A theoretical Direct Neuronal Detection study to estimate percentage local field perturbations

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Introduction

Direct neuronal detection (DND) using magnetic resonance imaging (MRI) has recently been hypothesized as a better alternative to standard blood oxygen level dependent (BOLD) functional MRI (fMRI) for evaluating brain function. The feasibility of DND as a practical diagnostic tool is still under consideration however, with studies reported using theoretical modelling [1], phantoms [2] and real human subjects [3]. The results so far have been mixed, and further detailed modelling is required together with a better understanding of the weak transient neuronal signals which cause local perturbations in the images. In this study the percentage signal change caused by a simulated neuronal population is estimated, resulting from stimulated axon firing.

Theory and Methods

Axonal stimulation causes firing in the form of action potentials flowing along the length of the axon. The change in potential is due to weak neuronal currents which generate commensurate transient magnetic fields. These fields have been calculated using a finite difference solution to Poisson's equation [4] and are found to be in the nano tesla range. In order to estimate the local signal perturbations this field causes we assume that there are K phase encode steps in an imaging frame, and that the simulation grid is meshed in to P points with N axons. The total magnetic field co-polar to B_o at point p and time kAt due to axonal firing can then be written as $\sum_N B_{p,n}(k)$, causing an MR signal phase perturbation at p of $\Delta\phi_p(k) = \gamma TE \sum_N B_{p,n}(k)$, where TE is the echo time and γ the gyro-magnetic ratio. The MR signal at p, $S_p(k)$ is perturbed as $S_p^R(k) = S_p(k) \times e^{j\Delta\phi_p(k)}$ and the total signal from the whole grid is then $S_T^R(k) = S_p(k) \sum_P e^{j\Delta\phi_p(k)}$, assuming the unperturbed signal is the same at all grid points. The percentage signal perturbation is then given by $\frac{S}{S_{eq}} = 100 \times (1 - \frac{S_T^R(k)}{PS_p(k)})$.

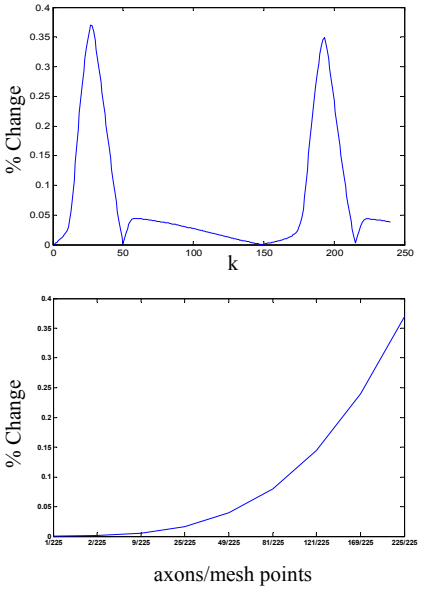

Figure 1 a) Percentage signal perturbation for fully populated grid b) Variation of % modulation with axons

Discussion

A maximum signal perturbation of 0.35% is calculated for a meshed grid fully populated with z-directed axons. The signal change falls for a sparsely populated grid to below the detection range of current scanners (~0.1%) when the grid axonal population is below 50%. The signal perturbation is shown as a function of time in figure 1a for a grid fully populated with axons firing synchronously, and variation with grid axonal population is shown in figure 1b.

Various random and linear firing delays are used next to study their effect on signal perturbation. With linear delays the variation of the signal perturbation is reduced, decreasing with increasing delay. In the case of random delays the variation is reduced close to zero and the mean signal change for a fully populated axonal grid is 0.25%. The results are shown in figure 2.

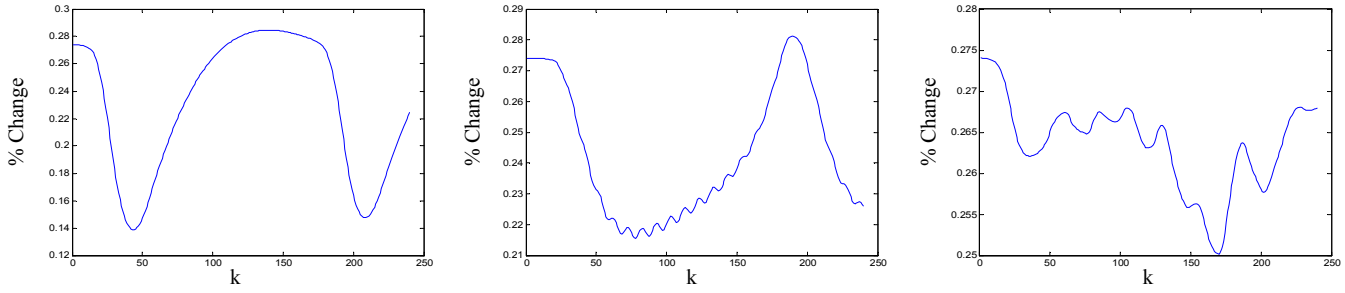

Figure 2 Percentage signal perturbation a) Linear delay in x-y direction b) Linear delay in x direction c) Random Delay in x-y for fully populated grid

Conclusion

Theoretical field estimates give a maximum MR signal perturbation of 0.35% due to synchronous axonal firing, which should be detectable using current MR imaging techniques. Sequential and random axonal firing reduces both the signal perturbation and its variation over time. Although these local transient field perturbations have been observed in some studies, the detection rate is low and results have not been reproduced on human subjects. This may be attributable to the low signal to noise ratio (SNR) of the neuronal modulation effect, and therefore better signal processing and post processing algorithms are required to enhance the SNR.

References

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