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CURRENTS INDUCED BY BODY AND ARM MOVEMENT IN A 3T MRI STATIC MAGNETIC FIELD

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Abstract:

MRI magnets generates strong and uniform magnetic fields within the imaging volume, but spatial fields gradients are present outside this central region, and people moving within magnet room experience time-varying magnetic field that can induce electric fields and currents in tissue
Aim of this study is the assessment, through direct static field measurements and model based calculations, of induced currents at trunk and head as effect of translating body movement within the magnet room and at wrist level as result of standard arm movements (vertical arm lift and horizontal arm opening) performed by operators during their ordinary working activity.

Introduction

Recent developments in Magnetic Resonance Imaging (MRI) based diagnostic technologies are leading hospitals towards high static magnetic fields scanners use; current tendency indicates the use of 3T scanners for common diagnostics and 7T units for interventional procedures in operating room, this leads to increased static magnetic fields exposure for the personnel.
In year 2004 European Union adopted the 2004/40/EC Directive [1] which gives the minimum health and safety requirements to protect workers from risks due to electromagnetic fields exposure; this Directive application may lead to severe limitations in MRI based techniques use for diagnostics.
Considering all those factors, European Parliament has postponed the deadline for transposing the Directive by Member States to year 2012 in order to permit a complete limits and guidelines revision by the ICNIRP [2].
The ICNIRP in the revised edition of “Static Magnetic Field exposure Guidelines”[3] has recommended that occupational exposure for head and trunk should not exceed a peak value of local magnetic flux equal to 2 T, but exposures up to 8T are allowed in a controlled environment and under appropriate operational procedures mainly aimed at reducing the impair effects induced by the movement.
In general the interaction of a static magnetic field with biological matter produces two different effects: orientation of molecules or molecular systems with a magnetic moment and the creation of forces on moving electric charges. If we consider living systems, the scientific research tends to confirm the absence of effects on health for exposures to fields up to 2 T. The only proved effect is the formation of visual stimuli, such as phosphenes, with induction thresholds varying from subject to subject. Detailed studies of physiological parameters including body temperature, respiratory rate, number of hearth pulses, blood pressure and body extremities oxygenation status, showed no significant changes in exposures up to 8 T [4]; electrocardiogram plot distortion and a slight increase in systolic blood pressure have been observed. From a behavioural point of view, no significant changes in short term memory, in reaction time and in performing working activities have been observed [5,6].
Static magnetic field levels in proximity of MRI scanners can be easily evaluated from measurements performed using an Hall effect probe on an appropriate measure grid; this data, provided by scanners

productors in standard tomograph covering documentation, can be representative of the exposure only in the case of a body standing motionless inside the field and in total absence of physiological movements (like blood flowing in veins and arteries), as consequence it is not to be considered conclusive. On the contrary
the evaluation of motion induced effects in high static fields are of extreme importance from a biological point of view.
Scientific literature [7,8] reports that motion induced electric fields and slowly varying currents produced in head and trunk may cause disturbances; for this reason an assessment of additional parameters taking into account the subject movement into the static field is needed. This parameter is the magnetic flux density dB/dt, related to the induced electric field by the equation:

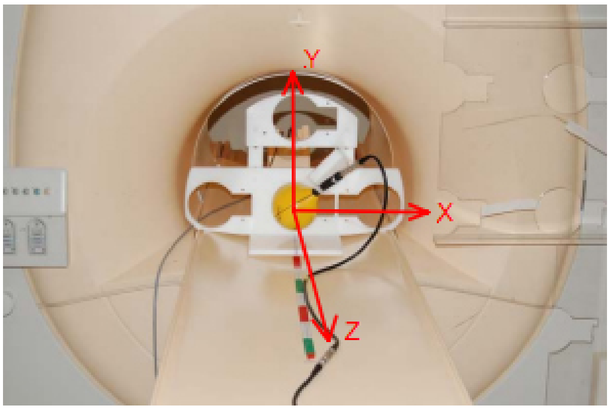
$$\oint E_b.dl = \int \frac{d(B.ds)}{dt} \qquad (1)$$

Where E_b is the induced electric field.

In the case of nuclear magnetic resonance, the electric field is induced by changes occurring in magnetic field vector due to linear or rotational body movements into a static field.
Aim of this study is the assessment, through direct static field measurements and model based calculations of induced currents at head and trunk as effect of translating body movement within different patterns into the magnet room, and induced current at wrists resulting from standard arm movements like vertical arm lift and horizontal arm opening performed by operators during their ordinary working activities.

Material and Methods

Measurements have been performed on a GE Signa 3.0 T clinical scanner, using a Metrolab THM1176 isotropic Hall effect probe able to detect static magnetic fields within the range 0 – 1999 mT with 2% of reading accuracy. The instrument was setted in the max hold configuration.
Mandatory boundary condition it the absence of active clinical sequences in order not to alter, with the presence of spurious radiofrequencies or magnetic fields gradients, values resulting from measures.
The scanner's isocentre has been chosen as reference system's origin and the axes has been identified as shown in Figure 1.



Fig, 1- Reference System

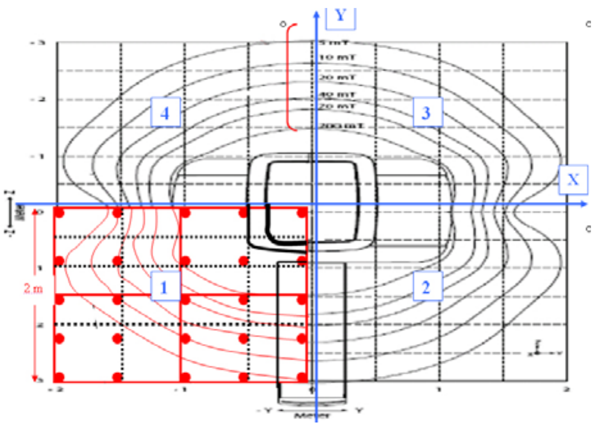


Fig. 2 - Micro grid

The magnet room has been divided into four quadrants symmetrical in respect to x and z axis; the symmetry of the static magnetic field make it possible to perform measurements only on a single quadrant.

A 25 cm square microgrid was traced in the room; the instrument was placed at the top of every single square at 100, 120, 150, 170 cm from the floor; for what concern induced currents at head and trunk seven different walking patterns, reported in Figure 3 have been investigated.
Preliminary to the measurements protocol compilation, operators have been interviewed on their ordinary activities and on the most common trajectories used to move from one place to another within the magnet room. Pattern selection is based on their answers. In this work we have considered only ordinary working activities and not emergency situations.

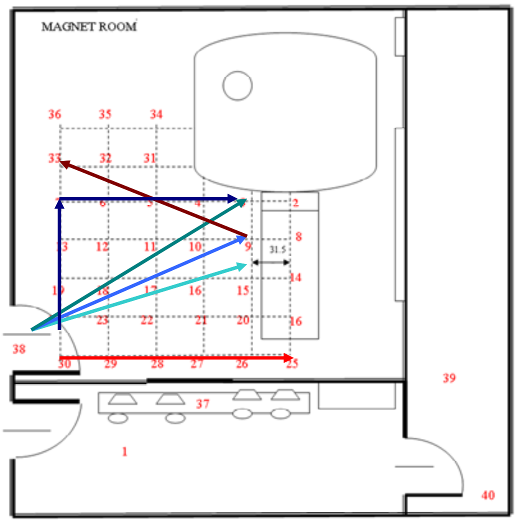


Fig. 3 - Paths investigated

For what concerns induced currents at wrists investigation two different movements have been taken into considerations:
a) vertical arm lift: in this case static magnetic field has been measured every 10 cm over an ideal circular path from the relaxed arm position parallel to the hips to an extended position parallel to the floor; this path is representative of the movement performed by the operator while lifting the patient to the right position
b) horizontal arm opening: in this case field has been measured every 10 cm over a circular path representing the natural horizontal opening of the arm; this path is representative of the movement performed by the operator while positioning the patient on the couch before the exam start.

The analytical model used to calculate induced current provides a the human body section modelled as an homogeneous disk (coil man) with constant conductivity and radius R, thus ignoring the biological tissues anisotropic proprieties. Under these conditions, from the integral form of magnetic flux

$$\oint_L E.dl = -\frac{d}{dt}\int_S B.u_n ds \qquad (2)$$

where L is the coil man circumference and S its surface, follows

$$J(R) = \frac{\sigma_t R}{2}\left|\frac{dB_{ave}}{dt}\right| \qquad (3)$$

where J(R) is the current density induced in the radius R coil man, σ_t is the tissue conductivity (0.2 S/m), B_{ave} is the average value of the magnetic field through the coil man.

The quantity described in (3) can be decomposed in the product:

$$\left|\frac{dB_{ave}}{dt}\right| = \left|\frac{dB_{ave}}{dx}\right|\left|\frac{dx}{dt}\right| \quad (4)$$

so the induced current density can be calculated as:

$$J(R) = \frac{\sigma_t}{2} R\, v \left|\frac{dB_{ave}}{dx}\right| \quad (5)$$

Where R is assumed to be 0.1 m for the head, 0.2 m for the trunk and 0.03 m for the wrists, translational v have been considered 1 m/s [9], this value attributed to translational body movement speed is a rational choice, as it leads to a maximization of the dosimetric quantity J(R). Two differents speeds have been considered for arm movements: 0.85 and 1.70 m/s for arm lift, 0.43 m/s and 1.30 m/s for arm opening. Those specific speeds have been evaluated sperimentally using a chronometer.

In order to perform the measurements necessary to apply the model each path has been divided into multiple subpaths, represented by segments on the floor or on the ideal circumference covered by the arm. ΔB and Δx values have been directly measured for every single segment edge and relative J(R) has been calculated using the espression in (5).

Results

For what concerns body movements in static magnetic fields effects, calculations performed for seven different paths, have shown current densities at head and trunk contained in the range 0.02 – 7.14 mA/m^2, well below the Directive 2004/40/EC 40 mA/m^2 basic restriction. The trajectory segmentation shows that the highest contribution to the induced current density for a diagonal trajectory is referable to the last 70 cm of the path, when, approaching to the magnet the quantity ΔB_i significantly increases: the relative contributions of the external part of the trajectory are negligible compared to the contributions from the paths closer to the magnet area. Table 1 shows the data for room entrance-bore edge diagonal walking path, B has been measured at 170 cm from the floor for the head and 150 cm from the floor for the trunk .

Table 1. Calculated induced current at head and trunk for room entrance- bore edge diagonal path

Position	B_{meas} (mT)	Δx_i (m)	ΔB_i (mT)	$\lvert \Delta B / \Delta x \rvert_i$ mT/m	J_{itrunk} (mA/m^2)
Start	0.3				
X_1	0.7	0.70	0.4	0.56	0.011
X_2	2.8	0.70	2.1	2.97	0.059
X_3	19.9	0.70	17.1	24.2	0.48
X_4	260	0.70	240.1	339.6	6.8
Position	B_{meas} (mT)	Δx_i (m)	ΔB_i (mT)	$\lvert \Delta B / \Delta x \rvert_i$ mT/m	J_{ihead} (mA/m^2)
Start	0.3				
X1	0.7	0.70	0.4	0.56	0.0056
X2	2.4	0.70	1.7	2.40	0.024
X3	12	0.70	9.6	13.6	0.13
X4	166.4	0.70	154.4	218.4	2.18

Table 2 shows the results for room entrance-patient couch (near to bore entrance) diagonal path.

Table 2. Calculated induced current at head and trunk for room entrance- patient couch diagonal path

Position	B_{meas} (mT)	Δx_i (m)	ΔB_i (mT)	$\lvert\Delta B/\Delta x\rvert_i$ mT/m	J_{itrunk} (mA/m^2)
Start	0.3				
X_1	1.7	1.11	1.4	1.26	0.025
X_2	7.2	0.70	5.5	7.78	0.16
X_3	51.9	0.70	44.7	63.2	1.26
Position	B_{meas} (mT)	Δx_i (m)	ΔB_i (mT)	$\lvert\Delta B/\Delta x\rvert_i$ mT/m	J_{ihead} (mA/m^2)
Start	0.3				
X_1	1.4	1.11	1.1	0.99	0.00099
X_2	6.6	0.70	5.2	7.36	0.074
X_3	25.8	0.70	21.9	30.97	

Table 3 shows the results for an hybrid path from gantry edge to (quadro comandi gas medicali), part of the trajectory is parallel and part perpendicular to the patient couch

Table 3. Calculated induced current at head and trunk for hybrid path

Position	B_{meas} (mT)	Δx_i (m)	ΔB_i (mT)	$\lvert\Delta B/\Delta x\rvert_i$ mT/m	J_{itrunk} (mA/m^2)
Start	270				
X_1	81.6	0.5	178.4	356.8	7.14
X_2	16.5	0.5	65.1	130.2	2.60
X_3	2.4	0.5	14.1	28.2	0.56
X_4	0.4	0.70	2	2.8	0.024
Position	B_{meas} (mT)	Δx_i (m)	ΔB_i (mT)	$\lvert\Delta B/\Delta x\rvert_i$ mT/m	J_{ihead} (mA/m^2)
Start	166.4				
X_1	57.6	0.5	108.8	217.6	2.18
X_2	11.0	0.5	46.6	93.2	0.93
X_3	2.1	0.5	8.9	17.8	0.18
X_4	0.4	0.70	1.7	2.4	0.02

The calculated values as well as being affected by instrumental errors represent an overestimation of the parameter under study, because the calculation was performed assuming that the motion takes place perpendicular to the axis of the bore, when in real situation the trajectory angle differs from a perfect 90°.

From what concerns arm movements, two standard movement have been taken into account:

a) vertical arm lift: in this case static magnetic field has been measured every 10 cm over an ideal circular path from the relaxed arm position parallel to the hips to an extended position parallel to the floor; this path is representative of the movement performed by the operator while lifting the patient to the right position
b) horizontal arm opening: in this case field has been measured every 10 cm over a circular path representing the natural horizontal opening of the arm; this path is representative of the movement performed by the operator while positioning the patient on the couch before the exam start.

Measurements for horizontal arm opening have been performed at 95 cm from the floor on the ideal line connecting the isocentre to patient's table en (corresponding to z axis in the chosen reference system), speed have been considered 0.43 m/s for slow movement and 1.30 m/s for fast movement.

For vertical arm lift speed have been considered 0.85 m/s for slow movement and 1.70 m/s for faster performance.

Figure 4 shows the induced currents at wrists for horizontal slow and fast arm opening starting from the arm extended forward perpendicular to patient couch at 22 cm from the bore edge and moving away from it.

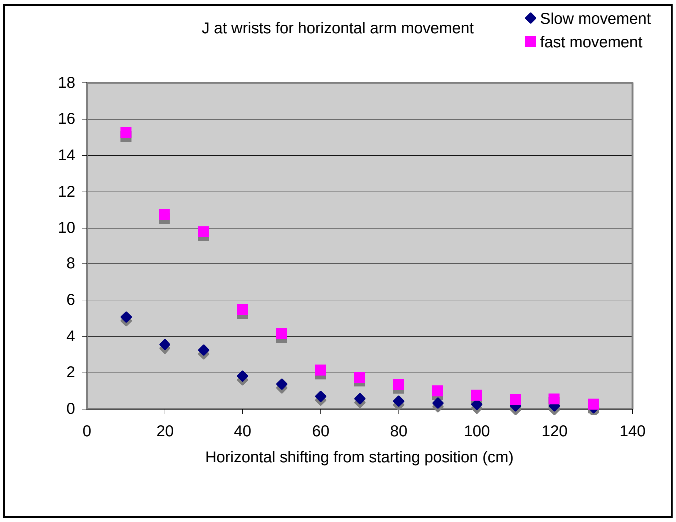


Fig. 4 - J at wrists for horizontal arm movement at two different speeds

Induced current at wrists is strongly dependent from movement speed, the faster the movement is performed the higher is the current induced. From this it is possible to assert that standard operations including translational arms movement within a static magnetic field should be performed slowly, in order to reduce the induced currents.
Induced current at wrist are dependent not only from movement speed but also from the distance from the gantry at which the movement is performed. The same movement performed near the gantry results in higher induced current levels as shown in figure 5 where are reported the results, in terms of induced currents, of the same arm opening movement performed at 22 cm and at 83 cm from the gantry.

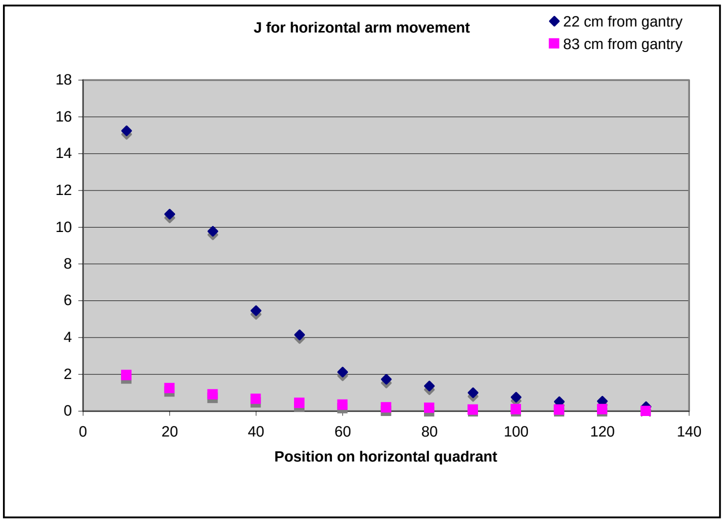


Fig. 5 - J at wrists for horizontal fast arm movement at 22 and 83 cm from the gantry

From data analisys results that currents induced by horizontal arm translation are higher than currents induced by vertical arm lifting.

Conclusions

For what concerns induced currents at head and trunk as effect of translational body movement in 3T static magnetic field, measurements and model based calculations have been performed on seven different patterns including diagonal, parallel and perpendicular to z axis trajectories divided into specific subpatterns: in each case the estimated values are well below the Directive 2004/40/EC 40 mA/m^2 basic restriction.
For what concerns standard arms movements we have calculated induced currents at wrists as effect of vertical lifting and of horizontal arm opening for fast and slow performances and for different distances from the scanner's isocentre. A specific restriction for current induced at wrists is not provided within Directive 2004/40/EC, if we consider the restriction applied at the moment for trunk and head, no exeedig should be reported.
Current induced at wrists are in general higher than currents induced ad head and trunk, this is due to the different speed; translational boby movement is in general slower than voluntary or accidental arm movement.
Induced currents for horizontal arm translation in a 3T static magnetic field are higher than currents induced as effect of vertical arm lifting within the same static magnetic field and distance from the isocentre.
The homogeneous coil man analytical model used to perform calculation represents a good simply way to perform in first approximation induced currents calculation.
For what concerns workers protection the proposed approach provides a simply and quite inexpensive method to assess induced currents. This method is based on a preliminary exhaustive investigation of the specific environment, interviews to the operators about standard movements during ordinary working activities, series of fast measurements performed within estabilished patterns and positions and subsequent evaluation of a dosimetric strategic parameter like induced currents.

This methodology can be applied for working exposure periodic assessment, requiring a relatively short time for measurement activities and therefore not interfering with the normal clinical activity; measurements in fact should be performed when clinical sequences are not active, for example before or after the regular daily clinical activity.

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