Correction for residual effects of B1+ inhomogeneity on MT saturation in FLASH-based multi-parameter mapping of the brain
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Target audience
MR physicists

Purpose
In magnetization transfer (MT) imaging, the evolution of the binary spin bath after the off-resonant saturation pulse can be described by simultaneous apparent T1 relaxation of both pools as in fast exchange and simultaneous equilibration of the partial saturation (1). From MT-w(eighted) FLASH, the MT-related partial saturation of the free water can be calculated using a PD-w and a T1-w reference signal (2). Such MT-sat(uration) maps are independent of the underlying T1 and largely compensated for flip angle inhomogeneities. For an established multi-parameter mapping (MPM) protocol at 3T (3), we discuss the source and correction of residual effects of flip angle inhomogeneity.

Theory
With increasing flip angle \( \alpha_{\text{sat}} \) of the MT-pulse, the z-magnetization of bound macromolecular pool is destroyed, but the effected saturation becomes increasingly lower than \( \alpha_{\text{sat}}^2 \) (as expected for small changes in \( M_z \)). Thus, the inherent B1+ correction of the MT-sat maps (by \( \alpha_{\text{sat}}^2 \)), results in a residual overestimation in regions of low B1+ and underestimation at high B1+ (Fig. 1A). For any given tissue and MPM protocol, an additional linear dependence of the MT-sat value \( \delta(\alpha_{\text{sat}}) \) was assumed:

\[
\delta(\alpha_{\text{sat}}) = A [1–B \alpha_{\text{sat}}] \alpha_{\text{sat}}^2
\]

where A and B are heuristic constants that can be calibrated by varying \( \alpha_{\text{sat}} \). When \( \alpha_{\text{sat}} \) is spatially modulated by the flip angle bias field \( f \), the square contribution cancels by calculation and the residual bias term is corrected by:

\[
\delta(\alpha_{\text{sat}}) = \delta(f \alpha_{\text{sat}}) [1–B \alpha_{\text{sat}}] / [1– f B \alpha_{\text{sat}}]
\]

Methods
In an established multi-parameter mapping (MPM) protocol (3) on a 3T MR system (Siemens TIM-Trio), the nominal flip angle of the MT-pulse (220°, 4ms Gaussian, 2kHz off-resonance) was varied between 280° and 120° in five healthy adults. The estimated MT-sat values from ROIs in splenium, caudate head and lateral ventricle were divided by \( \alpha_{\text{sat}}^2 \) to show the linear relationship of eq. (1). Maps of A and B were derived by linear regression with pertinent bias fields (4) using FSL. Estimated MT-sat maps were corrected by eq. (2) with \( B \alpha_{\text{sat}} = 0.4 \) and displayed as a color-overlay (Fig. 1).

Results
The linear relationship in (Fig 2) confirmed the residual bias model. Deviations were observed at \( \alpha_{\text{sat}} < 120° \). In the caudate head B was slightly smaller than in splenium (0.043±0.004 vs. 0.046 ±0.005), but the maximum of the gray matter (GM) mode of \( \delta(\alpha_{\text{sat}}) \) was consistent to splenium. Accordingly, maps of B did a single mode in brain tissue without differences between GM and WM (not shown). Thus, the averaged B across tissue and subjects can be used for a post hoc correction of MT-sat maps; with \( B \alpha_{\text{sat}} = 0.4 \) in eq. (2). Of note, the model is not valid for cerebro-spinal fluids with MT-sat being close to zero.

Bias-corrected MT-sat maps were more symmetric (Fig 1) and show more consistent values in subcortical WM and brainstem and a better seperation of modes in the histograms.

Discussion
We presented a heuristic model for B1-heterogeneity of MT-sat maps rooted in the saturation dynamics of the MT-pulse. The model parameter B needs to be calibrated for the specific MT-pulse and protocol. The model can also be used to scale MT-sat maps to a different value of \( \alpha_{\text{sat}} \). WM and GM yielded very similar values, which is in line with reports of similar absorption lineshapes in gMT (5). This permits a simple post-hoc correction of MT-sat using B1+ mapping yielding a small, but considerable improvement of MT-sat maps.

References

Figure 1: MT-sat map prior (left) and after (right) bias correction

Figure 2: Plot of \( \delta / \alpha_{\text{sat}}^2 \) over \( \alpha_{\text{sat}} \) (in rads)