Does the best distance beween 2 spokes match the inverse RF wavelength ?

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Target Audience: High Field MRI physicists/engineers involved in RF pulse design, in particular if scanner is equipped with a parallel transmit (pTx) system.

Purpose: Multiple fast-kz spokes have been introduced to compensate for B1 inhomogeneities in the slice selection (SS) process.[1] When used with pTx, spoke pairs can be sufficient to reach adequate in-plane excitation uniformity.[2] Upon solving the Flip Angle (FA) Magnitude Least Squares (MLS) problem,[3] it has been observed that RF pulse performance only depends on the magnitude of the $\boldsymbol{\Delta k}$ vector linking the two spokes in the (k_x, k_y) plane.[4] In this study, we hypothesize and want to verify that the magnitude $|\boldsymbol{\Delta k}|$ bringing the best performance is independent of the in-plane size of the slice of interest, and roughly matches $1/\lambda$, where λ is the RF wavelength in the observed body, e.g. ~13 cm in the brain at 300 MHz.

Methods: In order to validate our hypothesis, we designed spoke pair RF pulses for various axial brain slices in 5 different subjects whose head size and shape varied significantly. For each slice of interest, all (Δk_x, Δk_y) components of the $\boldsymbol{\Delta k}$ vector over the interval [-4;4]×2π/FOX (FOX = 25 cm) were tried with 128 steps in each direction. Our setup is a Siemens 7T Magnetom scanner (Erlangen, Germany), equipped with an 8-channel Tx-array, a home-made transceiver-array cylindrical RF head coil, and an AC84 head gradient set. Axial slices were selected because of the benefit of the azimuthal distribution of our RF coil elements with regards to the 2-spoke trajectory. Three-dimensional B0 and Tx-array B1 maps of human brains were acquired on informed and consenting subjects with standard measurement methods,[5] at an isotropic 5-mm resolution. This study focuses on a 10° FA target in 5-mm slices of interest. For pulse design, the MLS problem is solved in the Small Tip Angle approximation under strict power, global SAR and 10g SAR constraints, using the Active-Set algorithm initialized with the variable-exchange-method.[3,6] Global and 10-g SAR are assessed from the candidate RF waveforms combined to pre-computed normalized 10-g SAR matrices (Q-matrices). Those were found from HFSS (Ansys, Canonsburg, Pennsylvania) E-field simulations of a head model inside our coil.[6] The variable-exchange method is itself initialized with the target phase map of the circularly-polarized (CP) mode. RF pulse performance is obtained from a full Bloch simulator computing the final FA in every voxel of the slice of interest. The performance metrics is the in-plane FA rms error normalized to the mean target FA (NRMSE). For every slice of interest, the NRMSE landscape was plotted in the (Δk_x, Δk_y) plane, verifying its (upside-down) Mexican hat structure. In this k-space plane, the best NRMSE was sought along every polar angle direction (360 directions were spanned). The mean and standard deviation of the $|\boldsymbol{\Delta k}|$ corresponding to the smallest NRMSE's are reported for every slice of interest in all 5 subjects. Such values are then confronted to $1/\lambda$, with $\lambda = \frac{c}{f_0\sqrt{\varepsilon_r}}$ where the electric permittivity ε_r is picked from the literature for the brain at the 7T Larmor frequency f_0 = 300 MHz.[7] For the sake of simplicity, the study was limited to three axial slices of interest per subject in the inferior, central, and superior parts of the brain. Distances between the central and external slices ranged from 25 to 35 mm depending on the brain size, leading to significant in-plane size differences (cross-section roughly varying by 25-30%).

Results & discussion: Brain mask slices of interest are shown for the fourth subject along with their corresponding NRMSE k-space landscapes in Fig. 1. Note their somewhat ring-like structure,[4] with optimal NRMSE being located at a roughly constant radius, especially in the superior slice. This radius and its dispersion are reported in Fig. 2 for the slices of interest in all 5 volunteers. For instance Fig. 1's subject is shown in brown on Fig. 2. It can be appreciated how constant the best $|\boldsymbol{\Delta k}|$ radius seems to be across subjects, especially when the slice has a somewhat cylindrical symmetry (central and upper slices). When excluding (including) the inferior slices whose cylindrical symmetry is broken, the weighted mean of the best performance radii across subjects is $|\boldsymbol{\Delta k}|$ = 8.42 m^{-1} (8.61 m^{-1}). Taking the inverse of this value leads to 11.9 cm, which is between the grey and white matter wavelengths at 300 MHz (respectively 11.7 and 13.8 cm according to [7]). Now if pulse design is based on the generic inverse of the mean wavelength between white and grey matter (i.e. $|\boldsymbol{\Delta k}|$ = 7.8 m^{-1}), the obtained NRMSE is somewhat degraded with respect to the smallest NRMSE, as shown in Table 1. However, the small amount of performance loss (less than 1%) can be used as an argument to avoid complex and time-consuming k-spoke placement optimization and facilitate 2-spoke pulse design in routine exams.

Conclusion: In the process of uniform slice selection with a spoke pair at UHF, it was shown via simulations that the inverse of the MLS optimal distance between the spokes seems to be quite independent of the in-plane size of the slice. It seems that this quantity roughly matches the RF wavelength λ in the exposed object, in particular if the object has the same cylindrical symmetry as the spatial distribution of the RF coil elements. So far RF pulse design tailored to compensate for B1 inhomogeneities, whether using spokes or k_T-points[8], has been based on small k-space displacements proposed in 1/FOX units, where FOX is an arbitrary field of excitation usually taken as the field of view of the B1-maps. This study hints that it is more appropriate to think of these displacements in terms of 1/λ units. As demonstrated here, taking the 1/λ literature value as the distance between spokes or k_T-points should not degrade pulse performance significantly and could advantageously be used as a practical landmark for fast routine pulse design or as a starting point for elaborate k-space location optimizations.

References: **1**. Saekho et al, *MRM* 55:719 (2006). **2**. Setsompop et al, *MRM* 60:1422 (2008). **3**. Setsompop et al, *MRM* 59:908 (2008). **4.** Dupas et al, *ISMRM* 2015. **5**. Amadon et al, # 3358, ISMRM 2012. **6**. Hoyos-Idrobo et al, *IEEE Trans. Med. Imag.* 33:739 (2014). **7.** Gabriel et al, *Phys.Med. Biol.* **41:**2231 (1996). **8**. Cloos et al, *MRM* 67:72 (2012).

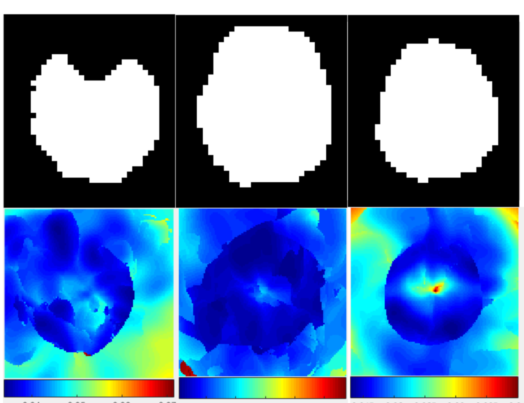

Figure 1: Axial brain slices of interest in subject 4 and their corresponding NRMSE landscape in the (Δk_x, Δk_y) plane.

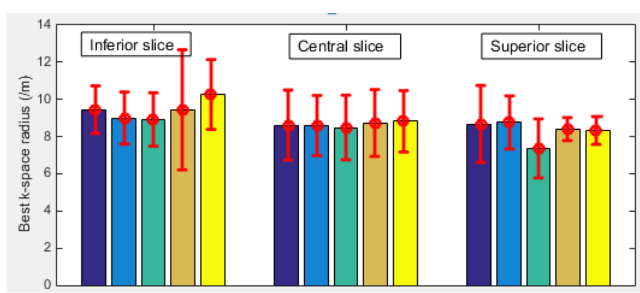

Figure 2: |Δk| radius leading to the smallest NRMSE across radius directions (error bars show standard deviation), subjects (5 colors), and slice positions.

Slice position	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	**Mean**
Inferior	0.66	0.85	0.57	0.42	0.77	**0.65**
Central	0.30	0.42	0.38	0.43	0.43	**0.39**
Superior	0.33	0.38	0.29	0.20	0.45	**0.33**

Table 1: NRMSE difference between generic |Δk|~1/λ and best |Δk| solutions (in absolute %)