Slice profile corrections in the XFL (magnetization-prepared turbo-FLASH) B1-mapping sequence

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Purpose: The XFL sequence is a very fast 2D multi-slice B1-mapping sequence relying on the measurement of the magnetization Flip Angle (FA) of a selective preparation saturation pulse immediately preceding a centric-ordered FLASH readout [1, 2]. For a good precision of the measurement, the encoded FA must be sufficiently large (> ~10-20°) due to noise contribution in the arccosine operation performed to retrieve it; this implies that in conditions of a large dynamic range of FA's such as those encountered in a transmission array (pTx) calibration at Ultra High Field, some measured angles can be as high as ~160°. At such high FA-values, the FA-measurement is biased by imperfect slice profiles as in most 2D methods [3]. Here we provide the means to correct for this bias by taking into account both the preparation and the FLASH excitation pulse profiles. Moreover we validate our correction method on a phantom at 7T.

Materials and Methods: In the conventional XFL method, the preparation FA is found in every voxel from $\alpha = acos(r)$ (Eq. 1), where r is the ratio of the magnetization-prepared image to the reference image [1]. If the phases of these two images are taken into account, the sign of r can be deduced, so that the FA dynamic range can interestingly be extended above 90°. In this way, in weak B1 locations such as those encountered in pTx calibration at UHF, FA's can still be produced above 10-20° to get a precise measurement of *acos(r).* However in that case, the preparation slice profile across which the FA is encoded can change dramatically over the FA dynamic range, especially when going above 100° (cf. Fig. 1). As in [2], the preparation pulse is a highly-selective minimum-phase SLR saturation pulse with a time-to-bandwidth (TBW) product of 10.7 (produced thanks to [7]). This pulse was VERSE'd at its peak to minimize both its duration and SAR contribution. Thus it is sensitive to B0 offsets (ΔB_0). As we want to correct for slice profile, we integrated ΔB_0 corrections in the Bloch simulation of the preparation pulse. The ΔB_0 map is acquired in a preliminary step with the B1 map resolution (it is assumed to be constant through each slice). Now the XFL imaging excitation pulse was a 1-ms apodized sinc with TBW = 2.5 (standard in selective turbo-FLASH train). Its slice width was set to half that of the preparation pulse to stay away from the imperfect saturation slice profile side effects. Let $s(z)$ be the signal amplitude delivered by the FLASH readout at the z thru-slice location; then the ratio r is given by: $r = \frac{\int s(z)\cos\alpha(z,\Delta B_0)dz}{\int s(z)\,dz}$ (Eq. 2). The α-value we are interested in is the one at the center of the slice ($z = 0$) for $\Delta B_0 = 0$, where the spins are on resonance, so that the linear relationship between α and B1 can hold. The normalized slice profiles $s(z)$ and $\alpha(z, \Delta B_0) / \alpha(0, 0)$ are known from numerical integration of the Bloch equation at each thru-slice location given the chosen excitation and preparation pulse shapes respectively. The excitation slice profile $s(z)$ is assumed to stay proportional to the Fourier transform of the excitation pulse, as the FLASH readout requires small FA's everywhere. Then the sought $\alpha(0, 0)$ can be obtained iteratively from the r-measurement. An initial guess is $\alpha(0, 0) = acos(r_{measured})$, leading to an $\alpha(z, \Delta B_0)$ distribution which is injected in the rhs of Eq. 2. The derived r is then compared to $r_{measured}$ and their difference is minimized with $\alpha(0, 0)$ as a free parameter. Eventually the corrected $\alpha(0, 0)$ can be tabulated versus the uncorrected initial guess $acos(r_{measured})$. All simulations and calculations were performed in Matlab (Mathworks, Natick, MA).

To validate our correction method, we compared our derived B1 amplitude results on a 7T scanner equipped with a pTx system (Siemens, Erlangen) with those from a presumably correct 3D AFI-mapping measurement [4, 5], using the Circularly Polarized mode as the baseline for subsequent XFL interferometric Tx-array calibration [2]. We used a 16-cm-diameter doped water phantom (T1 measured ~1440 ms). The properly-spoiled [5] AFI benchmark sequence was run with TR1/TR2 = 5 and TR = TR1+TR2 = 240 ms. The AFI B1-maps were corrected for T1 by solving eq. 4 in [4], and for the ΔB_0 map [6]. For XFL, 32 slices were acquired in TR = 10 s for a total acquisition duration of 20 s. The nominal FA's set for the preparation and imaging pulses were 60° and 6° respectively, corresponding to average FA's in the 3D volume. Both AFI and XFL sequences had the same isotropic 5-mm resolution.

Results: The preparation slice profile obtained from the Bloch equation integration is shown in Fig. 1 as a function of the nominal FA requested ($\Delta B_0 = 0$ assumed here). The slice profile deteriorates greatly above 90°; as a result, the FA found from signals integrated through the imaging slice underestimates the FA in the slice center, unless corrected with the tabulated FA shown in Fig. 2. In Fig. 3.a, the voxel-by-voxel XFL versus AFI scatter plot of the B1 amplitude deviates from linearity for high B1 when using Eq. 1. With the proposed correction method, the AFI/XFL scatter plot almost retrieves its linear relationship on the entire set of voxels as shown in Fig. 3.b.

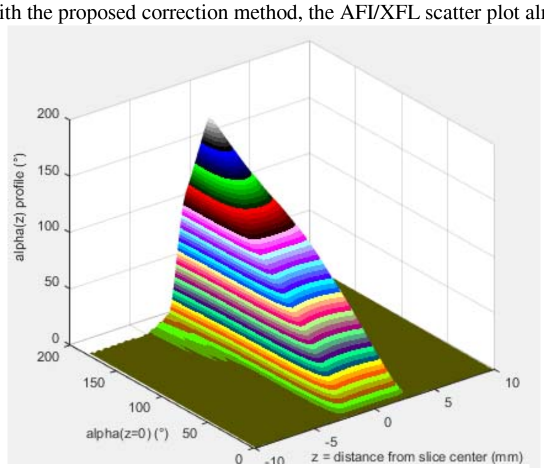

Figure 1: Preparation slice profile as a function of the FA at the center of the slice (no B0 offset)

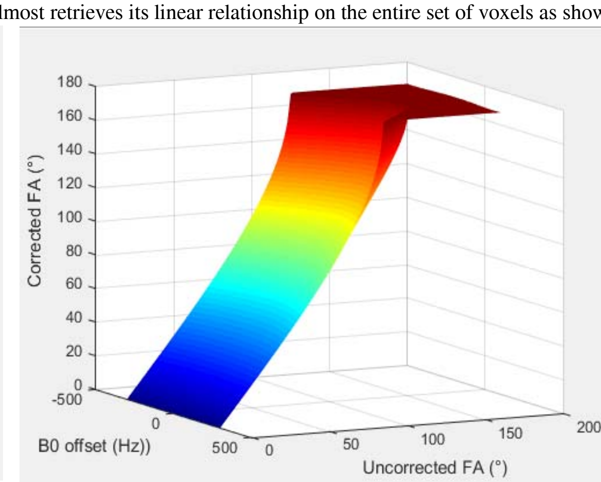

Figure 2: Corrected FA as a function of uncorrected FA and ΔB_0

Discussion and conclusion: 2D multislice sequences are usually faster than 3D sequences when acquiring B1-maps. Yet to reach the same level of accuracy, the process of taking slice profiles into account can be crucial. This is demonstrated here with the XFL sequence, which, with proper post-processing, achieves the same B1-mapping as the AFI sequence in a 25-fold faster acquisition time. The remaining residual non-linearity in Fig. 3b is due to the FLASH readout transient which goes towards a fixed steady state regardless of the encoded FA. This is the subject of further corrections not discussed here... The proposed method can be generalized to other 2D B1-mapping sequences such as XEP [8] or DREAM [9] where FA-encoding preparation pulses precede readout imaging schemes. In particular this will have strong impacts in Tx-array mapping efficiencies.

References : [1] H.-P. Fautz et al., p. 1247, ISMRM 2008. [2] A. Amadon et al, p. 3358, ISMRM 2012. [3] S.J. Malik et al, MRM 65:1393 (2011). [4] V.L. Yarnykh, MRM 57:192 (2007). [5] K. Nehrke, MRM 61:84 (2009). [6] N. Boulant et al, p. 4918, ISMRM 2010. [7] J. Pauly, Matlab 'rf_tools': cf. http://med.stanford.edu/rsl/research/camrt_software.html#pauly [8] A. Amadon et al, p. 2828, ISMRM 2010. [9] K. Nehrke et al., MRM 68 :1517 (2012).

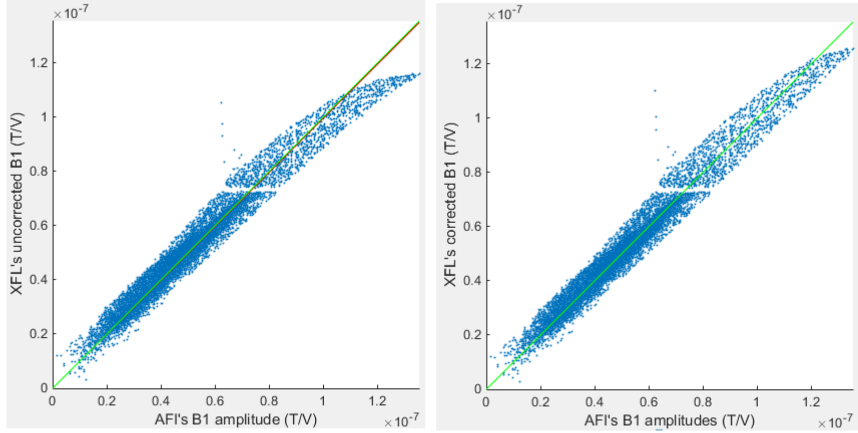

Figure 3: XFL vs AFI derived B1 amplitudes in every voxel of the phantom. a/ left: uncorrected XFL data. b/ right: corrected XFL data