/m^2. The chosen walking speed is very likely when the RM workers move quickly inside the scanner room. However, if the maximum walking speed chosen is equal to the average walking speed for adult (140 cm/s), the maximum current density is 36.13 mA/m^2.

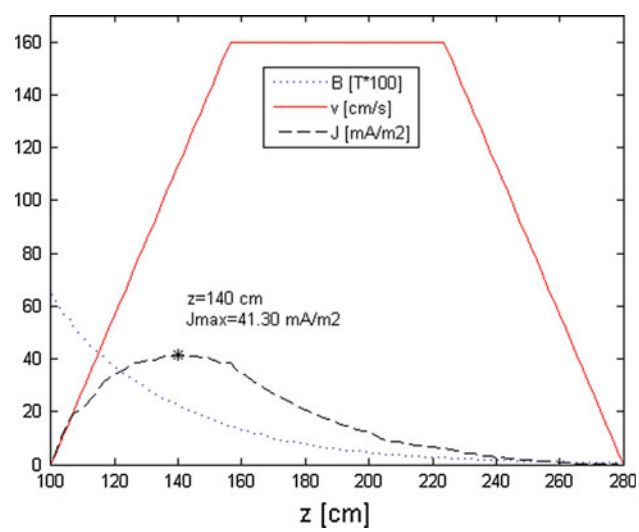

Fig. 5 Static magnetic field B, walking speed v and current density J along path no. 1

Figure 6 shows the results for path number 2: in this case, with a maximum value of walking speed equal to 160 cm/s the maximum current density is equal to

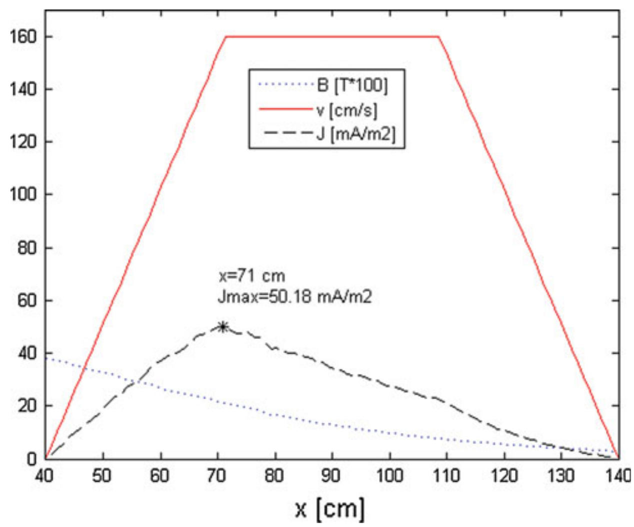

Fig. 6 Static magnetic field B, walking speed v and current density J along path no. 2

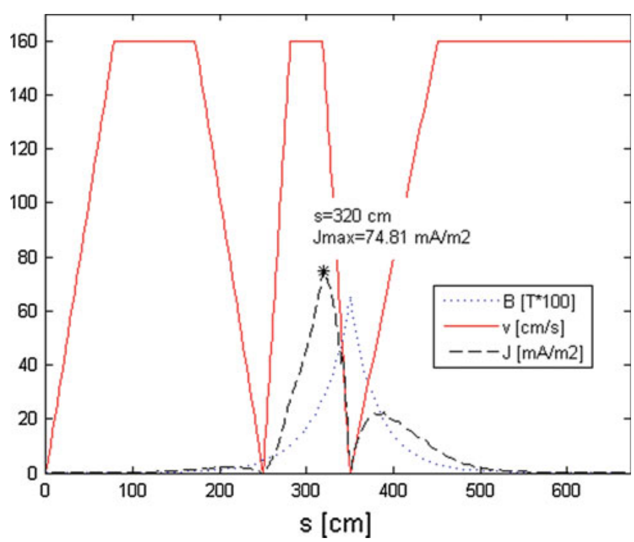

Fig. 7 Static magnetic field B, walking speed v and current density J along path no. 3

50.18 mA/m^2. However, if the maximum walking speed value chosen is equal to 120 cm/s the maximum current density is 37.64 mA/m^2.

Figure 7 shows the results for the third simulated path: in this case, with a maximum walking speed value equal to 160 cm/s the maximum current density is equal to 74.81 mA/m^2. If the maximum walking speed value chosen is equal to 140 cm/s or 120 cm/sec the relative maximum current density values are 65.46 mA/m^2 and 56.16 mA/m^2, respectively.

Discussion

Recent advances in MRI have resulted in an increase in static and time-varying magnetic fields as well as in occupational exposure. Although a recent World Health Organization (WHO) monograph concluded that there is insufficient scientific data for establishing health risks of exposure to static magnetic fields [4], European Parliament Directive 2004/40/EC indicates exposure limits in terms of induced current density due to worker movement in significant spatial heterogeneous static magnetic field. Hence, a valid and easy-to-use instrument to estimate this parameter would be essential for MR laboratories in order to make an accurate and precise risk evaluation for MR workers. Experimental measurement of exposure levels in terms of induced current density is very complex and thus cannot be used in daily routine assessment [14]. On the other hand, using numerical simulations of tissue-equivalent body models requires long computational times and complex body models [12].

This paper presents a novel tool for estimating the induced current density due to worker movement in the static magnetic field of an MR scanner. This tool can be used for all commercial MR scanners since it only requires the knowledge of the scanner room map with isogauss lines, generally provide by the manufacturer. Using a simple GUI, one can easily simulate typical operator movements during clinical MR exams. The walking speed can be also set to estimate the maximum current density relative to a specific path and compare it with the limits indicated by the regulations. Although legislation and limit values may be changed in any moment, the safety education aspects of this work will remain valid unlimited in time, despite the publication of subsequent directives. Physiological effects due to workers movements by the magnet [4], like visible sensations, cognitive effects and balance problems, may results in difficulties in the work, and safety education is useful to understand how to perform a work without similar effects. Therefore, regardless any legislation and limits, the educational value of the work presented here remains relevant.

In this paper, three paths that operators often follow during patient preparation for a MR exam have been simulated. Only the movement over the ground plane, that is along the x and z directions, were considered in the present work. The isogauss lines map for xz plane are relative to the height of the isocenter of the MR scanner that is approximately the height of an adult centre of mass. In order to calculate the induced current in the body by using our simplified model we can only consider the horizontal movements: a more realistic models (such as virtual models for numerical simulations) should take into account the variations of static field along all three directions. Moreover, the induced current estimation on the head should take into account the height of the subject respect to the MR isocenter.

Results reported here for all three path examples show that it is possible reduced the induced current density, and hence the exposure, decreasing the walking speed. Hence, using this easy-to-use assessment tool a MR operator can be simulate his/her movement path in the MR room and find an optimal walking speed to perform his/her work avoiding high exposure. Moreover, the operator can choose the best path to perform his/her activity with the minimum exposure.

Conclusion

The model used here for estimating induced current density makes many assumptions, including that the body has a homogeneous and isotropic conductivity and that the currents flows in simple circular loops. However, this model is the same adopted in ICNIRP guidelines, and can be used to have a first approximation of the workers exposure in any MRI centre (usually not equipped in very specialized simulation software for a more realistic exposure estimation). Hence, very important area of the use of presented method is while workers occupational safety education: it can be used for training MR workers to avoid high exposure, and change as much as possible, their behaviour in the scanner room (i.e. avoid running or following specific high-exposure paths). Moreover, using this tool a detailed exposure assessment can be made in order to determine which worker groups are most exposed to the risk.

Other possible applications of the proposed tool are: aids for study about the assessment of sensory effects and other health complaints that are reported by MR staff [21] and to build dose-effect curves for study of possible genotoxic effects due to time varying magnetic field exposure of MR workers [3]. Moreover, since the growing interest of the MR scientific community in developing devices for measurement of static magnetic fields and personal MR dosimeters [22,23], this tool can be used to validate and calibrate this kind of instrument.

The presented tool should be validated in order to understand the range of errors introduced by using such a simple model, compared to a fully segmented body model so that the errors can be quantified. However, this validation entails the implementation of complex numerical simulation which will be subject of future works.

Further future works will regards the implementation of induced current estimation relative to the rotational movements of worker head and trunk and to the worker movements in vertical direction (along y axis).

Finally, since the high education capacity of the presented assessment tool, we're going to create interactive education web page for workers or experts from MR centres to allow them to create own examples of exposure scenarios and to evaluate induced current hazards.

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