THE ROLE OF EDDY CURRENTS IN EPI THERMOMETRY FOR TRANSCRANIAL MR-GUIDED FOCUSED ULTRASOUND

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Introduction: Recent clinical studies have demonstrated the feasibility of transcranial magnetic resonance guided focused ultrasound (MRgFUS) surgery for brain tumors and functional neurosurgery [1]. The MRgFUS system used in these studies features a complex transducer setup (Fig.1) that integrates a hemispheric phased array transducer into a commercial MR system [2]. During sonication, single-plane temperature maps at the location of the thermal hot spot are extracted from fast spoiled gradient echo (SPGR) phase images [3] every three to four seconds. For accurate geometrical and temporal mapping of the thermal hot spot, multi-slice temperature maps are desirable. In this study, echo planar imaging (EPI) for fast image tracking and MR thermometry [4] in the presence of a transcranial focused ultrasound setup was explored. However, eddy currents induced in the ground plane of the transducer setup [5] may cause significant spatial distortions in the EPI images. These distortions can make precise temperature mapping during transcranial MRgFUS unfeasible. In this work, alternative ground plane segmentation patterns are suggested to reduce the eddy current artifacts. Gradient field strength and non-linearity are predicted by finite element simulation and verified by EPI scans of a spherical phantom. To mimic different transducer ground plane segmentation patterns, the phantom was wrapped with thin copper sheets covering the anterior hemisphere.

Fig.1: The phased array transducer setup with a dedicated 8-channel phased array receive coil, a gel phantom mounted inside the hemisphere and water lines for circulating water through the transducer.

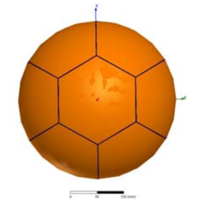

Fig.2: A schematic of the ground plane which forms the inside of the transducer hemisphere. It is made of copper segments that are connected by soldered joints.

Materials and Methods: The clinical prototype of the Insightec ExAblate 4000 platform (Insightec, Tirat Carmel, Israel) contains a 1024-phased array transducer ring operating at 660 kHz. The transducer setup is interfaced to a GE Signa Excite II 3.0T scanner (General Electric, Milwaukee, USA) [2]. The integrated body coil is used for RF transmit and either an 8-channel phased array torso coil or a dedicated 8-channel phased-array coil (Rapid, Germany) integrated into the FUS transducer is used as the receive coil. The transducer ground plane consists of a thin copper layer, partitioned in a set of individual segments (7 in total) (Fig.2). The segments are connected to a common ground. During image acquisition, the acoustic focus of the transducer is positioned inside the field of view (FOV) of image acquisition at the iso-center of the gradient system. Eddy currents induced in the ground plane (caused by switching of the gradients) were simulated using finite element simulations (Maxwell3D, Ansys, Canonsburg, USA). The simulation model consisted of the y-gradient of the Signa Excite system and a 0.25mm thick 30cm diameter copper hemisphere located at the iso-center of the gradient coil. For reference, the finite element evaluation was performed with a magneto-static solver to replicate the situation where no copper ground plane is present (a). The eddy current simulation was performed in frequency domain considering the induced current density in the ground plane. The simulated field response calculation includes the field degradation due to eddy currents. The maximum field strengths were extracted for the reference (a), full copper hemisphere (b), segmented hemisphere similar to the real setup (c), star pattern (d), and ring pattern (e) scenarios. (d) and (e) were combined into a star-ring pattern (f) to consider induced currents for both gradient axes. A frequency of 700Hz is used for the skin depth calculation of the occurring eddy current effect, which is the maximum frequency component in the considered EPI gradient echo imaging sequence (TE/TR=13.6/320ms,144x144 imaging matrix, flip angle=35°, slice thickness/spacing=3/0mm, 32cm FOV). The EPI protocol was used in the experimental validation and cases (a), (c) and the combined star-ring pattern with 54 segments in total (f) are verified. To mimic the segmented ground planes, 0.25mm thick copper sheets were cut to create a 7 segment (c) and a 54 segment (f) copper hemisphere. Each hemisphere was secured to the anterior end of the spherical phantom. All imaging was performed using the body coil.

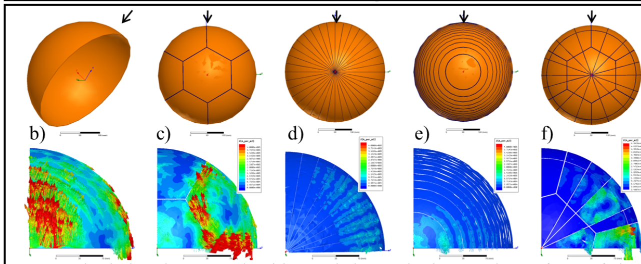

Fig.3: The induced current densities scaled to 40kA/m² on the surfaces of the electrode ground planes. The arrows indicate the point of view. Only ¼ of the model is shown due to symmetry boundaries within the finite element simulations.

Results: Fig.3 shows the current densities induced on the surface of the copper hemisphere for each simulated scenario. Due to Lenz' law, the induced currents opposed the desired gradient excitation pattern and resulted in decreased gradient field strengths (Fig.4). In the case of an un-segmented hemisphere (b), the hemisphere acted like a shield where nearly zero field strength was expected inside a volume of interest of a 20cm sphere. With a segmentation into seven parts (c), the field strength decreased by 37.6% and strong field non-linearity in the computed field map was observed. The star pattern in (d) resulted in a field reduction of 1.4%, whereas with the ring pattern a reduction of only 0.6% was calculated. In f), the gradient field strength was decreased by 5.6%. These results clearly demonstrate that with increased number of segments, the current flow on the surface of the copper hemisphere can be interrupted. In this simulation, where only the y-gradient was considered, optimal gradient field strengths were achieved with the ring pattern (e). Fig.5 shows acquired sagittal EPI images. With the 7-segment pattern that is similar to the currently used intracranial FUS setup (c), a SNR of 22.95 and strong imaging artifacts close to the copper hemisphere are visible in the magnitude images. With the 54-segment pattern (f), image distortions only occur at the proximity of the phantom and a SNR of 27.40 is achieved. For comparison, the reference EPI image has a SNR of 29.85 (a).

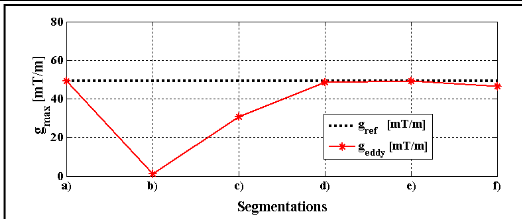

Fig.4: The maximum gradient strength calculated on a 20cm sphere is plotted for all segmentation options (g_{ref}=49.44mT/m).

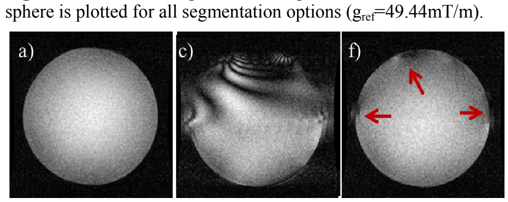

Fig.5: Sagittal EPI images of a spherical phantom where (a) depicts phantom wrapped with a 0.25mm copper foil over half the sphere representing the transducer ground plane. 5a) shows conventional EPI image, b) shows the EPI image using seven segments as given in the real setup, and c) shows the EPI image for 54 segments.

Conclusion & Discussion: Eddy currents in the copper ground plane can dramatically degrade EPI image quality. The root cause was investigated by simulations and results were verified by phantom experiments. Increased segmentation of the ground plane significantly reduced the unwanted eddy current effect. A setup with the ring pattern is recommended when considering the y-axis. When exciting both gradients, a setup with the star-ring pattern is expected to reduce the eddy current effect. Future investigations of this eddy current effect could focus on optimizing the number of segments of the ground plane regarding the star-ring pattern for both gradient axes and different material types. Additionally, specific eddy current compensation scans, i.e. also including higher order eddy current term compensation for EPI [6] could help to correct for the image distortions. In addition to fast multi-slice MR thermometry, the ability to acquire high-quality EPI images with the transcranial MRgFUS setup will enable DTI, DWI, and functional MRI to be performed *in situ* for more accurate treatment planning.

References: [1]McDannold N et al., Neurosurgery 66:323-332 (2010) [2]Martin E et al., Ann Neurol 66:858-861 (2009) [3]Peters R et al., MRM 40:454-469 (1998) [4]Stafford J et al., JMRI 20:706–714 (2004) [5]terHaar G et al., Int. J. Hyperthermia 23(2):89-104 (2007) [6] Xu D et al., ISMRM'11, #4564