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INDUCED CURRENTS IN PATIENT HEART IN MRI: AN ASSESSMENT METHOD

Simona Valbonesi, Marina Barbiroli, Ermanno Papotti, Roberto Sghedoni, Matteo Tiberti, Andrea Vanore, Paolo Zanichelli

Consorzio Elettra 2000 – Via Celestini, 1 – Pontecchio Marconi – Italy – svalbonesi@fub.it
Bologna University - Electrical, Electronic and Information Engineering Department "Guglielmo Marconi" – Viale Risorgimento – Bologna - Italy – marina.barbiroli@unibo.it
University of Parma – Health Physics Department - Parma – Italy – ermanno.papotti@unipr.it
Prevention and Protection Department, Arcispedale Santa Maria Nuova – Reggio Emilia – Italy - Andrea.Vanore@asmn.re.it and Roberto.Sghedoni@asmn.re.it
ARPA Emilia Romagna – Reggio Emilia - pzanichelli@arpa.emr.it and mtiberti@arpa.emr.it

Abstract

This works focuses on the research of a model thought to evaluate currents induced within the heart, as a consequence of the exposure to static magnetic field and non sinusoidal low frequency magnetic field gradients produced by an MRI scanner. Such induced currents, when too high, could have negative effects on heart's electric conduction. Starting from a simplified modeling of the heart and making detailed measurements of static magnetic field and gradient field, we propose a mathematical model, for the evaluation of the induced currents.

Material and Methods

The model used to evaluate the density of induced current has been developed in such a way as to determine currents within three crucial points: the Sinoatrial Node (SAN), the Atrioventricular Node (AVN) and the Aortic Arch (AA).
Those specific points have been chosen for their peculiarity: Sinoatrial Node and Atrioventricular Node represent the two natural pacemakers, primary and secondary respectively. They regulate heart electrical functionality: possible external disturbances on these specific cells clusters can cause electric alterations compromising the organ functionality [1,2,3]. The choice to evaluate Aortic Arch current was due to the fact that the blood, in this specific part of the heart, reaches the maximum speed, so that induced currents can turn out to be high.
The other internal and external points of the myocardium are less important for potential temporary changes imputable to induced currents

The application of the model started from direct measurements of the static magnetic field in specific points; such survey was carried out on a tomograph, GE Healthcare Signa® MR750 3.0 T (FOV dimension 48 cm – Gradient Maximun Amplitude 50 mT/m – Gradient Slew Rate 200 T/m/s), used for medical imaging in the Neuroradiology Ward at Parma Ospedale Maggiore.

Simplified model of the heart

Considering the anatomic complexity of the heart, a simplification became necessary. First of all the heart was hypothesized being in a static situation: we would not take into account the cardiac cycle and consequently the systole/diastole sequence phases, but only the blood flowing within the heart chambers.
The cardiac cavities has been assimilated to four cylindrical ducts with a suitable radius; the blood flows within each duct without any internal resistance and vorticity, with a constant speed and a direction following the longitudinal axis of the cylinders. These ducts, parallel to each other, has been placed in such a way that they turn out vertical if we consider the coronal section of the human body and present a 135° inclination in respect to the vertical plane if we consider the sagittal section, so to reflect the real position of the heart. A further horizontal duct, which simulated the flowing of the blood through the Aortic Arch, has been added. The flow in this case has been considered horizontal.

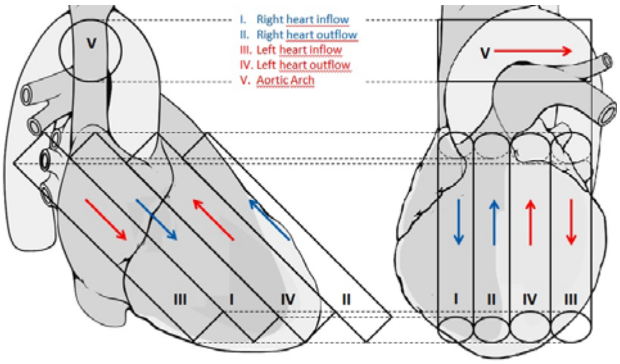

Fig.1 - Model cross section

Figure 1 shows the cross-section on the sagittal axis and on the coronal axis of the simplified model. The average speeds of the blood flowing through the specific valves and through the Aortic Arch has been taken into consideration for the calculation, while the vorticities had been ignored.

Mathematical model

Induced currents from static magnetic field evaluation

The mathematical model used for punctual evaluation of the static magnetic field induced current is based on the physical principle described by the Lorentz force:

$$F = q\ v \times B \qquad (1)$$

using Ohm's law local form, it is possible to get the following expression for the currents:

$$J = \sigma_s E = \sigma_s v \times B = \sigma_s\ v B \sin\alpha \qquad (2)$$

where σ_s is the blood conductivity, v the blood speed, B is the static magnetic field, and α is the angle between the speed vector and the static magnetic field direction.

In this way it is possible to derive the induced current density measuring the static magnetic field intensity within key points suitably located on a map of the heart. Knowing blood flow direction, speed and conductivity, it is possible to assess, through the application of (2), the induced current density for “selected points”.

Induced currents from non sinusoidal magnetic field gradients

In slowly varying magnetic fields gradients induced current is generated through two distinct ways:

a) magnetic field temporal variation produces a current J_{GR} linked to the dB/dt ratio;

b) the magnetic field gradient spatial variation due to the blood movement produced a current J_{BL}

To evaluate the component J_{GR} each duct has been assimilated to a R radius circular coil chained to a non sinusoidal magnetic field whose dB/dt ratio value is known. From induced electromotive force expression:

$$f.e.m = -\frac{d\Phi_B}{dt} \qquad (3)$$

is it possible to relate the induced current to the gradient field:

$$J_{GR}(R) = \frac{\sigma_s}{2} R \left| \frac{dB_{ave}}{dt} \right| \qquad (4)$$

The quantity σ_s is the electrical conductivity of the heart tissue which has been assumed equal to the electric conductivity of the blood, being the cardiac cavities mostly full of blood.

The mathematical model for J_{BL} evaluation is based on Faraday's Law and provides that the blood circulating in a specific section of the single cylindrical duct is treated as a constant radius R circular coil (with R equal to the cylinder radius) with homogeneous conductivity, moving with a constant speed v within the duct. Under these conditions, the magnetic flux can be written as:

$$\oint_L E.dl = -\frac{d}{dt}\int_S B.ds = -\frac{d\Phi_B}{dt} \qquad (5)$$

it follows that the induced current density can be expressed as a function of the duct radius by the formula:

$$J_{BL}(R) = \frac{\sigma_s}{2} R \left| \frac{dB}{dt} \right| = \frac{\sigma_s}{2} R \left| \frac{dB}{dx} \right| \left| \frac{dx}{dt} \right| = \frac{\sigma_s}{2} Rv \left| \frac{dB}{dx} \right| \sin\alpha \qquad (6)$$

where the term $\sin\alpha$ takes into account the inclination of the coils on the sagittal plane.

From a direct measure of the gradient field and a mathematical evaluation of dB/dt ratio it is possible to evaluate the J_{BL} component. Locally, the total induced current can be expressed as the vectorial sum of three terms [4]: $\vec{J}_{tot} = \vec{J}_S \pm \vec{J}_{GR} \pm \vec{J}_{BL}$ (7)

Measurements and currents assessment

Static magnetic field

The measurement campaign took place on May 21st 2012 on a magnetic resonance scanner, GE Healthcare Signa® MR750 3.0T, used for medical imaging in the Neuroradiology Ward at Parma Ospedale Maggiore.

Instantaneous measures of static magnetic fields have been carried out using a Metrolab THS7025 Hall effect probe.

In order to map the static magnetic field values a point grid, coherent to the model previously described, has been chosen (Figure 2). A wooden frame has been made out, with a precise report of the interesting spots in order to carry out exact measurements, particularly for what concerns the position of the Sinoatrial Node, the Atrioventricular Node and the Aortic Arch.

Such frame has been placed on a telescopic non-magnetic tripod. Measure campaign has been performed outside the normal clinic activity, in order to satisfy the unavoidable boundary condition which imposes, when measuring static fields, the absence of signals that can perturb the magnetic field, such as, radio-frequency field impulses or intense magnetic field gradients.

Fig. 2 - Frame

Measures has been taken at 100 cm,110 cm and 130 cm from the floor level to represent the position of the heart when the subject is respectively lying, sitting or standing. The value of the B field at the isocentre has been considered equal to 3.0 T as in the specifications given by the manufacturer and it was not measured.

The evaluation of the induced current density has been carried out for three specific key spots: SNA, AVN and AA, as shown in Figure 3. For this study we have taken into consideration static magnetic field measured placing the grid in the centre of the patient bed at different distances from the gantry (spots 2, 3, 4 in Figure 4) and in three other spots of interest placed around the bed (spots 5, 6, 7 in the same Figure 4). Points 5,6,7 are related to occupational exposures.

In addition to the seven spots, measures have been performed at the examination room entrance and in the computer workstations area used by the operators during clinical activity to set up sequences and to display the resulting images.

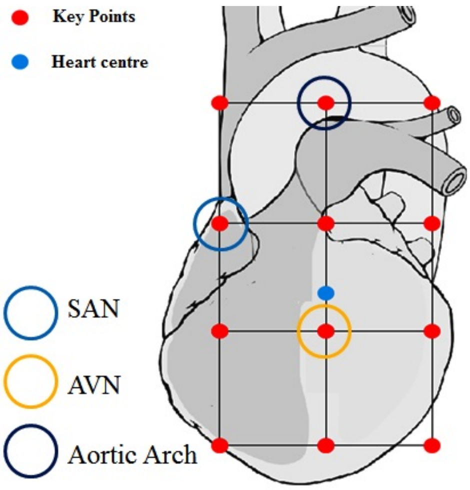

Fig. 3 - Key points

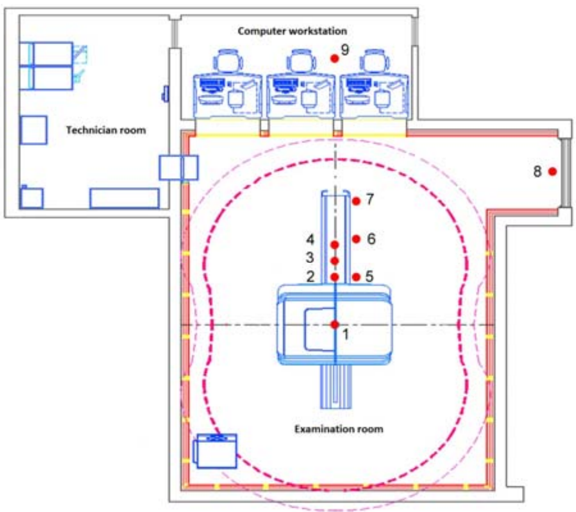

Fig. 4 - Selected spots

In order to calculate induced currents, the physiological parameters shown in Table 1 have been used in the model.

Table 1 - Physiological parameters used in the model

Parameter	**AA**	**SAN**	**AVN**
Blood speed [m/s]	0.52	0.50	0.50
Coductivity [S/m]	0.42	0.42	0.42
α angle	90°	135°	135°

The parameters choice is based on specific literature [5,6,7], in particular the average values are referred to a standard adult man adult man (174.5 cm/75 kg). The blood speed in the three sections has been considered as the average speed of the blood flowing through the specific cardiac valves and through the Aortic Arch, ignoring vorticities. The blood conductivity σ_s = 0.52 S/m derives from the specific literature.

Non sinusoidal gradient field

For gradient field assessment an instrumental chain composed by a portable meter Narda ELT 400 (a tool specifically designed to detect signals of magnetic field varying in time in a non-sinusoidal), coupled to a four channels LeCroy Wave Runner 6050 Oscilloscope has been used. The measurements have been performed, using the coil head, on a 3.0 T tomograph on which a Balanced FFE sequence repetition has been set . The signal has been acquaired for 50 s, the FOV (Field Of View) have been considered equal to 400 mm; those conditions are reported in literature as optimal for this kind of analysis [8]. Measurements have been performed at 110 cm from the floor for patient exposure assessment and at 130 cm for occupational exposures.

Table 2 - Sequence charactestics

Sequence	Balanced FFE
Tr	3.1 ms
Te	1.57 ms
Slice	5 mm
Central frequency	500 Hz

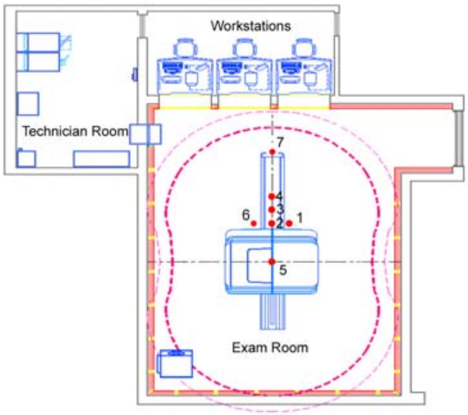

Fig. 5 - Key points

From an operating stand point, measurements have been performed within key point selected on the basis of information reported by healthcare workers on the position taken by patients (and operators) during clinical activity; points 2,3,4,5 in figure 5 represent patient exposure.
As a first step average value of magnetic induction within selected key points have been performed, using the oscilloscope it was possible to obtain voltage/time trend for the three channels, corresponding respectively to the three axes, x,y,z.
Magnetic induction B for the three axes have been derived from tension.

The overall B trend has been obtained by adding in quadrature the contribution of the three channels; dB/dt ratio evaluations have been carried out using sliding windows technique, setting a windows size t equal to 0.01 s. This value, chosen in the range 0.001- 0.1 s, has been considered as the most effective in terms of a proper evaluation of dB/dt ratio [9].

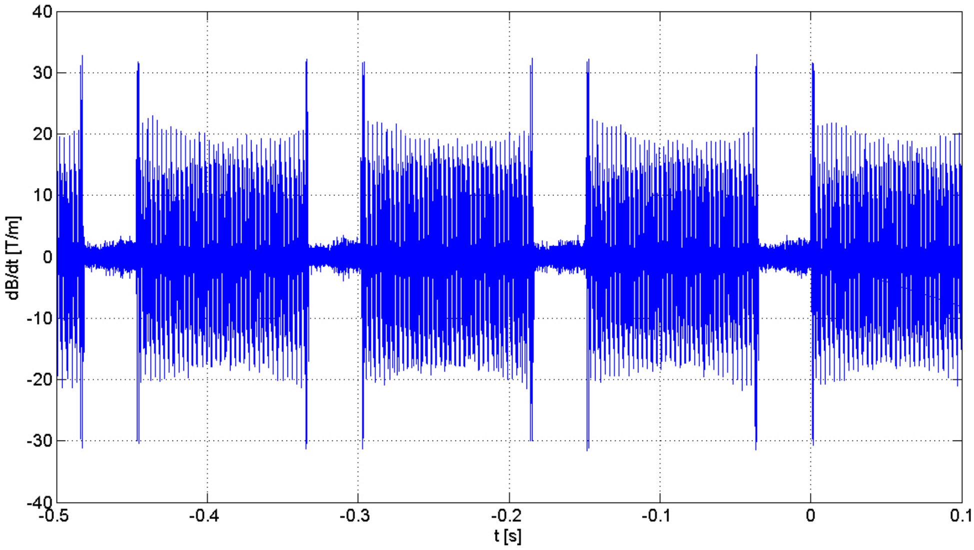

Fig.6 - dB/dt in balanced FFE sequence (isocentre)

In J_{BL} anc J_{GR} assessment blood speed has been considered as a constant not considering the effects attributable to vorticity. Some physiological parameters have been approximated in order to obtain constant radius cylindrical ducts. In particular the diameter of the pulmonary artery has been reduced from 0.30 to 0.20 cm, the same approximation was applied to the aortic semilunar valve to align it to the size of the left ventricule. The four pulmonary veins has been treated as a single vein whose diameter is the sum of the diameters of the four individual veins.

Results

For what concerns static magnetic field, Table 3 shows the induced currents evaluated using the mathematical model described above.

The evaluations carried out highlighted high induced current values on the crucial spots of the patient's heart, with specific markers which turned out to be almost seven times higher than the physiological ones. According to size, these data are coherent with Tenforde's [10,11] hypothesis in his numerical models. The highest values have been observed, as expected, in the Aortic Arch; within SAN and AVN spots the induced current turned out to be four times higher than the highest physiological value. Physiological values for currents produced by the heart are included in 10 – 100 mA/m^2 range.

Table 3 - Induced current density

Spot	AA *J [mA/ m²]*	SAN *J [mA/ m²]*	AVN *J [mA/ m²]*
1	655.20	441.24	441.24
2	390.94	232.83	210-62
3	140.65	80.60	78.54
4	48.92	30.44	27.36
5	95.22	58.39	72.21
6	8.21	5.24	6.18
7	2.71	1.73	1.93
8	0.03	0.02	0.02
9	0.03	0.02	0.02

For what concerns gradients fields, table 4 shows the maximum value of J_{GR} current calculated for positions 1 to 5 in Figure 5 and referred to each single duct :

Table 4 - induced J_{GR} currents in single ducts

Spot	$\lvert J_{GR}\rvert_{duct1}$ *mA/m²*	$\lvert J_{GR}\rvert_{duct2}$ *mA/m²*	$\lvert J_{GR}\rvert_{duct3}$ *mA/m²*	$\lvert J_{GR}\rvert_{duct4}$ *mA/m²*	$\lvert J_{GR}\rvert_{duct5}$ *mA/m²*
1	0.55	0.55	0.83	0.83	1.37
2	13.49	13.49	20.24	20.24	33.40
3	0.61	0.61	0.92	0.92	1.53
4	0.12	0.12	0.19	0.19	0.31
5	60.59	60.59	90.88	90.88	149.94

Induced currents J_{GR} are characterized by an extremely complex trend, currents are laminar, with peaks reaching, in isocentre for the AA, intensity equal to 150 mA/m^2, comparable with the highest physiological currents produced by the heart.
As for the current J_{BL} produced by blood movement within gradient field, the maximum induced currents calculated for single ducts in isocentre are reported in table 5

Table 5 - Induced J_{BL} currents in single ducts

Spot	$\lvert J_{BL}\rvert_{duct1}$ *mA/m²*	$\lvert J_{BL}\rvert_{duct2}$ *mA/m²*	$\lvert J_{BL}\rvert_{duct3}$ *mA/m²*	$\lvert J_{BL}\rvert_{duct4}$ *mA/m²*	$\lvert J_{BL}\rvert_{duct5}$ *mA/m²*
5	$1.14 .10^{-4}$	$1.19 .10^{-4}$	$1.71 .10^{-4}$	$1.80 .10^{-4}$	$2.97 .10^{-4}$

Evaluated J_{BL} currents are negligible for the fact that heart dimension is small so the gradient field spatial variation is minimum.

Conclusions

In the matter of a 3.0 T static magnetic field, from the analisis of experimental data emerges that the levels of induced current in patient's heart can be extremely high, up seven times higher than physiological levels, in particular within aortic Arch Area.
This value resulted to be much higher than the physiological ones but lower than the minimum value for ventricular extrasystoles excitation (800 mA/m^2) and three time lower than the

minimum threshold triggering ventricular fibrillation (2000 mA/m^2)

The presence of currents so intense could be the reason behind effects similar to the arrhythmia described by Shah [12], concerning patients undergoing to magnetic resonance examination with 9.4 T tomographs.

Regarding gradient field from data analysis came out that J_{BL} current can be considered negligible, while the maximum value for J_{GR} current is of the order of 150 mA/m^2, comparable with the endogenous currents maximum value.

In other position outside isocentre, the all the currents are inferior.

It is still unclear whether these surface currents present in SAN and AVN are able to induce disturbances in pacemaker cells action potentials or additional transmembrane currents causing damage in cardiac myocytes. This question will be the starting point for the ongoing study continuation.

Anyway, in the light of these results, preliminary to the examination, it could become necessary to give particular attention to patients who have myocardium deficits or pathologies in the electrical conduct system lying on atrial and ventricular areas. Anyhow it should be emphasized that these potential effects, whose clinical meaning is still unclear, should be considered not connected to pathological conditions.

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