EPI magnitude signal formation in the proximity of straight conductor subjected to a weak electric current.

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Introduction: Straight conductor immersion or in proximity to water solutions or gels and subjected to electric current pulses can be very useful for a wide range of MRI and NMR studies (1-5). This simple model system has been used for exploring MRI detection limits for ultra-weak and transient current-induced magnetic field changes with the help of EPI phase imaging (1,3). EPI phase imaging offers a direct way to map magnetic flux density distribution around the conducting wire. However, EPI magnitude signal formation in conducting wire proximity has not been fully understood. Recently, it has been suggested that MRI magnitude signal around wire may result from current-induced magnetic flux density spatial distribution inducing signal displacement in an EPI phase encoding direction (6). Here we will analytically and experimentally show that current-induced magnetic flux density, and also current-induced magnetic field gradient, are both necessary to explain EPI magnitude signal formation around the conducting wire. For weak current pulse on the order of a few hundred micro-ampers the resulting magnetic field-induced EPI signal displacement in the phase encoding direction do not fully explain the observed pattern. By taking into account the current-induced magnetic field gradient resulting in EPI signal magnification/scaling in a phase encoding direction the experimental results can be explained.

Theory: For simplicity we assumed that the wire is infinitely long, perpendicular to B_0 (or parallel to Y axis). For the coronal plane the current-induced z-component (parallel or anti-parallel to B_0) of magnetic flux density is given as:

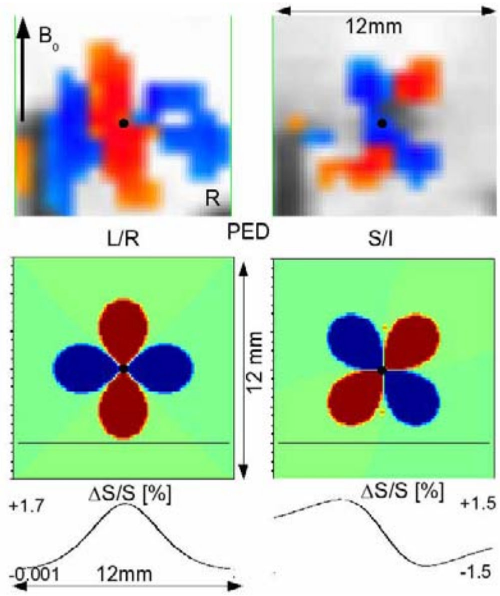
[1] $B_{CZ}= (\mu_0/4\pi)\, 2I\, (x \,/\, (x^2+z^2))$ where I is current intensity.

Current induced magnetic field gradients $G_{CZ}= dB_{CZ}/dz$ and $G_{CX}= dB_{CZ}/dx$ can be computed as follows:

[2.1] $G_{CZ}= - (\mu_0/4\pi)\, 2I\, (2xz \,/\, (x^2+z^2)^2)$ [2.2] $G_{CX}= (\mu_0/4\pi)\, 2I\, ((z^2-x^2)/(x^2+z^2)^2)$

So called, "off-resonance" (in this case due to current-induced magnetic field and gradients) EPI effects have been well characterized and appear in phase encoding direction (PED) (7). Both image misregistration or displacement and image scaling (loss/enhance of intensity) are observed. The EPI image net misregistration can be estimated from B_{cz}/J and image magnification from G_{ck}/J where J is an incremental change in the phase encoding gradient from view to view (given by equation 3) and k=Z,X, depending on chosen EPI readout/phase directions.

[3] $J= 2\pi \,/\, (\gamma L_p T')$ where L_p is phase FOV and T' is time to acquire one view.



Methods: Current phantom described elsewhere was used (1,3). Water $CuS0_4$ solution was used with short T2≅100ms<<TR. 3 Tesla GE HDx MRI scanner with system provided 8-element receive only head array and single shot full k-space gradient echo EPI were used (FOV=12cm, 96x96, TR=1s, TE=30ms, bandwidth per pixel in PED ≅ 17 Hz/pixel, voxel volume after 128x128 reconstruction =0.9x0.9x2 mm^3). To map current-induced signal changes around wire the current (400µA) was periodically turned ON for 10sec and then OFF for 10sec. This ON/OFF cycle was repeated for 3 minutes. Two different EPI phase encoding directions were used: L/R and S/I. Cross correlation (CC) with ideal reference was computed to map current effects. For numerical simulation equations 1-3 were used to estimate off-resonance EPI effects numerically in XZ plane for the infinite long conducting wire parallel to Y-axis.

Results: Figure in the upper row shows cross-correlation (CC threshold 0.7) maps of 400µA current-induced EPI magnitude signal changes for two PED directions (wire position marked as black dot). Red and blue maps positive and negative contrast, respectively. Corresponding numerical simulations are shown in the middle row where signal changes larger than 2% are masked out to compare with CC maps (J=0.033 G/cm). The lower row shows two projections (marked as black lines) from simulation maps.

Discussion: Current-induced "off-resonance" EPI effects explain magnitude signal formation in conducting wire proximity. Predominantly, the effect for a weak current order of a few hundred microamps is EPI signal loss/enhancement from current-induced magnetic field gradient. Characteristic pattern transformation was observed during swapping EPI phase/readout gradient directions closely following current-induced magnetic gradient spatial distribution. Considering B_{CZ} effects (misregistration) alone does not fully explain effects of the size and observed pattern. In addition to the current magnitude, the EPI sequence manipulation affecting bandwidth per pixel in PED also affected the size and shape of the current-induced magnitude pattern.

Conclusion: We have analytically and numerically explained electric current-induced EPI signal formation in the proximity of the straight conductor. The electric current-induced magnetic field and gradients are causing "off-resonance" effects in the EPI phase encoding direction. To enhance EPI magnitude signal sensitivity to small current-induced changes the lowest possible bandwidth per pixel in PED should be used.

References:(1) Bodurka et al. JMR 137:265, (1999); (2) Zhao et al. MRM 44:758, (2000); (3) Bodurka et al. MRM 47:1052,(2002); (4) Renvall et al. MRI 24:315,(2006); (5) Callaghan et al. Phys. Rev. Lett. 75:4532,(1995); (6) Pell et al. MRM 55:1038, (2006); (7) Farzaneh et al. MRM 14:123,(1990)