Measuring RF-Induced Currents inside Implants: Impact of Device Configuration on MRI Safety of Cardiac Pacemaker Leads

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Introduction: Radiofrequency (RF)-related heating of pacemaker leads in MRI is a serious concern, which, in conjunction with additional factors, currently prohibits routine MR imaging of pacemaker patients. It has been proposed that such heating is a direct result of electric currents inside the implant, which are caused by MRI-related eddy currents in the surrounding medium. These electric currents are held directly responsible for induced heating at high resistance locations within the circuit, such as, for example, the tip-to-tissue interface of cardiac pacemaker leads. The goal of this study is to better understand MRI heating mechanisms through the development of a technique for direct measurement of the electric current intensity inside the implant. To this end, a method for precise and at the same time fast and reproducible measurements of the RF-heating potential of cardiac pacemaker systems in various configurations was envisioned to render the examination of many systems and configurations possible. The implant configuration has been shown to be an important factor in the amount of induced heating. However, this relationship is still poorly understood, possibly because temperature measurements with fluoroptic probes are currently the gold standard for investigations in the field of RF heating in MRI, although this method is not only very time consuming, but also particularly vulnerable to positioning errors of the probes [1].

Methods: A custom pacemaker lead based on a commercially available design was built that allows for direct measurement of RF-induced currents inside the implant. The lead was equipped with a sensor at the lead tip based on the design of a probe for electric field measurements in MRI which has recently been established by our group [2]. This approach enables precise and reasonably fast investigations of MRI-related heating effects in various implant configurations. Because the output of the measurement amplifier is expected to be roughly proportional to the electric current intensity in the intended working range and because the sensor was placed directly behind the lead tip, this measurement system can be used to quantify the current flow into tissue. According to electric theory, a quadratic relationship between the current intensity measurements inside the lead and the temperature increase at the lead tip was expected (I^2 proportional to ΔT), which enables the calculation of absolute lead tip heating values from the current intensity measurements if the specifics of lead tip and surrounding medium are taken into account. Following calibration of the current sensor, an extensive set of experiments in a head and torso phantom filled with a gelled saline was performed to investigate the impact of the pacemaker device position (standard Biotronik Stratos pacemaker) and lead path on RF heating. The relationship between a total of 720 configurations and the induced current intensity was investigated in a 1.5T Siemens Avanto MRI scanner, covering all likely configurations for cardiac pacemakers implanted in the pectoral region, as determined from several X-ray photographs (Fig. 1). To this end, a short TrueFISP sequence (SAR 2.8W/kg, total acquisition time 4.9s) was employed. Heating values after 5 minutes of scanning were calculated using the current intensity values and the equation from the calibration procedure.

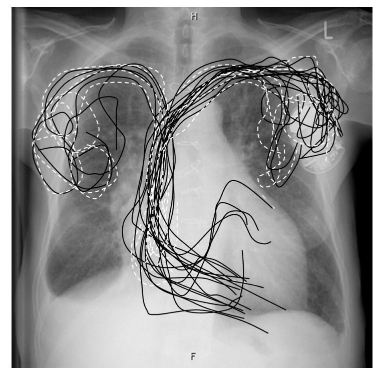

Fig. 1: Coronal plane of pacemaker lead pathways in the human body extracted from 20 size-normalized thoracic X-ray photographs of pacemaker patients. The case positions for the pacemaker device in the left and right pectoral region were determined separately.

Results: The quadratic function from electric theory (ΔT proportional to I^2) fit well with the calibration data ($R2=0.9997$). With the pacemaker device and lead path in numerous configurations, the highest current intensity induced during MRI corresponded to a ΔT of 68.5°C, while the lowest value corresponded to <0.1°C. Lead tip heating strongly depended on the combination of device position and lead path. No device position was found which was associated with only high or low induced currents. Fig. 2 gives a summary of the results focussing on the lead pathway in the coronal plane for three device positions in the right pectoral region.

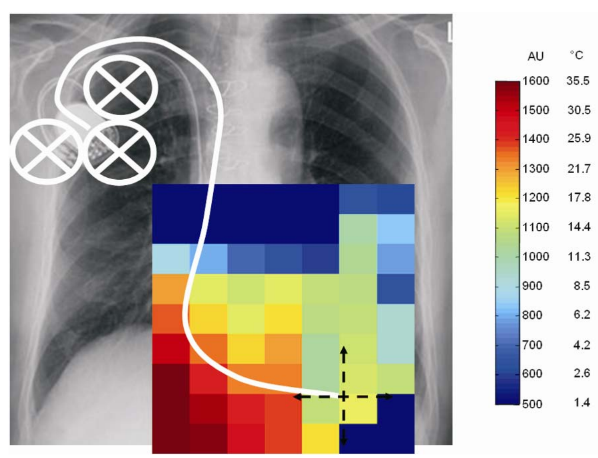

Fig. 2: Pacemaker lead tip heating of a single chamber system dependent on the device position and lead path. Three device positions in the right pectoral region (white crossed circles) are representatively shown. The lead paths were chosen to cover the entire predetermined approximate cardiac volume in all three directions. The MRI-related current intensity inside the implant (in arbitrary units, AU) was determined in each configuration and then converted to lead tip heating values assuming 5 minutes of scanning (in °C). Maximum respective heating values in this set of experiments are given as a function of lead tip position/path in the coronal plane.

Conclusion: The potential of MRI to induce RF-related heating in cardiac pacemaker systems was investigated through the measurement of the intensity of the electric currents induced inside the implant. This method was revealed to be a robust measurement technique for MR safety investigations, which, because it is both fast and precise, yields major benefits as compared to fluoroptic temperature measurements.

The position and configuration of a cardiac pacemaker system is crucial to the amount of heating that is generated. In this study, many different probable configurations were examined, helping to better explain why severe incidents sometimes, but not always, occur when performing MR imaging of pacemaker patients.

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