# Simulating the effect of TMS-pulses on the evolution of magnetization

**A. Bungert[1], and R. W. Bowtell[1]**
[1]Physics and Astronomy, University of Nottingham, Nottingham, Nottinghamshire, United Kingdom

**Introduction:** Transcranial Magnetic Stimulation (TMS) is a non-invasive method for stimulating cortical regions of the brain, which is widely used to study brain function and connectivity (1). The combination of TMS with functional imaging offers some particular advantages for brain studies and successful implementation of combined TMS/PET (2) and TMS/fMRI (3-5) has already been demonstrated by several groups. Performing TMS inside an MR scanner is not straightforward because of the large instantaneous forces experienced by the TMS coil when it is energised in the strong static field. In addition the strong, rapidly varying magnetic fields generated by the TMS coil pose some particular problems for combined TMS/fMRI because of their potential effects on the nuclear magnetization in proximity to the coil. Previous studies have experimentally explored the effects of TMS on MR image quality and established protocols that limit the degradation of image quality (3-5).

Here we aimed to gain further insight into the effect of TMS on MR images by analysing the evolution of magnetization during a real TMS pulse. A particular question that was addressed was whether the TMS pulse significantly effects the longitudinal magnetization. This is of relevance for the implementation of TMS in combination with arterial spin labelling to monitor stimulation-induced perfusion changes. In addition the dephasing of transverse magnetization generated by real and truly balanced bipolar pulses was evaluated.

(Eq.1)
$$\underline{B}_{eff}(t) = \underline{B}_0 + \underline{B}_{TMS}(t) = \left(B_{TMS\perp}, 0, B_0 + B_{TMS\parallel}\right)$$

(Eq. 2)
$$\underline{B}'_{eff}(t) = \underline{B}'_0 + \underline{B}'_{TMS}(t) = \left(0, 0, B_{eff}(t)\right)$$

(Eq. 3)
$$\Omega(t) = \underline{e}_y \cdot (\dot{\underline{B}}_{eff}(t) \times \underline{B}_{eff}(t)) / |B_{eff}(t)|$$

(Eq. 4)
$$\dot{M}'_x = \omega M_y - \Omega M'_z$$
$$\dot{M}_y = -\omega M'_x$$
$$\dot{M}'_z = \Omega M'_x$$

(Eq. 5)
$$\omega = \gamma |B_{eff}|$$

(Eq. 6)
$$\Delta\phi = \gamma \int_{Pulse} \left(|B_{eff}(t)| - B_0\right) dt$$

**Methods:** The spatial distribution of the magnetic field generated by a figure-of-eight, MR-compatible TMS coil (Magstim Company Ltd), $\underline{B}_{TMSs}(x,y,z)$, was calculated by applying the elemental Biot-Savart equation to the known form of the coil wirepaths. The field was normalized so that its maximum at the coil surface was 1 Tesla. The temporal variation of the magnetic field generated during a TMS pulse, $B_{TMSt}(t)$, was found by integrating the response of a small search coil placed adjacent to the TMS coil. The resulting effective magnetic field during the TMS pulse is: $\underline{B}_{eff} = \underline{B}_0 + \underline{B}_{TMS}$ (Eq. 1) where $\underline{B}_0$ is the static field of the scanner which is assumed to be applied in the z-direction and $\underline{B}_{TMS(x,y,z,t)} = B_{TMSt}(t) * \underline{B}_{TMSs}(x,y,z)$.

To study the effect of the TMS pulse on the longitudinal magnetisation, the Bloch-equations were solved in a reference frame which rotates at a temporally varying angular velocity, Ω (Eq. 3) around the y-axis so that its z-axis stays aligned with the effective magnetic field (Eq. 2). The resulting differential equations (Eq. 4) were applied numerically to the TMS-field and its temporal derivative. Relaxation effects were neglected because of the short duration of the TMS pulse (< 0.5ms) and it was assumed that the magnetization was initially aligned with $\underline{B}_0$.

To evaluate the dephasing of transverse magnetisation induced by the TMS pulse the difference between the integral of $\gamma |B_{eff}|$ and $\gamma B_0$ was evaluated (Eq.4) over the calculated field distribution.

**Results:** Figure 1 shows the variation of $dB_{TMS}/dt$ measured using a search coil. This was integrated to yield the $B_{TMSt}(t)$ waveform shown in Figure 2. Ideally the TMS-pulse should be a symmetric, biphasic pulse, but the measurements show that the first, positive lobe of the waveform has a larger area than the second, negative lobe.

Figure 5 shows the spatial distribution of the absolute magnetic field $|B_{TMS}|$ in the y-plane, which was calculated from the coil's wirepaths. For the results presented here an angle of 45° between $B_0$ and the plane of the TMS coil was assumed so as to represent a typical coil orientation used in combined TMS/fMRI experiments. Figure 3 shows the calculated relative change in longitudinal magnetization during the TMS pulse, indicating that for the situation considered here ($B_0$ = 1.5 T and $|B_{TMS}|_{max}$ =1 T) the TMS pulse causes a negligible change (< 0.0005 %) of $M_z$. This implies that the magnetization remains aligned with the effective field throughout the application of the TMS pulse, which is a consequence of the small ratio of Ω to ω (~1.6 x $10^{-4}$). Figure 4 shows the maximum relative change in $M_z$ for different strengths of the TMS-field and $B_0$ values of 1.5 and 3 T. It indicates that for realistic parameters the influence of the TMS-pulse on the longitudinal magnetisation is always negligible.

Figure 6 shows the TMS-induced phase offset assuming temporal and spatial variations of the TMS-coil field as shown in Figs. 1 and 5. The offset is so large, that signal from most of the FOV will be spoiled if the TMS-pulse is applied while magnetization is in the transverse plane. Figure 7 shows a similar map, for the case of a perfectly symmetric biphasic pulse. Here the phase offset is significantly lower and it decays more rapidly with distance from the coil.

**Conclusion:** The calculations presented here indicate that application of a TMS pulse has a negligible effect on the longitudinal magnetization of a sample, but as has been previously demonstrated (5) causes massive dephasing of transverse magnetization even at significant distances from the coil. This dephasing can be reduced, but not eliminated, by the use of a balanced bi-phasic TMS pulse. Overall these results imply that during execution of MRI pulse sequences TMS pulses can be applied during periods where the magnetization is aligned along the longitudinal axis without perturbing subsequent measurements. In the case of TMS applied with arterial spin labelling this means that TMS may be readily applied during the post-labellling delay without confounding measured perfusion values.

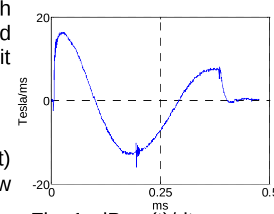

Fig. 1: $dB_{TMS}(t)/dt$

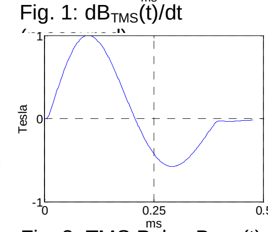

Fig. 2: TMS Pulse $B_{TMSt}(t)$

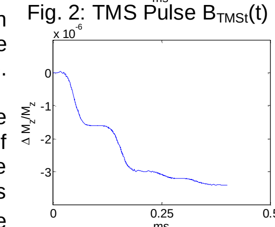

Fig. 3: Relative change of magnetisation parallel to the magnetic field ($B_0$=1.5 Tesla) during the TMS-pulse

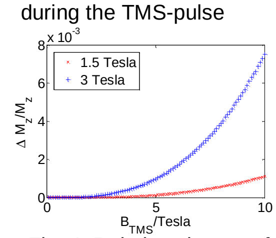

Fig. 4: Relative change of the magnetisation $M_z$ with different TMS-field strength in 1.5 and 3 Tesla

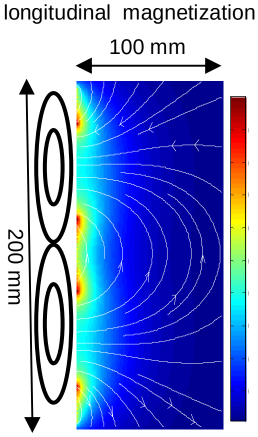

Fig. 5: Field distributio $B_{TMSs}(x,y=0,z)$. On the lef the shape of the TMS-coil

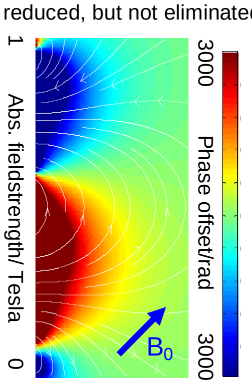

Fig. 6: Phase offset induced by the TMS-pulse ($B_0$=3 Tesla).

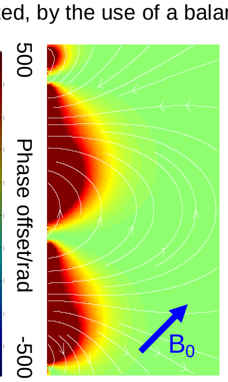

Fig. 7: Phase offset assuming symmetrical TMS-pulse ($B_0$=3T).

**References:** (1) Strafella *et al J Neurophysiol* 85: 2624-2629, 2001; (2) Paus *et al.* J. Neurosci. 17: 3178-3184, 1997; (3) Bohning *et al* Biological Psychiatry. **45**:385-394, 1999; (4) Baudewig *et al* Magn. Reson. Imag., 18:479-484 2000; (5) Bestmann *et al* J. Magn. Reson. Imag., 114:309-316 2003