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RESEARCH ARTICLE

MR safety: simultaneous B_0, $\mathrm{d}\Phi/dt$, and $\mathrm{d}B/\mathrm{d}t$ measurements on MR-workers up to 7 T

Jens Groebner · Reiner Umathum · Michael Bock · Axel J. Krafft · Wolfhard Semmler · Jaane Rauschenberg

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Abstract
Object The EU directive on safety requirements (2004/40/EC) limits the exposure to time varying magnetic fields to $\mathrm{d}B/\mathrm{d}t = 200$ mT/s. This action value is not clearly defined as it considers only the temporal change of the magnitude of $\vec{B}$. Thus, only the translational motion in the magnet's fringe field is considered and rotations are neglected.
Materials and methods A magnetic field probe was constructed to simultaneously record the magnetic flux density $\vec{B}(x, y, z)$ with a 3-axis Hall sensor and the induced voltage due to movements with a set of three orthogonal coils. Voltages were converted into time-varying magnetic flux $\mathrm{d}\Phi(x, y, z)/\mathrm{d}t$ serving as an exposition parameter for both translations and rotations. To separate the two types of motion, $\mathrm{d}B/\mathrm{d}t$ was additionally calculated on the basis of the Hall sensor's data. The calibrated probe was attached to the forehead of 8 healthcare workers and 17 MR physicists, and $\vec{B}$ and $\mathrm{d}\Phi/\mathrm{d}t$ were recorded during standard operating procedures at three different MR systems up to 7 T.
Results The maximum percentage of the translational motion referring the data including both translations and rotations amounts to 32%. During volunteer measurements, maximum exposure values of $\mathrm{d}\Phi/\mathrm{dt} = 21$ mWb/s, $\mathrm{d}B/\mathrm{dt} = 1.40$ T/s and $\left|\vec{B}\right| = 2.75$ T were found.
Conclusion The findings in this work indicate that both translations and rotations in the vicinity of an MR system should be taken into account, and that a single regulatory action level might not be sufficient.

Keywords Exposure limits · Static magnetic field probe · Time-varying fields · EU directive · Magnetic flux · Hall sensor · Ultra high field MRI · Sensory effects

Introduction

The draft European Union (EU) directive of 2004 [1] seeks to limit electromagnetic exposure due to movement in strong static magnetic fields to an action value of $\mathrm{d}B/\mathrm{d}t = 200$ mT/s for frequencies up to 1 Hz. This action value is not a limit, but a means of assessing compliance with the exposure limit. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) recommends a peak value of 1 T/s during handling volunteers and patients to avoid cognitive effects such as dizziness and vertigo [2]. IEEE recommends calculating the peak environmental field from the maximum permissible exposure limit of the magnetic flux density [3]. Fuentes et al. [4] calculated a peak environmental field of 768 mT/s in the range of 0–7 Hz. The action values of the EU directive would, in particular, affect healthcare workers in the vicinity of MR systems, so that access to, as well as exposure time in, the MR magnets' stray fields would need to be monitored and restricted [5–7]. After strong criticism by various organizations, the implementation of the EU directive into national law has been postponed until April 30th, 2012 [8]. The EU directive is currently being amended to reflect the concerns of the MRI community—a proposal for the amended directive has been available since 14th June 2011 via the European Commission [9].

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J. Groebner · R. Umathum · M. Bock · A. J. Krafft · W. Semmler ·
J. Rauschenberg (✉)
Department of Medical Physics in Radiology (E020),
German Cancer Research Center (DKFZ), Im Neuenheimer Feld 280,
69120 Heidelberg, Germany
e-mail: j.rauschenberg@dkfz.de

Recently, several magnetic field exposure measurements on personnel during MRI assembly and testing in the environment of 1.5 and 3 T magnets have been performed [10]. The magnetic field exposure of MR personnel has also been investigated in the environment of MR systems up to 4 T [4,11–13]. A report concerning magnetic field exposure of a few sample measurements in the environment of 1.0, 1.5, 3 and 7 T MR systems has been published in which volunteers' movements in the stray field were filmed with cameras, and the exposure was calculated using data from prior $\vec{B}$ field mapping [14].

In all of these studies the measurement area was restricted to the waist of the volunteers. Only one study exists in which the movement of the volunteers' heads was measured in the vicinity of 1 and 3 T MR systems [15]. It has been reported that head movements in the stray field of 3 and 7 T MR magnets (e.g. turning, bending into the bore) can generate time-varying fields which easily exceed recommended peak values [16–18].

However, using $\mathrm{d}B/\mathrm{d}t$ as a limit parameter is not suitable as it considers only the temporal change of the magnitude of $\vec{B}$, whereas the spatial components of $\vec{B}$ are also essential: For example, a simple rotation of the head near the bore entry does not involve a translational movement, and thus would result in $\mathrm{d}B/\mathrm{d}t = 0$. Nevertheless, in this situation currents are induced in the head, and volunteers often complain about the well-known side effects such as metallic taste or dizziness. Thus, the often used $\mathrm{d}B/\mathrm{d}t$ as a limit parameter is not sufficiently defined as it considers only translational movement in a static magnetic field.

In this work a portable magnetic field probe was constructed to simultaneously record all three directions of the magnetic flux density $\vec{B}(x, y, z)$ using a 3-axis Hall sensor. In addition, the induced voltage due to movements with a set of orthogonal loops was recorded. These voltages were converted into the time-varying magnetic flux values $\mathrm{d}\Phi(x, y, z)/\mathrm{d}t$ as an exposition parameter for both translational and rotational movements. To determine the difference between the rotational and translational component, $\mathrm{d}B/\mathrm{d}t$ values were also calculated from the Hall sensor data. All exposure quantities were measured during daily routine work of healthcare workers and MR-physicists at MR systems with different static magnetic field strengths.

Materials and methods

Theory

At the terminals of a wire loop, a time-varying magnetic flux $\mathrm{d}\Phi(t)/\mathrm{d}t$ (e.g., caused by movements in the MR-systems' stray field) induces a voltage V_{ind} according to Faraday's law of induction:

$$\begin{aligned} V_{\mathrm{ind}} &= -\frac{\mathrm{d}\Phi}{\mathrm{d}t} \\ &= \underbrace{-\frac{\mathrm{d}\left|\vec{B}\right|}{\mathrm{d}t} \cdot A \cdot \cos\left(\vec{B}, \vec{n}\right)}_{V_{\mathrm{ind(trafo)}}} \underbrace{- \left|\vec{B}\right| \cdot \frac{\mathrm{d}A}{\mathrm{d}t} \cdot \cos\left(\vec{B}, \vec{n}\right)}_{V_{\mathrm{ind(var)}}} \\ &\quad \underbrace{+ \left|\vec{B}\right| \cdot A \cdot \sin\left(\vec{B}, \vec{n}\right) \cdot \frac{\mathrm{d}\varphi}{\mathrm{d}t}}_{V_{\mathrm{ind(gen)}}}. \end{aligned} \tag{1}$$

Here, A denotes the effective cross sectional area of the loop, $\left(\vec{B}, \vec{n}\right)$ is the angle between the normal vector $\vec{n}$ of A and the magnetic flux density $\vec{B}$, and $\mathrm{d}\varphi/\mathrm{d}t$ is the momentary angular velocity. Three different terms contribute to the induced voltage: The first term

$$V_{\mathrm{ind(trafo)}} = -\frac{\mathrm{d}\left|\vec{B}\right|}{\mathrm{d}t} \cdot A \cdot \cos\left(\vec{B}, \vec{n}\right) \tag{2}$$

scales with the temporal change of the magnitude of $\vec{B}$. During translational motions along a trajectory parallel to the magnetic field lines (e.g., along the symmetry axis of a solenoid magnet), only $V_{\mathrm{ind(trafo)}}$ contributes to the measured voltage. The second term $V_{\mathrm{ind(var)}}$ is proportional to the change of the effective loop area, and thus can be neglected for a rigid coil setup. The third term $V_{\mathrm{ind(gen)}}$ describes the voltage which is induced during rotations of the loop in the magnetic field:

$$V_{\mathrm{ind(gen)}} = \left|\vec{B}\right| \cdot A \cdot \sin\left(\vec{B}, \vec{n}\right) \cdot \frac{\mathrm{d}\varphi}{\mathrm{d}t}. \tag{3}$$

Note that the generator term is non-zero during rotations of the coil about its own axis, even if $V_{\mathrm{ind(trafo)}}$ vanishes. Thus, for a sensor consisting of a wire loop the measured voltage V_{ind} during motion in the magnet's stray field is given by

$$\begin{aligned} V_{\mathrm{ind}} &= -\frac{\mathrm{d}\Phi}{\mathrm{d}t} \\ &= \frac{A}{N} \cdot \left(-\frac{\mathrm{d}\left|\vec{B}\right|}{\mathrm{d}t} \cdot \cos\left(\vec{B}, \vec{n}\right) + \left|\vec{B}\right| \cdot \sin\left(\vec{B}, \vec{n}\right) \cdot \frac{\mathrm{d}\varphi}{\mathrm{d}t}\right), \end{aligned} \tag{4}$$

where N is the number of turns of the coil. To compare the change in magnetic flux with the EU and IEEE action values in units of $\mathrm{d}\Phi/\mathrm{d}t$, Eq. 4 was used for conversion of the values. The coil area A of the employed probe was used (2,642 mm^2) and $\cos\left(\vec{B}, \vec{n}\right)$ was set to 1 which would correspond to the maximum $\mathrm{d}\Phi/\mathrm{d}t$ limit.

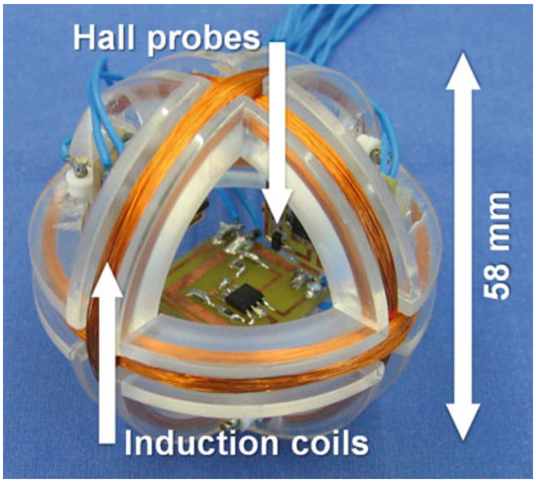

Fig. 1 The probe to measure the magnetic flux density with three orthogonal Hall sensors and the temporal changing magnetic flux with three orthogonal induction coils. It was worn at the volunteer's forehead

Magnetic field probe

The field probe consisted of two measurement systems (Fig. 1). Three orthogonally arranged commercial Hall sensors (CY-SJ106C, ChenYang Technologies GmbH & Co. KG, Finsing, Germany) were used to detect each spatial component of $\vec{B}$ separately. The sensitive area of each Hall sensor was 1 mm^2. To achieve an optimal sensitivity profile, the bias of each Hall sensor was set to a value of 500 µA using an adjustable current source. To quantify $\mathrm{d}\Phi/\mathrm{d}t$, the induced voltage was detected by three orthogonal induction coils. Each coil with a diameter of 58 mm had $N = 200$ turns of 0.1 mm insulated copper wire with a total resistance of 0.6 Ω. The diameter and the number of turns were chosen to obtain a sufficiently high voltage while moving in regions of low magnetic fringe fields. Figure 1 shows the constructed probe.

Each Hall sensor and induction coil was connected to a separate voltage amplifier. An integrated active low-pass filter (cut-off frequency: 10 Hz) suppressed high-frequency noise. The supply voltage for the amplifiers and the Hall sensors was provided by two MR-compatible accumulators (LIPOLY 740H 2S1P, Kokam Co. Ltd., Siheung, South Korea). The amplifier output was digitized using a USB-6009 data acquisition board (National Instruments, Austin, Texas, USA). All three spatial components of $\vec{B}$ and $\mathrm{d}\Phi/\mathrm{d}t$ were recorded as a function of time. Absolute values of $\vec{B}$, and $\mathrm{d}\Phi/\mathrm{d}t$ were calculated according to

$$\left|\vec{B}\right| = \sqrt{B_x^2 + B_y^2 + B_z^2} \tag{5}$$

and

$$\frac{\mathrm{d}\Phi}{\mathrm{d}t} = \sqrt{\left(\frac{-V_{\mathrm{ind}(x)}}{N \cdot G}\right)^2 + \left(\frac{-V_{\mathrm{ind}(y)}}{N \cdot G}\right)^2 + \left(\frac{-V_{\mathrm{ind}(z)}}{N \cdot G}\right)^2}, \tag{6}$$

where G was the amplification factor of the operational amplifier used. Additionally, to compare $\mathrm{d}\Phi/\mathrm{d}t$ values (Eq. 6) that include translational and rotational components with the absolute values of the time variable magnetic field (Eq. 2), $\mathrm{d}B/\mathrm{d}t$ was calculated from the Hall sensor data by:

$$\frac{\mathrm{d}\left|\vec{B}\right|}{\mathrm{d}t} = \frac{|B(t_{n+1}) - B(t_n)|}{t_{n+1} - t_n}. \tag{7}$$

Two adjacent time points t_{n+1} and t_n were chosen so that a time span of 1 s (33 samples per time span) was obtained. Therefore, a good compromise between signal to noise and temporal resolution could be achieved.

The Hall sensors were calibrated using a 20 T-Hall-probe (Three-axis Hall Magnetometer THM1176, Metrolab Instruments SA, Plan-les-Ouates, Switzerland) placed at the iso-center of the 7 T MR system (Magnetom 7 T, Siemens Healthcare, Erlangen, Germany). To determine the accuracy of the $\vec{B}$ measurements, a calibration curve for each of the orthogonal sensors was measured over a range of 30 mT–7 T which corresponds to a distance of 5.8 m from the iso-center.

$\mathrm{d}\Phi/\mathrm{d}t$ probe calibration

To calibrate the $\mathrm{d}\Phi/\mathrm{d}t$ probe, each coil of the probe was placed orthogonally to the magnetic field $\vec{B}$ at iso-center height onto the patient table of a 1.5 T-MR system (Magnetom Avanto 1.5 T, Siemens Healthcare, Erlangen, Germany). The table was moved back and forth with a maximum velocity of 200 mm/s and an elongation of 2,874 mm around the region of highest $\vec{B}$ gradient ($\mathrm{d}B/\mathrm{d}z = 2.56$ T/m at $z = 823$ mm distance from iso-center).

The induced voltage $V_{\mathrm{ind(trafo)}}$ was recorded during motion, and $\mathrm{d}B/\mathrm{d}t$ was calculated using Eq. 2. In parallel, the table velocity $v(z)$ was measured with an MR safe tachometer consisting of a sponge rubber tire with a diameter of 50 mm mounted on a light chopper wheel, and the light impulses per second were counted. From the velocity of the patient table, the spatial derivate $\mathrm{d}B/\mathrm{d}z$ was calculated according to

$$\frac{\mathrm{d}B}{\mathrm{d}t}(z) = \frac{\mathrm{d}B}{\mathrm{d}z}(z) \cdot v(z). \tag{8}$$

These values of $\mathrm{d}B/\mathrm{d}z$ were compared to known field mapping data of the magnet which were employed to calculate the spatial derivatives $\mathrm{d}B/\mathrm{d}z$ numerically.

Volunteer experiments

Using the calibrated magnetic field probe, several exposure measurements were performed during standard operational procedures in the scanner rooms of whole-body MR systems of three different magnetic field strengths (Magnetom Avanto 1.5 T, Magnetom TIM Trio 3 T, Magnetom 7 T, all Siemens Healthcare, Erlangen, Germany). The probe was attached to a cap at the volunteer's forehead. It was worn by eight healthcare workers during their daily routine with patients (e.g. patient preparation, coil placement, etc.) and by 17 MR physicists. The volunteers were instructed to follow their typical daily routines while wearing the magnetic field probe.

The following exposure parameters were determined: The average and peak values of $\vec{B}$ and the average and peak values of $\mathrm{d}\Phi/\mathrm{d}t$. Additionally, average and peak values of $\mathrm{d}B/\mathrm{d}t$ were calculated from the measured $\vec{B}$ data. These values were compared with the results from the induction probe, to determine the percentage of the translational motion due to total movement, including both translational and rotational motions. Measurements were started when the volunteer entered the RF-cabin and stopped when leaving the RF-cabin.

Results

Table 1 summarizes the peak values with the respective coil geometry, converted from EU and IEEE. Figure 2 illustrates the sensitivity profile of one Hall sensor probe in a range from 30 mT to 7 T. The graph indicates a decrease in sensitivity with increasing field strength: below 2 T the sensitivity amounts to 0.74 ± 0.02 V/T. From 2 to 3 T the sensitivity was 0.31 ± 0.01 V/T, and from 3 to 4 T it was 0.18 ± 0.01 V/T. In the measurement range of 4–5 T it amounts to 0.12 ± 0.01 V/T, and between 5 and 7 T it was below 0.10 ± 0.02 V/T. The maximum difference between the measurement data of the three Hall sensors amounts to 1%.

Figure 3 depicts the result of the $\mathrm{d}\Phi/\mathrm{d}t$ probe calibration. The solid grey line presents the $\mathrm{d}B/\mathrm{d}z$ data measured with the $\mathrm{d}\Phi/\mathrm{d}t$ probe and the associated velocity $v(z)$ acquired by the tachometer. The dashed black line indicates the $\mathrm{d}B/\mathrm{d}z$ data calculated from Hall sensor $\vec{B}$ measurements. The residual of both measurements is given by the solid black line. A maximum deviation of ±0.25 T/m was found at low velocities (e.g. the turning point at the isocenter). Additionally, the $\mathrm{d}B/\mathrm{d}z$ values calculated from the Hall probes were compared with data from the induction coils (not illustrated in Fig. 3). A variation up to ±0.30 T/m could be observed.

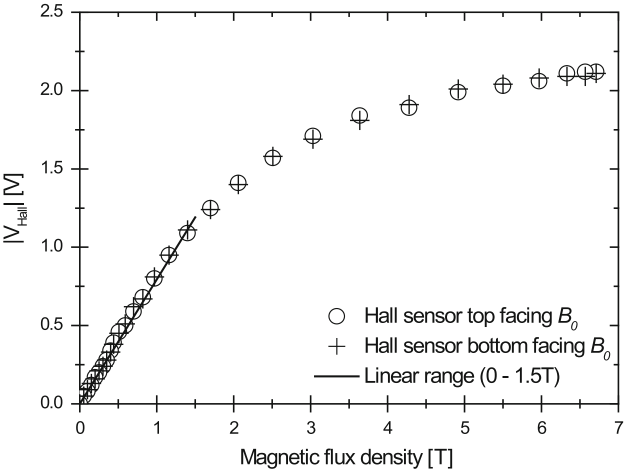

Fig. 2 Sensitivity profile as a function of the magnetic flux density for the used Hall sensor

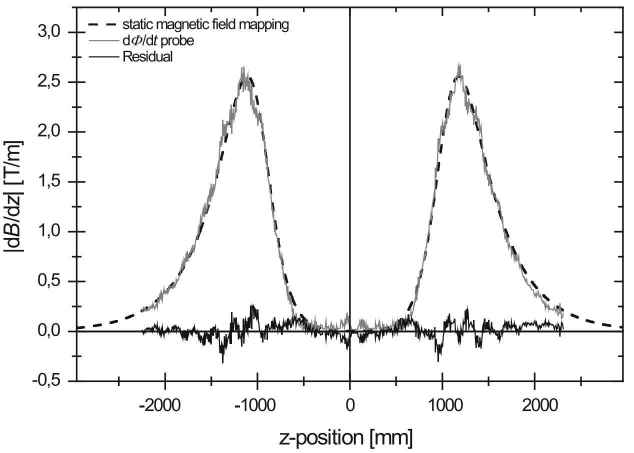

Fig. 3 Calibration of the $\mathrm{d}\Phi/\mathrm{d}t$ probe. $\mathrm{d}B/\mathrm{d}z$ of the $\mathrm{d}\Phi/\mathrm{d}t$ probe (*solid grey line*) is compared to the local gradient of the 1.5 T system along the traveling path (*dashed black line*). The *solid black line* shows the residual

Volunteer experiments

Figure 4 summarizes the exposure measurements of all volunteers. $\mathrm{d}B/\mathrm{d}t$-action values of both EU and IEEE (converted

Table 1 Overview of the converted threshold values with the accordant coil geometries

Organization/name	$\mathrm{d}B/\mathrm{d}t$ value (mT/s)	$\mathrm{d}\Phi/\mathrm{d}t$ value (mWb/s)
EU Directive 2004/40/ EC action value [1]	200	0.528
ICNIRP patient limit [2]	1,000	2.642
IEEE recommended limit [3]	768	2.029

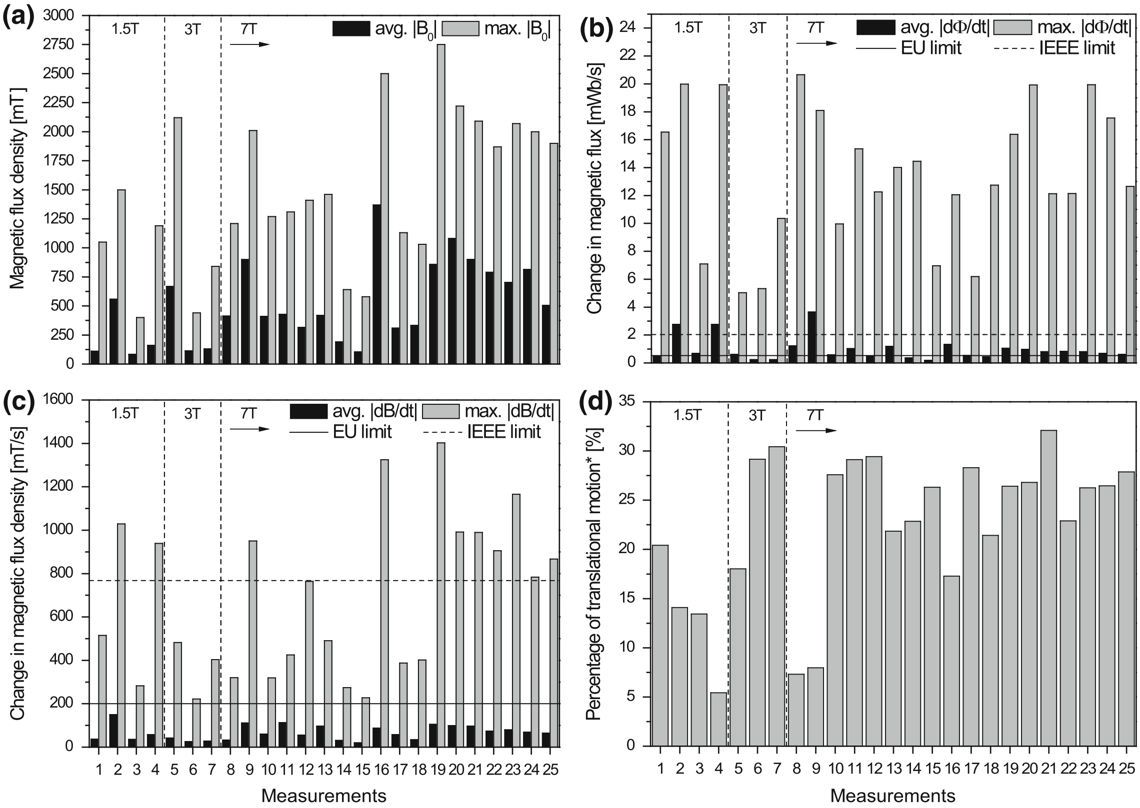

Fig. 4 Exposure data during different actions of MR-workers at the 1.5, 3 and 7 T MR system. In all measurements but d: *black bars* indicate average values, *grey bars* illustrate peak values. The *horizontal lines* mark the limit values (*solid*: EU; *dashed*: IEEE) **a** B_0 measurements. **b** $\mathrm{d}\Phi/\mathrm{d}t$ measurements. **c** $\mathrm{d}B/\mathrm{d}t$ calculation. **d** Percentage of the translational motion. *Here, $\mathrm{d}\Phi/\mathrm{d}t$ calculated from $\mathrm{d}B/\mathrm{d}t$ was compared to $\mathrm{d}\Phi/\mathrm{d}t$ values from induction coils

into $\mathrm{d}\Phi/\mathrm{dt}$) were exceeded in most of the measurements: The peak values of $\mathrm{d}\Phi/\mathrm{d}t$ exceeded the EU and IEEE action values during all procedures at all field strengths. Also the average values exceeded the action values during many measurements (EU: measurement no. 2–5, 7–14, 16–25; IEEE: measurement no. 2, 4, 9, Fig. 4b).

The $\mathrm{d}\Phi/\mathrm{d}t$ values calculated from the Hall probe data were much less than the values from the induction coils: In Fig. 4d the percentage of translational and rotational motion of $\mathrm{d}\Phi/\mathrm{d}t$ is given and varies between 32 and 5%.

Even if only the translational motion were to be considered, the EU action value of 200 mT/s would have been exceeded in all measurements at all field strengths, and so were the IEEE limits in several procedures (cf. #2, 4, 9, 16, 19–25, Fig. 4c). The $\mathrm{d}B/\mathrm{d}t$ maximum value of 1.40 T/s was detected during coil plugging at the 7T-system. During the same procedure, also, a maximum $\left|\vec{B}\right|$ value of 2.75 T was reached. Figure 5 shows data during coil and phantom placement at the 7 T MR system. In this case, peak values of $\mathrm{d}B/\mathrm{d}t = 1.17$ T/s, $\mathrm{d}\Phi/\mathrm{d}t = 20$ mWb/s, and $\left|\vec{B}\right| = 2.07$ T were found.

Discussion

In this study, magnetic field exposure data were acquired in different MR systems using two different measurement principles simultaneously. The activity of both MR healthcare personnel and MR physicists was measured with a probe developed in-house.

The Hall probes used in this work provided reliable sensitivities and small relative measurement errors of up to ±3% in the measurement range of 30 mT–3 T. Beyond 3T the sensitivity decreased due to saturation effects in the Hall elements, and the measurements showed that the Hall sensors used are not suitable at $\vec{B} > 5$ T due to high relative errors (more than ±15%). However, even when bending far into the bore of the 7 T MR system (e.g., to reach the coil plug sockets) the static magnetic field never exceeded 5 T, and thus the Hall probes could be used in this experiment.

The $\mathrm{d}\Phi/\mathrm{d}t$ probe was calibrated at the 1.5 T MR system because of the availability of an automatic patient table. As only translational movements were used for calibration, the induced voltage V_{ind} could be converted into $\mathrm{d}B/\mathrm{d}t$ using

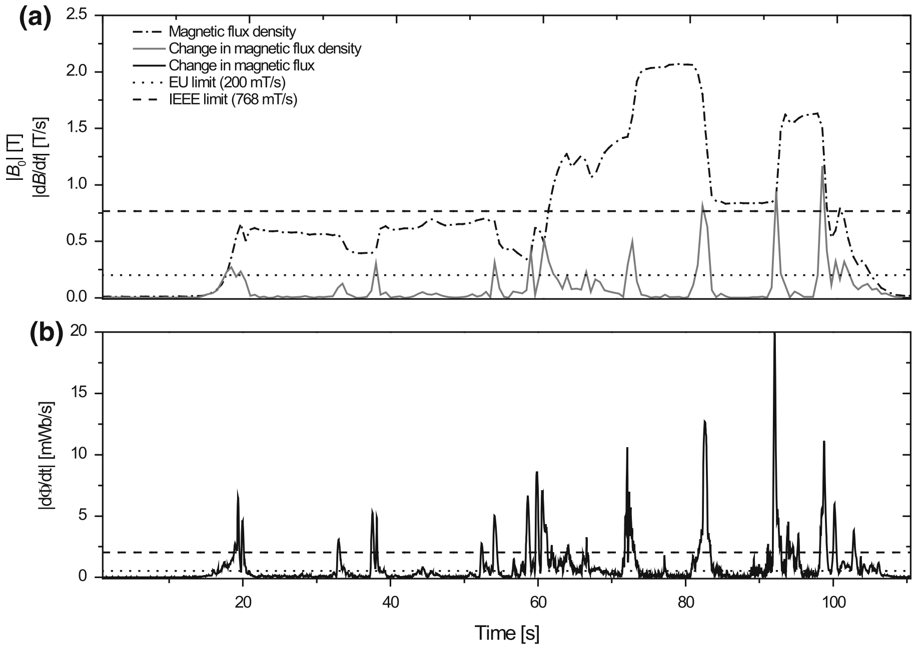

Fig. 5 Exposure measurements of an MR worker during coil plugging and phantom placement at 7 T (cf. #23 in Fig. 4). **a** The *dash-dotted black line* illustrates the B_0 exposure during the work in the RF cabin. The *solid grey line* shows the change in magnetic flux density. **b** The *solid black line* illustrates the change in magnetic flux during the measurement

Eq. 2. The motion in the bore was tracked with a tachometer, which provided data for the velocity of the patient table. Due to the dimensions of the sponge rubber tire (Diameter: 50 mm) and the 36 gaps of the light chopper wheel, minimum distances of 4.36 mm could be resolved with this tachometer. The comparison between the measured $\mathrm{d}B/\mathrm{d}t$ data and the derivative map of $\vec{B}$ shows good agreement with a maximum relative error of ±5%. At the turning points, the error of the measurement system is higher because a small velocity results in very low $\mathrm{d}B/\mathrm{d}t$ values and, therefore, the signal from the induction coils is dominated by noise. The measurement range limit of the $\mathrm{d}\Phi/\mathrm{d}t$ probe depends on the induced voltage, the velocity, and the magnetic fringe field. With the setup described here, $\mathrm{d}\Phi/\mathrm{d}t$ values of up to 21 mWb/s could have been measured, whereas higher induced voltages would be truncated by the operational amplifier due to the limited supply voltage. This measurement range could be extended by using accumulators that provide higher voltages, or with induction coils with fewer turns. However, during all procedures the maximum measurement range was never reached. The integrated cut-off filter of 10 Hz greatly reduced noise from higher frequencies (e.g. mains frequency near the magnet room entrance). However, integrating a hardware filter is a tradeoff between noise reduction and sensitivity for rapid head movements.

An advantage of this device compared to published exposure measurement systems is the simultaneous acquisition of three exposure parameters $\vec{B}$, $\mathrm{d}B/\mathrm{d}t$, and $\mathrm{d}\Phi/\mathrm{d}t$. $\vec{B}$ was measured to quantify the total exposition of the magnetic field and to calculate the exposure parameter $\mathrm{d}B/\mathrm{d}t$ (accounting for translational movement only). The change in magnetic flux $\mathrm{d}\Phi/\mathrm{d}t$ was measured to translate electromagnetic induction effects due to rotational and translational movements of the volunteer into one measurement parameter.

By fixing the magnetic field probe at the volunteer's forehead, rapid head movements (e.g. turning the head, bending into the bore) could be detected which led to high induced voltages in the $\mathrm{d}\Phi/\mathrm{d}t$ probe. These movements can provoke sensory effects, such as vertigo, dizziness or metallic taste [17]. Due to the simultaneous measurement of $\mathrm{d}B/\mathrm{d}t$ and $\mathrm{d}\Phi/\mathrm{d}t$, rotational and transverse components of the induction voltage $V_{\mathrm{ind(gen)}}$ (cf. Eq. 3) could be calculated. From the percentage of induced voltage attributed to the translational motion, it could be seen that high voltages are induced mainly by rotational movements. In some procedures (cf. #4, 8, 9, Fig. 4) the translational component is below 10%, while turning and bending in the fringe field caused $\mathrm{d}\Phi/\mathrm{d}t$-values of up to 20 mWb/s. In all procedures the maximum percentage of the translational component $\mathrm{d}B/\mathrm{d}t$ is only 32%. At some time points (cf. Fig. 4) calculated $\mathrm{d}B/\mathrm{d}t$ values exceed even the $\mathrm{d}\Phi/\mathrm{d}t$ values, which can be explained by the discrete measurement intervals of 1 s and the measurement errors of both devices.

Unfortunately, the current action value by the EU and limit value by the IEEE are not clearly defined and may include only translational changes of the magnetic field $\mathrm{d}B/\mathrm{d}t$. In this study the change in magnetic flux is used additionally as an exposure parameter, which includes both translational and rotational movements. This is especially important, because here translational motions contribute only to a small degree to the induced voltages.

On the other hand, using $\mathrm{d}\Phi/\mathrm{d}t$ to define a safety limit would require the knowledge of the size of the anatomical structures in which the currents are induced. In this work, the main intention was to indicate that temporal change of the magnitude of $\vec{B}$ is not the only factor which has to be taken into account when discussing static magnetic field exposures.

The simply-designed measurement system could be proved to provide reliable data during the activities in the different MR systems. For measurements at lower magnetic fields the signal acquired by the induction coils was relatively low. Therefore, the probe was designed with a large diameter (58 mm) in comparison to anatomical structures (e.g. inner ear, about 20 mm diameter). Size adoptions of the measurement system to anatomical dimensions are planned for future developments. Another limitation is that the field probe position at the forehead is not at the rotational center of the head. Thus, a head rotation leads to additional translational movements of the field probe and consequently, the measured exposure value is overestimated. However, even a very small probe directly attached to the forehead's skin would result in such additional movements. Due to the long cables for data transmission the volunteer had to be more attentive while working in the magnet room—this could have systematically influenced the body (and thus the head) motion. For this reason a wireless transmission system is currently being developed to make the probe more suitable for everyday use.

Conclusion

For comparison with the acquired $d\Phi/dt$-data the actual EU action value and the IEEE limit were converted into $d\Phi/dt$ with Eq. 2, where the magnetic field vector $\vec{B}$ is parallel to the normal vector $\vec{n}$ on the coil cross area. The acquired volunteer data easily exceeded these limits (up to 1.4 T/s). Even in lower stray fields, such as those of 1.5 T MR systems, these values were high enough to reach the current limit values. However, up to now only transient effects such as vertigo, dizziness, etc., which disappeared after leaving the magnet room, have been reported [18,19]. To date, after more than 500 million MRI examinations worldwide, of which more than one thousand examinations were conducted at 4, 7 or 8 T, no indications of any long term health effects on humans have been observed. New studies show that the static magnetic field affects neither vital signs nor neurocognitition [20–24]. The findings in this work support the efforts which are currently being taken to amend the exposure limits for high fields and ultra high fields at MRI. The referred action values may change and would not to be relevant to MRI by 2014 [9].

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