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MRI induced heating of pacemaker leads: effect of temperature probe positioning and pacemaker placement on lead tip heating and local SAR

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Abstract— **The radio frequency field used in Magnetic Resonance Imaging (MRI) procedures leads to temperature and local absorption rate (SAR) increase for patients with implanted pacemakers (PM). In this work a methodological approach for temperature and SAR measurements using fluoroptic probes is presented. Experimental measures show how the position of temperature probes affects the temperature and SAR value measured at the lead tip. The transversal contact between the active portion of the probe and the lead tip is the configuration associated with the highest values for temperature and SAR, whereas other configurations may lead to an underestimation close to 11% and 70% for temperature and SAR, respectively. In addition measurements were performed on a human-shaped phantom inside a real MRI system, in order to investigate the effect of the PM placement and of the lead geometry on heating and local SAR.**

I. INTRODUCTION

THE presence of a metallic implants, such as a cardiac pacemaker (PM), are currently considered a strong contraindication to MRI [1]-[4]. The presence of linear conductive structures (e.g. PM leads) may produce an increase in power deposition around the wire or the catheter [5]-[7]. This increased local absorption rate (SAR) is potentially harmful to the patient: an excessive temperature growth may bring living tissues to necrosis and then to death.

The most direct way to measure the SAR deposition along the wire is by using a temperature probe. The use of fluoroptic thermometry to measure temperature has become the "state-of-the-art" and is the industry standard in this field [8,9]. When the investigation involved small objects and temperature gradients rapidly changing in space and time, it seems clear to define a standard protocol for probes positioning, to minimize the error.

In most of the publications dealing with heating of conductive structure during MRI, the generated heat is confined in close proximity to the lead tip, but the temperature increases appear significantly different, even in case when the experimental set-ups appears similar [7],[10]-[13]. The relative positioning of the temperature probe and lead tip may significantly affect the measure and can explain, at least partially, such an inconsistency in results.

The aim of this paper is first to identify the optimal positioning of fluoroptic probes to measure the maximum heating of the tip of a PM lead. Then, we used these results to perform temperature measurements in a real MRI system, in order to investigate the effect of the placement of the PM and of the lead geometry.

II. MATERIALS AND METHODS

A. Probes positioning

A PVC box (28 × 20 × 26 cm) was filled with a gelled saline solution. A grid was submerged in the phantom gel to support the implant and maintain consistent separation distances between the implant, phantom material surface and temperature probes. The phantom material gel is composed of the following materials in percentages by weight: 2% hydroxy-ethyl-cellulose (*HEC*), 98% water, and 0.36% sodium chloride. It produces a gelled material with a conductivity of 0.59 Sm^{-1}, a permittivity of 79 at 64 MHz, and a heat capacity of 4178.3 J $Kg^{-1}K^{-1}$ [14].

SAR and temperature measurements were performed on the tip of a 62 cm-long monopolar lead (S80TM, *Sorin Biomedica CRM*, Italy) which was not connected to a pacemaker can. A RF signal was injected into the lead tip by using a coaxial cable, connected to the lead. The outer conductor (signal ground) was connected to a 1x20x10 mm silver plate located on a side of the PVC box, so that the current flows in the gel from the lead tip to the plate. The inner conductor was connected to the lead. The lead was arranged in the phantom material 5 cm below the tissue phantom top surface, simulating an implant in the human body. The distance between the silver plate and the lead tip was set at 7 cm.

Temperature was measured using a fluoroptic thermometer (*Luxtron*, Model 3100, USA), with resolution of 0.1°C, operating at 8 samples per second. Three sinusoidal excitations were applied: 25, 64 and 128 MHz,

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which nearly correspond to the RF field used in 0.5, 1.5, 3 T MRI system. Signals were generated by a RF generator (*Rhode & Schwartz* - SMT 06), and then amplified (*RFPA* – RF 06100-6, France); a power meter (*Rhode & Schwartz NRT* – Z14) was connected to the output of the amplifier, to measure the average power and the reflection coefficient. The net input power was held constant for all measurements. Although this configuration does not establish a realistic and calibrated setup it provides a practical method to generate constant lead heating for relative temperature measurements.

Four configurations were studied: transversal contact between the side of the probe and the circular surface of the lead tip (Fig. 2): transversal contact between the tip of the probe and the side surface of the electrode (tip-to-side); axial contact between the tip of the probe and the circular surface of the lead tip (tip-to-tip) and axial contact between the tip of the probe and the side surface of the electrode (side-to-side).

B. Temperature measurement and SAR calculation

The effect of the position of the probes on the temperature measure was expressed as the percentage error respect to the configuration giving the maximum temperature increase:

$$T\ \%\ error = 100*(\ T_{probe} - T_{max}\ )\ /\ T_{max}$$

where T_{probe} is the temperature measured by the probes in different configurations and T_{max} the maximum of these values. Local SAR was estimated as the slope (dT/dt) of the line that best fits the initial temperature increase. This estimation was assumed valid when the Pearson coefficient r^2 was grater than 0.98 [15]. The underestimation in SAR measurement due to the different contact configurations was expressed in terms of percentage error, respect to maximum value of SAR:

$$SAR\ \%\ error = 100*(SAR_{probe} - SAR_{max})\ /\ SAR_{max}$$

where SAR_{probe} is the SAR measured by the probes in different configurations and SAR_{max} the maximum of these values.

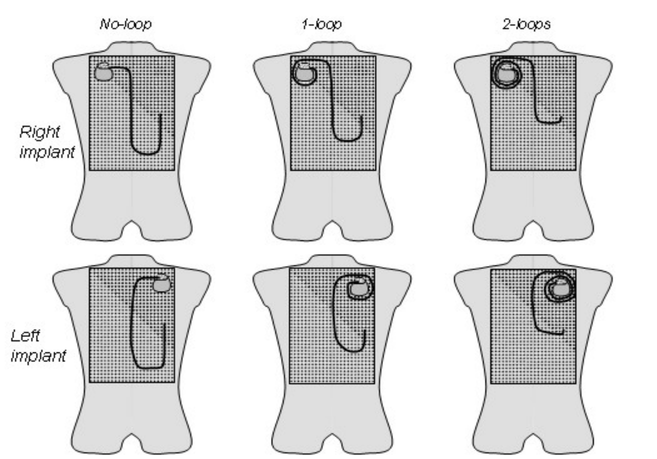

Fig. 1. Sketches of the six implant configurations tested in a real MRI using the human-shaped phantom. No-loop, 1-loop and 2-loops for both right and left pectoral implant.

C. Human-Shaped Phantom

Experiments in real MRI scanning system were performed using a human-shaped torso simulator realized at the Dept. of Technology and Health of the National Institute of Health in Rome. The simulator consists of a torso-shaped transparent PVC phantom of the size of a 70 kg male. Internal volume of the torso is 32 liter [14]. A PVC grid is mounted inside the torso to support the PM, the PM lead, and the temperature probes. The torso was filled with the same gel as described above.

D. Implant configurations and experimental protocols

The actual lead geometry and PM placement can vary from patient to patient. The PM can be located in the left or right pectoral region. Since the length of the lead may not fit the patient anatomy and size, the exceeded length is usually wrapped near or around the PM. In the experiments on the human-shaped torso simulator, the geometry of the implant reproduced left and right PM placements. For each implant, three lead paths have been tested (Fig. 1): without lead loop around the PM (no-loop configuration) and with the lead forming one or two loops around the PM (1-loop configuration and 2-loops configuration, respectively). For each lead path, the length and the position of the linear section of the lead as well as the lead tip localization were kept constant. Only the PM was moved from the left to the right pectoral location. Experiments were performed on a 1.5 T *Siemens Magnetom Sonata Maestro Class* scanner. The main parameters of the sequences used are summarized in Table I. The MRI parameters (TR, TE and Flip Angle) were adjusted to reach a WB-SAR of 2 W/Kg, estimated by the scanner.

III. RESULTS

A. Probes positioning

The position of the probe affects significantly the measure: transversal contact between the side of the probe and the circular surface of the lead tip is associated with the highest temperature increase (see Fig. 2 “Reference: transversal contact” which leads to maximum T and SAR). An underestimation of about 10% at 25 and 64 MHz, and of about 3% at 128 MHz was obtained. The error associated to the estimation of local SAR at the lead tip showed a similar behavior: transversal contact between the side of the probe and the circular surface of the lead tip is the configuration associated with the highest SAR.

The SAR underestimation associated to the other probe configurations is reported in Fig. 2, upper panel. In the worst case, an underestimation down to 70% was observed. The effect of the frequency of the excitation on SAR estimation is less marked than for the temperature measurements.

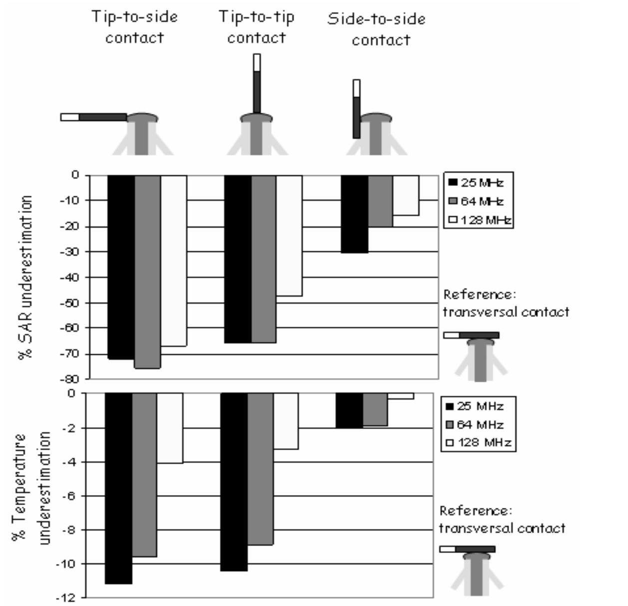

Fig. 2. Percentage errors of SAR and temperature increase, respect to probe giving the highest temperature and SAR (i.e. transversal contact).

B. *Human-shaped phantom*

The temperature increase and local SAR values for the experiments using a real MRI scanner are reported in Table II. As for the clinical sequences, the gradient echo did not induce detectable temperature increase in all the configurations tested. Sequences with relatively high whole body SAR, led to a temperature increase up to 12.3 °C. For left pectoral PMs the lead area appears to be the major factor relevant for the heating. A high implant area (no loop) showed always a higher temperature increase than the 1-loop and 2-loops configurations. Surprisingly, in right pectoral implants, the lead path seems to play the major role: no-loop configurations showed always a temperature increases significantly greater then the 1- and 2-loops configurations.

TABLE I

Siemens sequence name	Sequence type	TR (ms)	TE (ms)	Flip Angle	Length (s)
FLASH (short)	Spoiled gradient echo	960	40	20	53
FLASH (long)	Spoiled gradient echo	960	40	20	417
TrueFISP(short)	Steady state free process	3.78	1.89	54	38
TrueFISP (long)	Steady state free process	3.78	1.89	54	379
HASTE (short)	Single shot (turbo fast) spin echo	1190	83	150	42
HASTE (long)	Single shot (turbo fast) spin echo	1190	83	150	402

Main parameters of the MRI clinical sequences used during the human-shaped phantom experiments.

In addition, the temperature increases were greater then those of the left pectoral implants. In both configurations (left and right) the temperature increase and local SAR were proportional to the whole body SAR reported by the scanner. The comparison between short and long sequences showed that the major temperature increase occurred within the first minute. Experiments were repeated changing other MRI parameters such as the center of view (chest, abdomen and pelvis) and the field of view (200, 300 and 400 mm) without significant changes in the heating.

TABLE II

	Right pectoral implant			SAR* (W/kg)
	No loop	1-loop	2-loops	
FLASH (short)	<0.10 (---)	<0.10 (---)	<0.10 (---)	0.02
FLASH (long)	<0.10 (---)	<0.10 (---)	<0.10 (---)	0.02
TrueFISP (short)	8.17 (2192)	1.93 (---)	0.62 (---)	1.70
TrueFISP (long)	12.26 (2375)	2.50 (536)	0.96 (---)	1.70
HASTE (short)	9.41 (2871)	2.09 (643)	0.74 (365)	1.94
HASTE (long)	11.91 (2345)	2.68 (641)	1.01 (---)	1.72

	Left pectoral implant			SAR* (W/kg)
	No loop	1-loop	2-loops	
FLASH (short)	0.10 (---)	<0.10 (---)	<0.10 (---)	0.02
FLASH (long)	0.10 (---)	<0.10 (---)	<0.10 (---)	0.02
TrueFISP (short)	4.20 (1055)	0.65 (---)	0.40 (---)	1.72
TrueFISP (long)	6.17 (1255)	0.97 (---)	0.60 (---)	1.70
HASTE (short)	6.92 (2214)	1.03 (281)	0.72 (291)	1.96
HASTE (long)	6.35 (1362)	0.92 (---)	0.68 (---)	1.70

Lead tip temperature increase (°C) and SAR (W/kg) of human-shaped phantom experiments. Average whole body SAR calculated by the scanner is also reported. *SAR: average whole body specific absorption rate computed by the scanner. (---) SAR not estimable, due to low temperature increase

IV. Discussions

Fluoroptic thermometry has become the most popular method to measure heating of metallic objects due to MRI RF exposure. However, some methodological issues have found limited attention so far. Among them, the positioning of the probes as well as the estimation of the error in temperature and SAR measurement need to be investigated and standardized. Thin linear structure such as PM leads may generate temperature gradients which can not be neglected respect to the physical dimension of the probes. In our experiments on a real model of a PM lead we found that the positioning of fluoroptic probes strongly affects temperature and SAR values. Most probe positions lead to a systematic underestimation of the real value of local temperature and SAR. We found that a transversal contact with the lead tip always gives the highest temperature and SAR measures. Assuming this configuration as reference, the underestimation related to other configurations may be as high as 11% for temperature and 70% for SAR, at 25 and 64 MHz, while the measure error seems to decrease for 128 MHz. The different contact configurations between fluoroptic probes and the lead tip may explain, at least partially, the large variability of previous studies [6],[10],[11],[13]. Other types of lead tips might even show larger underestimations for temperature and SAR values. The measurements on a human-shaped phantom showed how the lead geometry significantly affects the amount of induced heating. When PMs are implanted in the left pectoral region, the implant area, i.e. the area formed by the lead, the PM can and a straight line connecting the tip to the PM, plays a significant role on the lead tip heating. Right pectoral implanted PMs cover smaller areas than left pectoral ones, but the temperature increase observed were higher, suggesting that the coupling to the electric field contributes to the heating. Resonance phenomena in various kinds of linear metallic leads and wires has been hypothesized by various groups [7,16]. During our experiments we have not seen any resonance phenomena.

V. CONCLUSIONS

Experimental measures performed on the gelled-box phantom allowed to identify the best contact configuration for temperature and SAR measurements: the transversal contact between the active portion of the fluoroptic probe and the lead tip leads to the highest temperature and SAR values. Other contact configuration may cause an underestimation of about 11% for temperature measurements and about 70% for SAR measurements. Experimental measures on the human-shaped phantom showed that the MRI induced electrode tip heating strongly depends on the implant geometry. Implants with relatively large lead area (250-300 cm^2) exposed to MRI scans with a whole body SAR of about 1 W/kg, may experience temperature increase at the lead tip up to 12°C and local SAR up to 3000 W/kg.

DISCLAIMER

The opinions and conclusions stated in this paper are those of the authors and do not represent the official position of the Department of Health and Human Services. The mention of commercial products, their sources, or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products by the Department of Health and Human Services.

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