Modeling the influence of TR and excitation flip angle on the MTR obtained from 3D FLASH MRI

G. Helms[1], H. Dathe[2], and P. Dechent[1]

[1]MR-Research in Neurology and Psychiatry, University of Göttingen, Göttingen, Germany, [2]Biomechanics Group, Dept. of Orthodontics, Universityhospital, Göttingen, Germany

Introduction

Spoiled gradient-echo (FLASH) sequences are commonly used for magnetization transfer (MT) quantification and clinical MRI at higher field strengths. Considerable work has been devoted to optimize the MT ratio (MTR) via the properties of the MT pulse (1,2). However, little attention has been paid to the influence of TR and excitation flip angle. By accounting for excitation and relaxation in the MT-FLASH signal equation, we have recently derived a novel semi-quantitative parameter for MT, describing the fractional reduction of longitudinal magnetization by a single MT-pulse (3). This “MT saturation” reflects mainly the effect of the MT-pulse with only minor residual influence of T_1, flip angle and RF inhomogeneities. The model can be readily applied to the MTR, revealing the influence of TR and the excitation flip angle.

Theory

The rational approximation of the Ernst equation (4) without MT-pulse,

$$S = A(\mathrm{TE})\ \ \alpha\, R_1\mathrm{TR} \,/\, [R_1\mathrm{TR} + \alpha^2/2] \qquad [1]$$

depends on signal amplitude, A(TE), and the rate of longitudinal relaxation, R_1. It is extended to MT-FLASH (3) by introducing the tissue-dependent MT saturation, δ:

$$S_{\mathrm{MT}} = A(\mathrm{TE})\ \ \alpha\, R_1\mathrm{TR} \,/\, [R_1\mathrm{TR} + \alpha^2/2 + \delta]. \qquad [2]$$

This immediately yields the dependence of the MTR on TR and flip angle, α (in rads):

$$\mathrm{MTR} = (S - S_{\mathrm{MT}})/S = \delta \,/\, [R_1\mathrm{TR} + \alpha^2/2 + \delta] = 1 \,/\, [1 + (R_1\mathrm{TR} + \alpha^2/2)/\delta\,]. \qquad [3]$$

Inhomogeneity of the transmitted RF affects the MTR via local deviations of flip angle ($f_T\alpha$) and MT saturation ($f_T^2\delta$ for B_1^2-dependent RF absorption):

$$\mathrm{MTR} = f_T^2\delta \,/\, [R_1\mathrm{TR} + f_T^2\alpha^2/2 + f_T^2\delta] = \delta \,/\, [R_1\mathrm{TR}/f_T^2 + \alpha^2/2 + \delta]. \qquad [4]$$

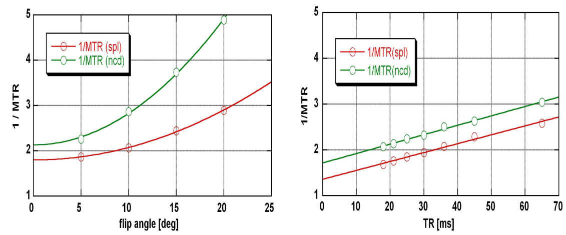


Fig. 1: Fitted dependence of 1/MTR on flip angle and TR (Eq. [3]) in caudate nucleus (green) and splenium (red)

Methods

Experiments were performed on consenting healthy adults on a 3T whole-body system (Siemens TRIO) using the 8-channel receive-only head coil and the body coil for transmission. 3D MT-FLASH imaging at 1.25 mm resolution (non-selective excitation of 128 sagittal partitions, 240 mm field-of-view) was performed at constant TE = 4.92 ms at varying flip angles (TR/α=25 ms/5°,10°,15°,20°) and (α/TR=5°/18,21,25,30,36,45 ms) using Gaussian MT-pulse applied 2.2kHz off resonance (12.8 ms/540° or of equivalent power). Measuring time was reduced to 2 x 3.05 min for TR = 25 ms using partial acquisition (6/8 partial Fourier and 2x GRAPPA).

Results

As predicted by Eq. [3], the inverse MTR showed a quadratic dependence on α and a linear dependence on TR (Fig. 1). MT-w FLASH images and MTR maps showed an opposite behaviour: Excitation by 5° yielded a high contrast between white and gray matter (WM/GM) on the MT-w images (Fig. 2), but reduced contrast on the MTR maps (Figs. 3). On the other hand, excitation by 20° yielded a better MTR contrast, despite impaired contrast of the images. Higher flip angles also reduced the flip angle bias, as appreciated from the pseudo-color display (Fig. 4). The influence of RF inhomogeneity is inevitable due to the finite TR. At longer TR values, the MTR contrast increased, but so did the influence of RF inhomogeneity. Histogram analysis of the whole brain showed that the WM/GM MTR-contrast is reduced compared to the MT saturation, while the mode of CSF appeared at MTR values larger than zero. (Fig. 4)

Discussion

The MTR refers to the reduction of the steady state signal, which by necessity depends on the relaxation and thus also TR and flip angle. The heuristic approximation was based on free relaxation between the RF pulses (3,5). Often, a continuous-wave approximation is used (1) which does not permit to account specifically for relaxation effects by TR and flip angle. The approximate equation for the FLASH-derived MTR also provided a model for the influence of RF inhomogeneity, which differed from the phenomenological linear correction suggested by others (6,7). As shown in (2), application of MT-pulses of higher power and/or smaller offset will result in higher MTR, which in the context of our model is explained by a stronger MT saturation. Unlike the MTR, the MT saturation is largely independent of T_1 and flip angle bias (3). For given δ, Eq.[3] may be used to analytically derive TR and α for optimal SNR or CNR in the MTR maps.

Conclusion

For MT-FLASH, the choice of short TR and higher flip angles improves contrast of MTR and reduces the influence of RF inhomogeneity.

Fig. 2: MT-w FLASH images

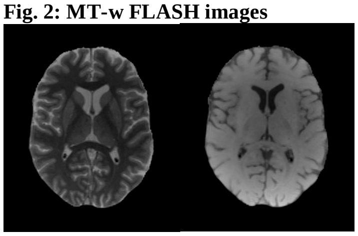


Fig. 3: MTR maps

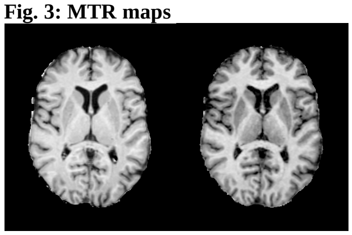
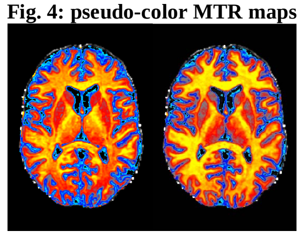
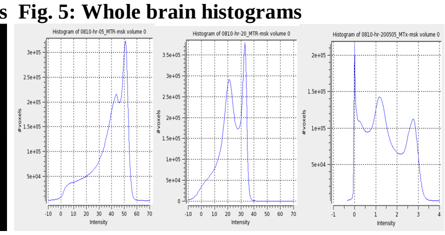


Fig. 4: pseudo-color MTR maps



Each figure showing corresponding slices for 5° (left) and 20° (right) excitation flip angle.

Fig. 5: Whole brain histograms



Left: 5°MTR; center 20°MTR; right MT saturation

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