Is a 2D-spiral excitation trajectory sufficient for 3D Inner Volume Imaging ?

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Purpose: Numerous examples of 2D selection have been shown in the parallel transmission (pTx) community. They usually make use of either EPI-like or spiral trajectories in excitation k-space. As for 3D selection, stacks of spirals, 3D spirals or concentric shells have been proposed[1], but their longer pulse duration may hinder their use in some applications. Here we investigate the possibility to use a mere 2D-spiral to insure 3D selectivity for Inner Volume Imaging (IVI), by making the third dimension be the readout axis of a 3D sequence. We thereby observe to what extent the excitation profile is preserved along the readout direction. Eventually, for demonstration, a zooming experiment is performed at 7T on a post-mortem baboon brain.

Methods: Let *V* be the parallelepiped of interest (VOI) with dimensions *X, Y, Z*, with *Z* being the largest dimension. In a 3D isotropic imaging experiment where the reduced FOV is equal to or slightly larger than *V*, taking *Z* as the readout axis is the least time-consuming way of acquiring the 3D dataset. Readout oversampling and band-pass filtering is commonly used to avoid aliasing along that direction so that selectivity can in fact be obtained for free along *Z*. This implies that the excitation profile is uniform in that direction, at least in the VOI. To this end, we design a pTx pulse based on a spiral trajectory in the (k_x, k_y) plane, whose primary goal is to be selective in the *(x, y)* dimensions (i.e. our phase-encode directions). Here we limit the present study to the Small Tip Angle regime, whereby we want to solve the Magnitude Least Squares problem[3]: $\boldsymbol{b} = \arg\min\,(||\boldsymbol{A}\,\boldsymbol{b}| - \boldsymbol{\theta}|^2 + \lambda\,|\boldsymbol{b}|^2)$, where $\boldsymbol{b}$ gathers the RF waveforms on all transmit channels *c*, $\boldsymbol{\theta}$ is the assembly of complex flip angles (FA) wanted in every voxel, λ is a Tikhonov regularization parameter, and $\boldsymbol{A}$ is the k-space encoding matrix, which includes *B0* and $B1_c^+$ information. For our problem, rather than specifying $\boldsymbol{\theta}$ as a 2D target as is commonly done in a spiral transmit design, we introduce a 3D target map: nominal FA in *V*, and zero elsewhere in the *Z*-slab of interest. The remaining voxels, those not contained in the latter, are simply dropped out of the RF design problem, as they should not contribute to aliasing in the reduced FOV.

On a 7T Magnetom scanner (Siemens, Erlangen) equipped with an 8-channel pTx system, a home-made head RF coil was used, consisting of 8 transceiver dipoles azimuthally-distributed along a cylindrical structure. First a 16-cm-diameter spherical doped water phantom was picked to show how effective 2D beam-selective excitations can be for 3D IVI, even in the presence of strong RF inhomogeneities. The readout direction was along the magnet axis. Then a qualitative demonstration of zooming (reduced FOV imaging) was perfomed on a post-mortem baboon brain.

A variable density spiral was designed with the vds package[b] under Matlab (the Mathworks, Natick, MA). Our spiral parameters for the spherical phantom were: outwards, variable Field-of-Excitation FOX = 14-24 cm, spatial resolution = 4 mm, acceleration factor = 2, time-step = 2 µs. The 3D B1-maps associated with each channel were acquired with the AFI sequence[2] used in the interferometric fashion, with a 5-mm isotropic resolution. A 10°-FA was targeted in a centrally-located *V* with dimensions X = 4 cm, Y= 3 cm and variable Z = 4-8 cm. The Magnitude Least Squares problem was addressed by solving the above equation with the LSQR algorithm repeatedly[3]. To start the algorithm, the initial phase pattern was that of a 3D RF-phase-shim mode. The obtained pTx pulse was then evaluated in a 3D fast GRE sequence (FLASH), with a full FOV to check for its selective excitation performance. The measured reception profile and T1-corrections were used to obtain the FA-map. For the baboon experiment, parameters were similar except for halved dimensions for voxel resolution and FOX. The zooming sequence on the baboon brain was a 3D FLASH sequence with sub-millimetric isotropic resolution; the phase-FOV slightly exceeded the VOI to show the transition between zero signal expected at the edge and nominal signal inside the VOI.

Results & discussion: A 4.85-ms pulse was obtained within a couple of minutes on a 4-Gb-memory laptop. For the spiral pulse validation, Fig. 1 shows the full-FOV 5-mm-resolution images of the VOI selected in the spherical phantom. A beam is nicely selected along the readout direction, with a fairly homogeneous profile along the specified VOI depth (cf. Fig. 2). However the indirect measurement of the FA from the FLASH sequence seems to account for a ~10% underestimation of the FA when compared to simulation. Nevertheless the profile shapes do match nicely and look like the one obtained from a non-selective pulse in RF-phase-shim mode. As the Z-slab thickness increases, the deviation of the FA from the target in the entire Z-slab slowly rises as expected (Fig. 3). In addition to the 10%-scaling error, the difference between simulation and experimental NRMSE is likely due to eddy currents and imperfect knowledge of the $B1_c$-maps. Further investigation is needed to take the true k-space trajectory into account as proposed elsewhere[1]. Preliminary zoomed ex-vivo baboon brain images were also obtained (not shown here). They depict the details of the anatomy inside the selected VOI, and show no sign of aliasing artifacts as expected.

Conclusion: In most cases, a single spiral trajectory for beam selective excitation may be sufficient to perform 3D IVI as long as the readout direction is oriented along the axis perpendicular to the spiral plane. To improve the spatial profile along this axis in case of strong RF inhomogeneities, it may be advantageous to work with a z-segmented pTx coil and/or to include k_T-points or a fast k_z-spoke along this readout direction in the pulse k-space trajectory. This is the subject of further study. At last, these beam-selective excitations could be most useful in spectroscopic imaging, making the time- and SAR-consuming Outer Volume Suppression pulses outdated.

References: 1. Schneider et al, MRM doi: 10.1002/mrm.24381. 2. V.L. Yarnykh, MRM 57:192 (2007). 3. Setsompop et al, MRM 59:908-915 (2008).

Acknowledgements: a/ Sponsor: European Grant FP7/2013-2018 ERC 309674. b/ vds package: Hargreaves, http://www-mrsrl.stanford.edu/~brian/vdspiral.

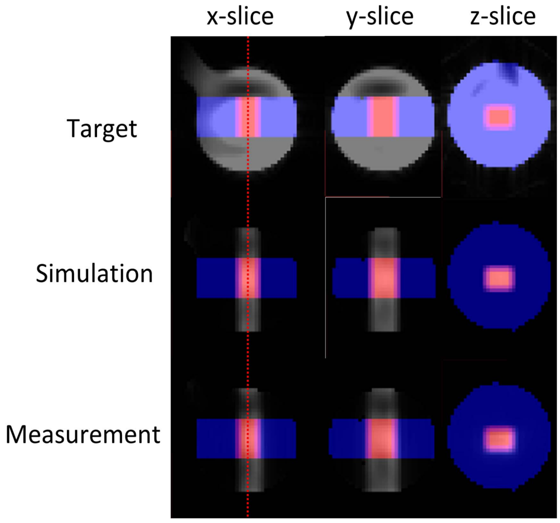

Fig. 1: Beam-selective excitation demonstrated on a spherical phantom. In this example, the specified VOI depth along z is 6 cm. Top row shows the slab of interest for pulse design (background image obtained from non-selective pulse in RF-shim mode); middle row depicts the FA-map found from Bloch-simulation of the obtained pulse; bottom row shows the equivalent FA-map found from dividing the receive profile from a FLASH acquisition loaded with the same pulse. On all images, blue = 0°, pink = 10°. Note how strong RF inhomogeneities are in top row.

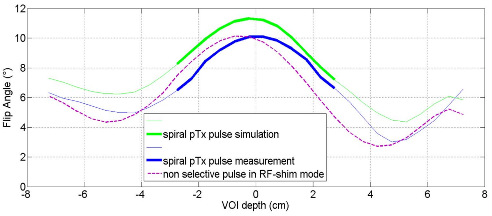

Fig. 2: Profile of the FA along the main z-axis (cf. red line in Fig. 1). The bold parts correspond to the specified VOI. The non-uniform shape shows the same limitation as a 3D RF-shimming experiment.

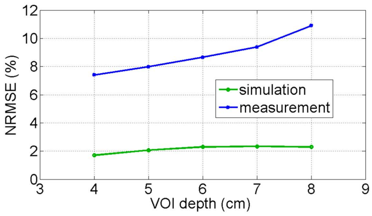

Fig. 3: Root Mean Squared Error of the FA normalized to its 10°-target across the Z-slab of interest as a function of the slab thickness.