A Random Regressor Model for T1-Correction of SPGR Variable Flip-Angle Acquisition without Experimental B1-Inhomogeneity Correction

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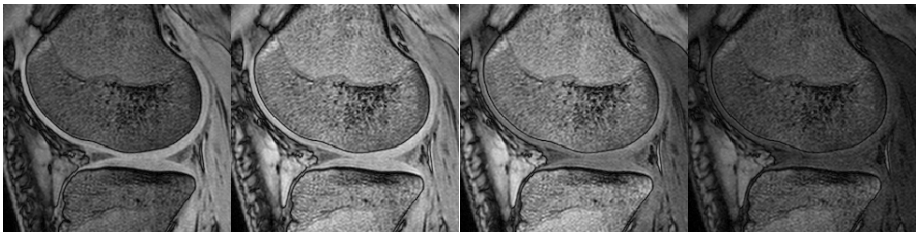
Introduction: The methods of quantitative T_1-mapping from spoiled gradient recalled echo (SPGR) image acquisition with varying flip angles under steady state conditions allow fast and high resolution T_1-quantification in a clinical feasible timeframe [1]. The accuracy of the computed T_1-maps from the measured SPGR signal depends strongly on the SNR and number of measurement points (number of various flip angles FA) but even more critical is the correct knowledge of FA and its variation across the field of view. Especially at higher field strength (>1.5T) a calibration of the true FA across the VOI becomes inevitable. Previously introduced methods have been described that either provide the necessary FA-information by acquiring separate RF-transmit homogeneity maps (B_1-maps) [2] or incorporating B_1-determination approaches into the same sequence [3].
Nevertheless, both strategies require additional scan time and if the B_1-information was not provided for already performed scans the estimated T_1-values might differentiate significantly from the true values. We introduce a novel method of numerically estimating the error of the presumably known FA from the behaviour of the SPGR-signal with varying FA by means of a "Trust Region" fitting method also known as orthogonal distance regression ODR or measurement error model [4]. The improved algorithm (ODRPACK95) provides estimates for the error in the independent variable FA and even allows implementation of bound constrains very efficiently [5]. The primer application is for T_1-quantification in dGemric (delayed Gd-enhancement of MRI in cartilage) of the knee and hip joints.

Methods: Measurements were performed on a Philips Achieva 3.0T using a phased-array eight-channel knee coil and a 3D-SPGR sequence with the following parameters: FOV=160mm, acquisition matrix 320x320 leading to an in-plane resolution of 0.5mm at a slice thickness of 2mm. 40 slices in sagital orientation were required to cover the entire region of the medial and lateral condyle of the femur as well as the patella cartilage; TR=9ms, TE=3.5ms (out-of-phase); four different flip angles were used: 5,10,20,40° leading to a total scan time of 8:00min.
The ODRPACK95 code was implemented in IGOR 6.02 (Wavemetrics, Boulder, CO). The corrected T_1-values for articular cartilage, bone marrow and muscle were compared to values obtained from other already verified quantitative T1-mapping approaches.

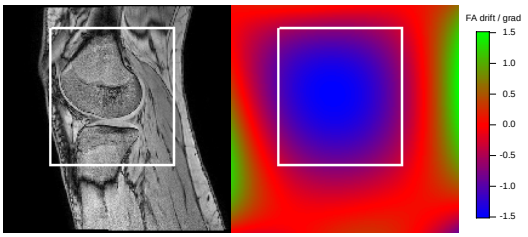
Analysis: Common Least-Squares (LS) fitting of an even non-linear function yi with an error implies that there are no errors in the independent measurements of $x_i : y_i + \varepsilon_i = f(x_i, \beta)$. Under this conditions the parameters β can be estimated by solving the classical LS-problem: $\min \frac{1}{2}\sum_{i=1}^{n}\left[f(x_i,\beta) - y_i \right]^2$.

If, however the error in x_i cannot be ignored LS modifies to: $y_i + \varepsilon_i = f(x_i + \delta_i, \beta)$ with δ_i being the error in x_i. Solving this equation for the parameter vector β becomes known as the ODR: $\min_{\beta,\delta} \frac{1}{2}\sum_{i=1}^{n}\left[\left(f(x_i+\delta_i,\beta) - y_i \right)^2 + \delta_i^2 \right]$ and provides error estimates δ_i for the independent variable x_i (FA).

Results: We tested the robustness and reliability of this technique for providing estimates of the FA-variation on a pixel-by-pixel base. The first iteration using ODR estimates T_1 and provides error for the flip angles α_i from the signal equation of a SPGR-sequence: $S(\alpha_i) = \left(M_0 \cdot (1-A)\sin\alpha_i \right) \Big/ \left(1 - A\cos\alpha_i \right)$, with $A = \exp\left(-TR/T_1\right)$. The resulting FA-error maps $\Delta\alpha_i(x,y)$ are then fitted with a 4th order polynomial to produce smoothly varying noiseless FA-maps. During the second iteration which uses the classical LS-Levenberg-Marquardt algorithm, the corrected T_1 are estimated with prior knowledge of the FA-maps. The resulting FA-corrected T_1-maps obtained similar values for cartilage, bone marrow and muscle as previously established techniques [6].



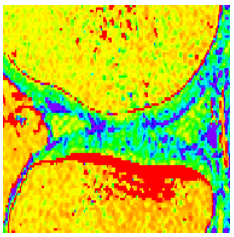
3D SSFP-spoiled gradient echo images of the knee with four different excitation flip angles: FA=5°,10°,20°,40°



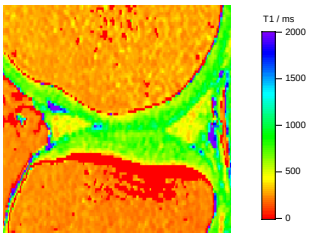
3D-SSFP FA=10

Orthogonal regression estimate of the independent variable FA (B1-estimate) from ODR

1st iteration T1-Map with uncorrected FA



T1-Map from ODR which also provided FA-errors



Corrected T1-Map

References: [1] S.C.Deoni et al., MRM 46 (2003): 515-526; [2] S.C.Deoni, Proc ISMRM 15 (2007): 42; [3] R.D.Newbould, Proc ISMRM 15 (2007): 38; [4] P.T. Boggs et al, SIAM J.Sci.Stat.Comput. 8, 6 (1987): 1052-1078; [5] J.W.Zwolak et al. ACM Trans. Math.Soft., 33,4 (2007); [6] D. Burstein, et al. MRM. 45 (2001): 36-41.