Wide-Range T1 Mapping Using Two Variable Flip Angle Acquisitions

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Introduction: Volumetric T1 mapping using two variable flip angle (VFA) acquisitions has become a popular clinical tool for T1 estimation due to short scan times and ease of implementation. The conventional approach to flip angle selection has been based on maximization of the signal-dynamic range (S-DR) product for a single T1 value of interest (typically ≤ 1000 ms), with estimation accuracy and precision maintained only within a limited range of the chosen value [1,2]. However, no studies to date have investigated systematic bias in the S-DR product based on different choices of flip angle pairs (i.e. corresponding to different T1s of interest) and the potential implications for the range of effective T1 estimation. While alternative VFA approaches have been developed to allow T1 mapping over the whole biological range [3,4], the need for additional acquisitions may limit their utility when scan time is limited and/or signal averaging is required to achieve minimum SNR thresholds. Here we investigate the effect of flip angle selection on bias in the S-DR product with the aim of performing wide-range T1 mapping using only two VFA acquisitions.

Methods: Numerical simulations were used to evaluate different flip angle sets with S-DR products optimized to progressively increasing T1 values from 1000ms to 4000ms (500ms intervals). Signals were generated with added complex Gaussian noise (as described in [4]) to examine accuracy and precision of T1 estimates across the range T1 = 200-3000ms for each flip angle set at different SNRs. Phantom experiments were then conducted to validate the performance of a candidate flip angle set that we refer to as the Wide-Range Angle (WRA) set. Scanning was performed on a 3T Philips Achieva System (Philips Medical Systems) using the transmit-receive birdcage head coil to obtain 3D T1W FFE acquisitions (TR/TE = 15ms/3.7ms, $\alpha = [3^o, 15^o]$, FOV = 240x240x48, voxel = 1x1x2mm, overcontiguous slices). A phantom was prepared using 15mL samples of distilled water with varying concentrations of $MnCl_2$ (Sigma-Aldrich) to yield 11 T1s over a range of 100-3000ms. A second 1000mL water phantom doped with 770mg $CuSO_4.5H_2O$ was used to validate T1 estimation in the presence of significant B1 inhomogeneity. Reference T1 values for both phantoms were obtained from single-slice IR data (TR/TE = 9.5ms, TR = 6000ms, TI = [50, 150ms, 200ms, 400ms, 800ms, 1600ms, 3200ms]). To validate the technique in vivo, we obtained informed consent from three volunteers to perform spinal cord T1 mapping. Volunteer scanning was performed using body coil excitation and a 16-channel neurovascular coil for reception to obtain 3D T1W FFE acquisitions (TR/TE = 100ms/10ms, $\alpha = [6^o, 34^o]$, FOV = 212x212x40, voxel = 1x1x4mm, remaining parameters as in [2]). For all phantom and volunteer experiments, we applied an actual flip angle imaging (AFI) technique [5] to obtain a voxelwise B1 map over the same volumetric coverage as the double-angle FFE acquisitions [TR_1 = 30ms, TR_2 = 100ms, TE = 5ms, $\alpha = 60^o$].

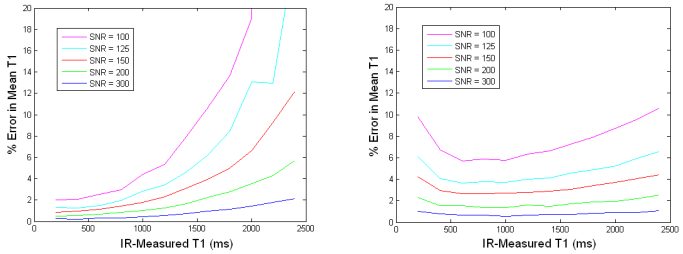

Figure 1. Simulations show conventional flip angle optimization (left) results in large errors at longer T1s due to S-DR product bias. The WRA set (right) corrects for this bias to provide high uniformity across the biological range.

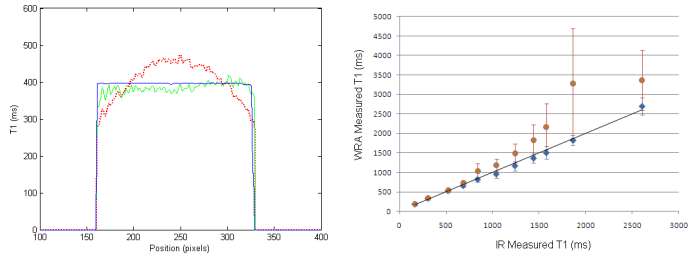

Figure 2. WRA set phantom experiments. Left: $CuSO_4$ phantom. B1 mapping applied to original T1 profile (red) produces new T1 profile (green) that shows good agreement with reference IR T1 profile (blue). Right: $MnCl_2$ phantom. WRA set (blue) corrects for T1 bias associated with conventional approach (red).

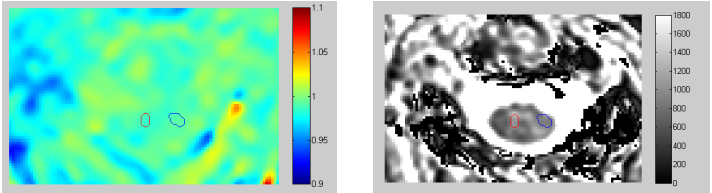

Figure 3. Spinal cord B1 map (left) used to produce corrected T1 map (right). T1s from ROIs drawn for gray matter (red) and lateral column white matter (blue) after B1 correction showed good agreement with IR-measured values [2].

Results: Simulations showed a bias against long T1s in the S-DR product in conventional flip angle optimization which was progressively corrected by choosing flip angle sets optimized for increasing values of the T1 of interest. Optimization of the S-DR product for T1 = 3000ms (the WRA set) yielded optimal uniformity of accuracy (Fig 1) and precision across the biological range, beyond which significant biases against short T1s emerged. Results of phantom experiments (Fig 2) validated the uniform performance of the WRA set (mean error = 4.7%, mean T1NR = 12.3 across T1 range). Finally, spinal cord T1 maps (Fig 3) showed good agreement with reported IR-measured values: 873 ± 51 ms for lateral column white matter (vs. 863 ± 23 ms [2]) and 1057 ± 67 ms for spinal cord gray matter (vs. 972 ± 36ms [2]).

Discussion and Conclusions: The conventional strategy of optimizing the S-DR product for a specific tissue T1 of interest is not appropriate when the expected T1 range is either unknown or relatively wide (>500 ms). The WRA approach presented here compensates for S-DR product bias resulting from the asymmetry of the spoiled gradient recalled echo curves by providing signal uniformity across T1s for the low SNR acquisition, which dominates error in slope estimation for the linearized signal model. While a three angle set has been shown to be most efficient above an SNR threshold of 250 before signal averaging [4], the dual angle WRA set represents a compelling strategy for flip angle selection in clinical applications where scan time is limited and/or SNR is below the threshold prior to signal averaging.

References:

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