# Neuronal current imaging: sensitivity of magnitude and spatial distribution to changes in current timing

**I. Drobnjak[1], G. Pell[2], and M. Jenkinson[3]**
[1]University of Oxford, Oxford, Oxfordshire, United Kingdom, [2]Brain Research Institute, Melbourne, [3]University of Oxford

**Introduction:** Direct neuronal current imaging is a method that could potentially provide direct access to neuronal activity with an excellent spatial (mm) and temporal resolution (ms) [1-3]. However, so far it has not been convincingly demonstrated that MRI has adequate sensitivity to detect neuronal currents *in vivo*. In order to pin down the most influential factors in the signal formation, with the goal of eventually optimizing them for the MR detectable signal change, Pell *et al.* used a simple conducting wire model with various scanning and field parameters to investigate signal magnitude changes [1]. The experimental results indicate not only significant changes in signal magnitude but also in spatial pattern. Specifically, the current can create a very localized Gibbs ringing in the image. We show both experimentally and analytically that the timing of the current within the pulse sequence completely determines the width and the magnitude of the ringing. Since currently we are on the limit of neuronal-current MR sensitivity, this is a significant finding as it can help us both tune the parameters of the acquisition to achieve maximal sensitivity as well as understand the effects of arbitrary neuronal currents on the MR signals.

**Methods:** As in [1], a phantom was constructed from a hollow glass sphere, filled with SF96/50 silicone oil, and a carbon fibre conductor (diameter 0.015mm) was placed inside the glass sphere and a Perspex support structure was constructed to hold it in its place. T1=1420ms and T2=530ms, GE Med Sys 3T vH3 system was used and gradient echo EPI partial k-space (85/128 lines were acquired) with homodyne reconstruction, TR=1s, TE=36ms, BW=125KHz, matrix 128x128, voxel size 1.5x1.5x6 mm^3, FOV=20cm, coronal slices (x-z plane) with B0 in z, PE in x, and a conductor in a y direction. The current (I=7.8mA of 5ms duration) was "walked-through" the pulse sequence. That is, the timing of the onset of the current pulse was increased in 1ms steps every alternate TR over a series of image acquisitions. Here we concentrate on three particular timings of the current: A (current ON during acquisition of lines 61-64), B (lines 76-79) and C (lines 88-91). The magnitude of the signal change was calculated by normalising the difference betweeen the ON current and the OFF current images (in %). The same experiment was also performed numerically using an MRI simulator POSSUM [5]. This was done in order to show that the result are fully reproducable with "perfect" currents and field patterns and are not due to artifacts or complicated/secondary field effects or interactions.

**Results:** Fig2 shows the current effects (dS/S [%]) for three different timings of the current A, B and C, The three columns on the left show the spatial pattern of the signal change in the proximity of the wire (experimental results in the top row, numerical simulations in the bottom row). To the right of these images are plots of the signal change across the horizontal mid-line of the images, where the wire position is taken to be 0 voxels and colours correspond to the current timing. It can be seen that substantially different patterns of ringing arise for the different timings, but that experimental data and the numerical simulations show a very good match. Fig3 shows the results of the more general "walk-through" experiment, with timing indicated in the top row and the experimentally and numerically calculated signal changes shown as a function of current timing in the two rows below. Note that the largest signal change occurs at A, which is when the current occurs at the echo time (TE) for this partial acquisition.

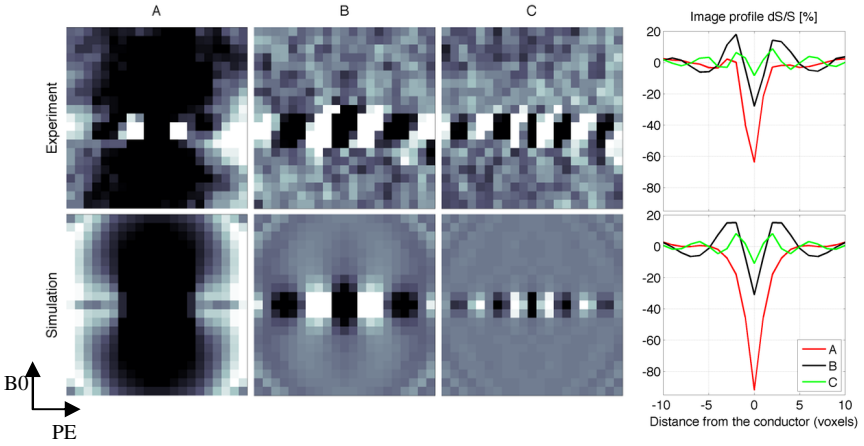


**Fig2:** Signal formation around a conducting wire (positioned in the centre of the images and perpendicular to the plane). On the right are the intensity profiles through the horizontzal mid-line.

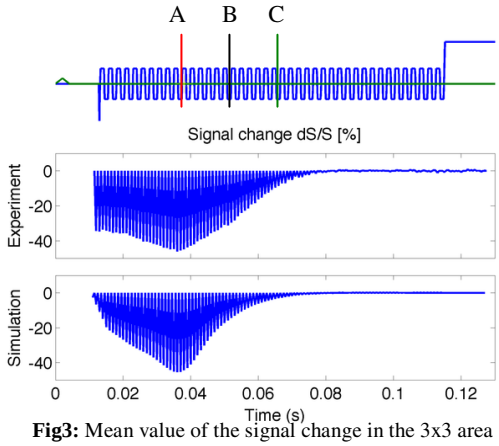


**Fig3:** Mean value of the signal change in the 3x3 area of the voxel with the conducting wire.

**Discussion:** EPI magnitude signal formation for neuronal current imaging has been previously explained by the current-induced magnetic flux density [1] and by the current-induced magnetic field gradients [4]. Here we further showed the importance of another factor, the timing of the current within the pulse sequence. Depending on when the current pulse occurs relative to the k-space acquisition, various amounts of localised Gibbs ringing are observed. The ringing observed is due to the fact that the k-space of these images can be divided into three different regions (in phase-encode direction) which are acquired before, during and after the current is ON. For short duration currents only a few lines of k-space are acquired with the pulse ON, and so the main effect can be modelled using just the before and after portions of k-space. This allows that the width of the ringing to be calculated using the equation W=Ny/(2X+1), where Ny is the matrix size in the PE direction and X is the timing offset of the pulse, in lines of k-space, from TE. This gives widths for cases A, B and C as 18, 4.2, and 2.4 voxels respectively, which can be seen in Fig2 on the right.

**Conclusion:** We have both experimentally and numerically showed how the timing of the current within the pulse sequence impacts the EPI signal magnitude and spatial pattern formed around the conducting wire. Since both the spatial localisation and magnitude of the signal vary significantly as a function of current timing, it is critical that this mechanism is understood in order to optimise neuronal current pulse sequences for maximum sensitivity. These results also suggest that it may be possible to tune the pulse sequence to be preferentially sensitive to neuronal currents within a given timing window, which could have interesting applications in differentiating the fine timing details for neuronal current experiments. In addition, we have shown that the experimental results and the numerical simulations performed with POSSUM agree well (the more detailed validation of the POSSUM simulator was shown in [5]). Such numerical simulations can prove to be an invaluable aid in investigating realistic neuronal current imaging, and to optimise the sequences for sensitivity, as they can separate the effects of current-induced and BOLD-induced signal change while allowing more complicated and realistic phantom geometries to be used than would be possible for physical phantoms.

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**References:** [1] Pell et al. MRM 55 (2006); [2] Bodurka et al. MRM 47:1052 (2002); [3] Bowtell et al. MRM 50:40 (2003) [4] Bodurka et al. ISMRM 15 (2007); [5] Drobnjak et al. MRM 56:364 (2006);