Detailing RF Heating Induced by Coronary Stents at 7.0T Using Numerical EMF Simulations and Heating Experiments

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Target audience: Basic researchers and clinical scientists interested in MR safety aspects of scanning patients/volunteers equipped with intracoronary stents at ultrahigh fields (UHF).

Purpose: The sensitivity gain and signal-to-noise ratio (SNR) gain inherent to UHF MR (B_0≥7.0Tesla) holds the promise to enhance spatial and temporal resolution in MR imaging [1-2]. Such improvements could fuel a number of cardiovascular MR (CMR) applications. However, intracoronary stents commonly used in percutaneous interventions are currently considered to be contraindications for MR at B_0≥7.0Tesla. The antenna effect due to the presence of an electrically conductive implant in combination with RF fields could induce local heating which exceeds the safety limits given by the IEC guidelines. For all these reasons this work examines RF induced heating of a copper tube and of a coronary stent. For this purpose numerical electro-magnetic field (EMF) simulations, RF heating experiments and MR thermometry (MRTh) are performed at 7.0T.

Methods: EMF simulations were conducted to investigate E-field coupling with a copper tube and two non ferromagnetic coronary stent configurations (PRO-Kinetic Energy Cobalt Chromium Coronary Stent System, Biotronik, Bülach, CH product #360553 l_1=40mm, d_1=4mm; product #360541 l_2=27mm, d_2=4mm). An in-vivo situation was simulated using a transceiver array tailored for cardiac MR at 7T [3] together with the human voxel model "Duke" of the virtual family [4]. For this setup SAR distribution was assessed w/wo a copper tube mimicking an intracoronary stent. For RF heating experiments an eight rung highpass birdcage RF coil was used [5]. MRTh applying the proton resonance frequency method (PRF) was performed [6]. A fiber optics system (OpSens, Quebec, CA) was utilized to validate the MRTh temperature maps. RF Heating was performed for 60 minutes using an input power of 198W. A cylindrical agarose phantom was used to emulate the electrical properties of human myocardium (ε=78, σ=1.2S/m).

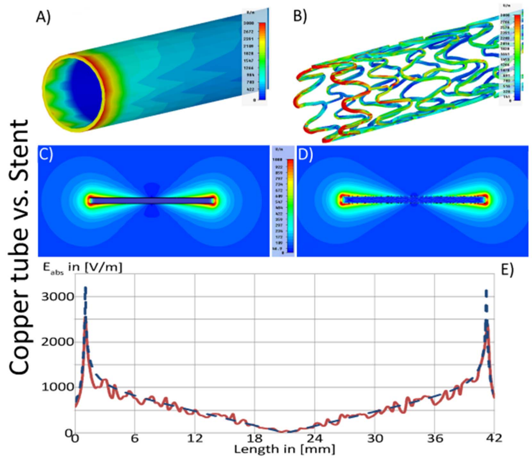
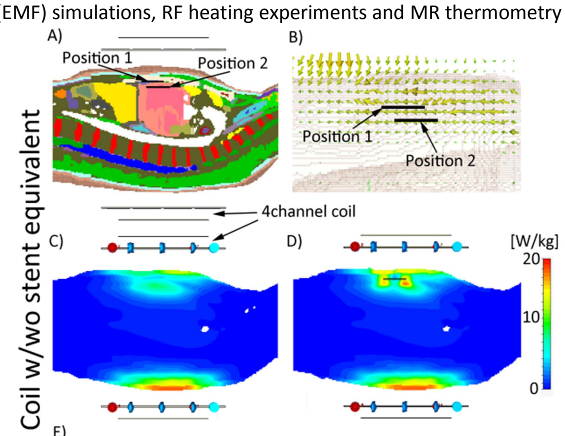


Figure 1 EMF simulations of a copper tube and a stent. A uniform E-field was generated along the main axis of the devices using an electric dipole configuration for transmission. A,B) E-field at the tips of the devices. C,D) Distribution of the E-field along the main axis of the devices. E) E-field magnitude at a distance of 100µm from the surface of the copper tube (blue dotted line), and the stent (red solid line).

Results: Our EMF simulations showed that a copper tube provides a reasonable approximation of a coronary stent since its antenna effect is similar to that of a coronary stent (Fig. 1 A-D). The weaving network structure of the stent induces minor peaks in the E-field for regions very close to the stent as demonstrated in Fig. 1E. However these local E-field peaks never exceeded $|\vec{E}|_{max}$ 2560V/m (stent) at the tips, Fig. 1E. For the simulations using the human voxel model the copper tube was positioned at two locations which showed $|\vec{E}|_{max}$ 310V/m for the 4 channel transceiver array (Fig. 1F-G). During the presence of the copper tube no increase in local SAR_{10g} above the safety limits defined by the IEC guidelines [7] was found for arbitrary phase settings (Fig. 1 H-I) including a B1 optimized phase setting (Tab. I). For RF heating, the birdcage coil (Fig. 3A) was used to exceed the IEC SAR limits by a factor of ~3. For the reference phantom (Fig. 3B) a maximum temperature increase of ΔT=27K was found in the absence of a conductive device. An extra temperature increase of ΔT=3±2K was obtained for the presence of a copper tube in the agarose phantom. For a coronary stent the temperature difference maps are shown for a l_2= 27 mm stent (Fig. 3C) and a l_1=40mm stent (Fig. 3D). The extra temperature increase due to the presence of the stent was found to be ΔT=3±2K for l_2=27mm and ΔT=2±2K for l_1=40mm.



Phase setting	Max Local SAR_{10g} [W/kg]		
	Reference	Position 1	Position 2
Min SAR	6.6	6.9	6.9
Max SAR	18.0	18.3	18.3
B1-Shim Heart	12.0	16.8	15.3

Figure 2 A) Positioning of the cardiac coil together with the locations of the copper tubes in the human voxel model "Duke". B) E-field distribution at the positions for the conductive devices. C) Local SAR_{10g} distribution of the coil without the device. D) Local SAR_{10g} distribution of the coil with the device in Position 1. E) Calculated max local SAR_{10g} values for an input power of 30W, with (Position 1, Position 2) and without (Reference) the device. Min, max and B_1-optimized phase settings are applied. Please note that for every configuration the values are not exceeding 20W/kg local SAR_{10g} as defined by IEC guidelines.

Discussion: The coronary stent examined here showed an RF heating behavior similar to that of a copper tube with the same geometry. Our results show an overall agreement between RF heating induced temperature changes derived from EMF simulations versus temperature maps deduced from MRTh at 7.0T and the fiber optic system. Our results demonstrate that, the electric field distribution of the RF coil hardware used together with the position and orientation of the stent is of profound relevance for RF induced heating. The simulation results presented here, can be potentially utilized for safe multichannel transmission together with the use of virtual observation points [8-9].

Conclusion: Our EMF simulations and phantom studies suggest that if IEC guidelines for local SAR_{10g} values are strictly followed, the extra RF heating, induced in myocardial tissue due to the presence of the stent, may not be significant versus the baseline heating induced by a cardiac optimized transmit RF coil at 7.0T.

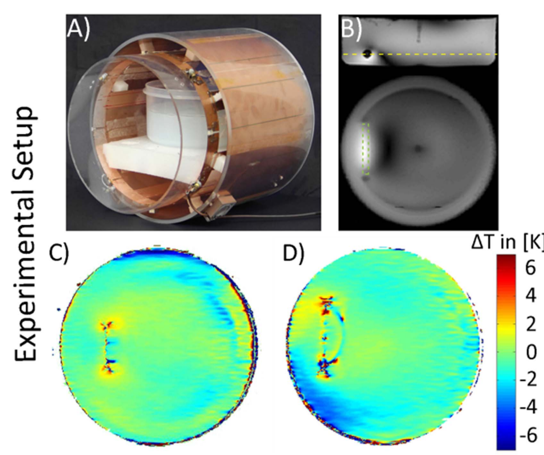


Figure 3 Experimental setup and results from the RF heating experiments. A-B) Birdcage RF coil used for RF heating. C-D) Difference of the temperature maps obtained without and with a l_1=27mm (C) and a l_2=40mm (D) stent after 60 min of RF heating using an input power of 198 W. Two hotspots are present near the tips of the stents with an induced temperature increase of ΔT=3±2K (C) and ΔT=2±2K (D).

References: [1] Niendorf T, et al., Eur Radiol 2010 [2] von Knobelsdorff-Brenkenhoff F and Schulz-Menger J, JMRI, 2012 [3] Winter L, et al.,Eur Radiol, 2012 [4] Christ A, et al., Phys Med Biol, 2010 [5] Santoro, et al., PLOS ONE, 2012 [6] Wonneberger U, et al., MRM, 2010 [7] IEC 60601-2-33, 2010 [8] Eichfelder G and Gebhardt M, MRM, 2011 [9] Eryaman Y, et al., MRM, 2011