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Phase matched RF pulse design for imaging a reduced field of excitation with a fast TSE acquisition

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Title page**Phase Matched RF Pulse Design for Imaging a Reduced Field of Excitation with a fast TSE acquisition**

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Manuscript**Phase Matched RF Pulse Design for Imaging a Reduced Field of Excitation with a fast TSE acquisition****Abstract**

A method is described to design parallel transmit (PTX) excitation pulses that are compatible with turbo spin echo (TSE) sequences, based on information available from conventional per-channel B_1^+ mapping. The excitation phase of PTX pulses that generate a reduced field of excitation (rFOX) is matched to the phase the quadrature mode of a PTX coil. This enables TSE imaging of a PTX-enabled rFOX excitation combined with standard nonselective refocusing pulses transmitted in the quadrature mode. *In-vivo* imaging experiments were performed at 7T using a dual channel parallel transmit head coil. In combination with simulations, the CPMG-required excitation phase was confirmed in TSE sequences with refocusing pulses of variable flip angle. Further experiments showed that the same rFOX was generated in TSE and gradient echo sequences, enabling high-resolution imaging with parallel imaging acceleration of the rFOX.

Keywords: RF pulse design, TSE, CPMG, B_1^+ maps, phase matching, rSENSE

Introduction

Tailored radio frequency (RF) excitation pulses [1] can create a personalized reduced field of excitation (rFOX), allowing acquisitions shortening [2] and avoiding motion artifacts from outside the region of interest [3]. These qualities are increasingly important at (ultra) high field, where the long scan times that are associated with high-resolution imaging increase the risk of motion artifacts. Parallel transmission (PTX) can be used to shorten tailored RF pulses [4].

Application of tailored excitation pulses is simple for gradient echo (GRE) sequences: through amplitude scaling any flip angle up to 90° can be obtained [5]. In turbo spin echo (TSE) sequences however, the CPMG conditions [6,7] constrain the phase of the tailored pulse: the excitation phase should offset the refocusing pulse's phase by $\pi/2$, at every location of the imaged volume. This is particularly important when the refocusing pulses are nonselective and of variable flip angle (VFA) [8]. With these short, less than 180° , refocusing pulses, more than 100 echoes can be solicited from a single rFOX-generating tailored excitation pulse. The spiral-in transmit k-space trajectory is especially suited for this sequence: the center of k-space is sampled at the end of the pulse, allowing the first pulse of the refocusing train to follow rapidly and consecutive pulses with short spacing. Although tailored excitation in combination with a default-mode (turbo) spin echo acquisition has been reported in the past [9,10], this has been done without describing how the phase of the personalized pulse should be treated.

For the acceleration of rFOX-featuring sequences, rSENSE [3] has been shown to be more efficient than only reducing the field of view (FOV), allowing rFOX shapes that are non-rectangular and discontinuous. This method works by excluding voxels from parallel imaging reconstruction, after identifying these voxels based on a receive coil reference scan acquired with the same rFOX. Since the reference scan is acquired with GRE sequences, tailored pulses that generate a sequence-nonspecific rFOX are advantageous for rSENSE acceleration of rFOX-TSE acquisitions.

The aim of this paper is to provide this missing link between tailored pulses and nonselective refocusing pulses, thereby expanding their application to VFA-TSE sequences. Previous applications of rFOV imaging with TSE [9,10] illustrate the desire for such a combination, however the phase issue of CPMG was not addressed adequately. To allow the same pulse to be used in different sequence types, including rSENSE calibration scans, phase-matching is preferably achieved without sequence-specificity. Furthermore, we aim to achieve this by using the information that is already known from B_1^+ maps used for PTX radiofrequency pulse design (RFPD).

Materials and Methods

Phase-matching conditions

Tailored excitation pulses can in principle shape the magnetization pattern to any complex-valued target. The RF waveforms are numerically optimized, in combination with predefined gradient waveforms, and taking into account measured field distributions (B_0 and B_1^+). Conversely, the nonselective refocusing pulses that follow the excitation pulse in VFA-TSE

sequences produce a spatial phase pattern that is governed solely by the transmit phase of the driving mode.

The phase profile of the magnetization after excitation ($\varphi_{magnetization}(r)$) should be CPMG-matched to the phase of the refocusing pulses:

$$\varphi_{magnetization}(r) = \pi/2 + \angle[\sum_{j=1}^N c_j A_j(r) e^{i\varphi_{tx,j}(r)}],$$

where $A_j(r)$ and $\varphi_{tx,j}(r)$ are the amplitude and absolute phase of the B_1^+ field per transmit channel j , at location r , for N channel, and the complex weights ($c_j = C_j e^{i\varphi_{c,j}}$) govern the combination of individual transmit channels. As $A_j(r)$ is measured using a B_1^+ -mapping method, and c_j is defined, both of these are known. The transmit phase $\varphi_{tx,j}(r)$ is not known explicitly, but is nonetheless contained in any recorded signal, combined with additional contributions from the receive system and the specific sequence that was used to measure the signal.

In B_1^+ -mapping methods that measure each channel sequentially (for example: AFI [11], DREAM [12,13]), the additional phase terms are identical for the measured signal¹ of each transmit channel. This measured signal phase can be used, instead of the unknown absolute transmit phase, to define the transmit coil sensitivities in RFPD. Since the additional phase terms are equal for all channels, they will result in an offset in the magnetization phase with respect to any arbitrary target:

$$\varphi_{magnetization}(r) = \varphi_{target}(r) - \varphi_{sequence+receive}(r).$$

For the magnetization to satisfy CPMG after excitation, the target phase requires pre-correction for this phase offset:

$$\varphi_{target}(r) = \pi/2 + \angle[\sum_{j=1}^N c_j A_j(r) e^{i\varphi_{tx,j}(r)}] + \varphi_{sequence+receive}(r).$$

Even though the individual phase elements are still undetermined, the total expression is found if we calculate the phase of the refocusing mode using the measured B_1^+ maps, where again the phase of the measured signals replaces the absolute transmit phase:

$$\begin{aligned} \angle[\sum_{j=1}^N c_j A_j(r) e^{i(\varphi_{tx,j}(r) + \varphi_{sequence+receive}(r))}] = \\ \angle[\sum_{j=1}^N c_j A_j(r) e^{i\varphi_{tx,j}(r)}] + \varphi_{sequence+receive}(r). \end{aligned}$$

The phase is as an *additional* requirement next to the targeted magnitude profile that describes the rFOX. The resulting rFOX is therefore expected to be the same in both TSE and GRE sequences.

Experiments

All experiments were conducted with a birdcage head coil (Nova Medical, Wilmington, MA) of which the two ports could be driven either in quadrature mode or independently, using the two transmit channels of the scanner (7T Achieva, Philips Healthcare, Cleveland, OH). When tailored

¹ For example the stimulated echo and the free induction decay in DREAM [12]

excitation pulses were used, the two channels were driven independently (PTX). During B_1^+ -mapping, one channel was active at a time. All other RF pulses were emitted using the quadrature mode.

Healthy volunteers were scanned, after having provided informed consent. Calibration scans were performed as follows. First a B_0 -map (multi-echo 3D GRE, $\Delta TE = 1$ ms) was acquired for image based shimming on the brain with up to 3rd order shims. These shim settings were used for all subsequent scans of the same subject. A second B_0 -map was acquired to determine the remaining static field variations for RFPD. For parallel imaging, the receive coil sensitivities (32 channel head coil, Nova Medical, Wilmington, MA) were measured using a 3D spoiled GRE sequence at 1° flip angle. A signal was recorded once using the individual receive channels and (in lieu of a body coil as external reference source) once using the two-channel head coil in quadrature mode. B_1^+ maps of the individual transmit channels were acquired using DREAM [13] (FID first, STEAM angle 40°).

Tailored pulses were computed on-site [14], using the B_0 and B_1^+ maps of one transverse slice, to generate a two-dimensionally selective rFOX. The complex RF waveforms were numerically optimized for a spiral k-space trajectory, of which the maximum k-space value to be sampled was adjusted for each experiment. Local SAR was monitored using a look-up-table of maximum local SAR values for each combination of amplitude ratio and relative phase of the two channels, summed over all samples of the PTX RF pulses [15].

Parallel imaging acceleration of scans featuring an rFOX was done using rFOX-adapted SENSE: rSENSE [3]. A full FOV is reconstructed, but the reconstruction is informed of the rFOX so that voxels outside the rFOX can be 'blanked'. For this, the receive coil sensitivity mapping was repeated with the same rFOX-generating pulses, scaled to 1° flip angle.

Experiment 1: phase matching in a CPMG sequence, full brain excitation

The first experiment was designed to test phase matching in a sequence in which the CPMG conditions are essential: VFA-TSE with 213 echoes per excitation. To facilitate analysis over a large area, the tailored pulse was targeted to excite the entire brain on a transverse slice. A second pulse was designed to target a spatially constant phase, reflecting a situation in which the transmit phase is (assumed to be) corrected for the phase of the quadrature mode. A third image was acquired using the scanner's default non-selective excitation pulse.

Pilot experiments (not shown) revealed a maximum achievable flip angle of 40°; higher values would exceed the hardware limit of 20 μ T RF amplitude for these tailored excitation pulses (duration: 2.7 ms). This excitation flip angle was chosen for all scans in this experiment. Acquisition parameters are listed in **Table 1**. An exemplary sequence diagram (**Figure 1**) shows how tailored excitation relates to the VFA-TSE refocusing train.

Experiment 2: phase-matched excitation pulses in GRE and TSE sequences, excitation of the visual cortex

The second experiment tested if the same rFOX is created in GRE and TSE sequences. To this end, a tailored pulse was used in the low-resolution GRE-based sequence for receive coil sensitivity mapping. Subsequently, VFA-TSE images were acquired using the same excitation pulse, and using the coil sensitivity maps for rSENSE unfolding. A consistent rFOX between the calibration scan (GRE) and accelerated images (TSE) is important for this technique, otherwise signal unfolding artifacts could occur [3]. The rFOX target was the visual cortex and the hardware-limited flip angle was 85°. This was a small deviation from the 90° excitation in the reference VFA-TSE image with non-selective excitation and otherwise identical parameters. The receive coil mapping parameters were the same as the standard protocol, but with a longer TR to incorporate the tailored pulse (duration: 9.7 ms), see **Table 1**.

Experiment 3: high resolution imaging of the temporal lobe using GRE and TSE

In experiment 3, phase-matching was tested in an area that generally suffers from poor B_1^+ performance at 7T, the temporal lobe. This rFOX was imaged at high resolution using both VFA-TSE and GRE with multishot EPI (GRE-EPI). Previous work has shown that instead of using a reduced field of view acquisition, the rFOX can be used to acquire a full field of view with higher SENSE acceleration factors compared to nonselective excitation [3]. Therefore, in this experiment with a small rFOX area, a higher SENSE factor could be chosen compared to the full brain excitation in Experiment 1.. Pulse duration was 9.7 ms, scan parameters are in **Table 1**.

Results

Experiment 1: phase matching in a CPMG sequence, full brain excitation

Figures 2a-d show the B_1^+ maps and targets (**Figures 2e** and **2g**) that were generated in this experiment. The phase-matched RF pulse had a maximum amplitude of only 11.7 μ T, versus 19.7 μ T for the constant-phase-targeted pulse (**Figures 2f** and **2h**).

The TSE images with phase-matched excitation (**Figures 3b** and **3e**) match the appearance of those acquired with standard excitation (**Figures 3a** and **3b**). The ratio of these images (**Figure 3i**) confirms that the signal intensity levels are fairly similar, with a higher signal level in the temporal lobes. Patterns of reduced signal intensity are seen in the images with constant-phase excitation (**Figures 3c, 3f, and 3j**). Bloch simulations[16] (**Figure 3h**) show the excitation phase is off-CPMG in the same area, confirming the sequence's sensitivity to the CPMG conditions.

Experiment 2: phase-matched excitation in GRE and TSE sequences, visual cortex

The rFOX was successfully created in the GRE scan (**Figures 4b** and **4d**), and similarly in the TSE scan (**Figures 4e** and **4g**). No artifacts are observed when the zoomed-in rFOX-TSE and reference images (**Figures 4i** and **4j**) are compared, confirming that rSENSE was applied successfully.

Experiment 3: high resolution imaging of the temporal lobe using GRE and TSE

High resolution images were successfully obtained (**Figure 5**). Some improvements in image quality can be seen in the rFOX images: the TSE image appears more homogeneous (**Figures 5h** vs. **5j**) and the GRE-EPI displays a lower noise level towards the center of the brain (**Figures 5g** vs.

5i). The first observation is attributed to a locally homogeneous excitation, the second to a lower g-factor from using rFOX with SENSE.

Inspecting the rest of the excited volume, a distinct artifact can be seen in the rFOX-TSE image that was reformatted at a position inferior to the slice used for RFPD (**Figure 6h**). The signal void does not appear in the T2*-weighted images (**Figures 6e and 6g**), nor in the rFOX-TSE image reformatted at a superior location with respect to the targeted slice (**Figure 6f**). Measured local B_0 deviations (**Figure 6n**) and the simulated deviation from CPMG phase (**Figure 6p**) in this area indicate that ΔB_0 -induced phase deviations are causing the TSE artifact. Indeed, sudden susceptibility changes near the base of the brain are known to cause B_0 fluctuations in this region. The measured B_1^+ in this slice also deviated from the values obtained in the target slice (**Figure 6m**), and so did the simulated flip angle (**Figure 6o**), but these values vary only gradually across the slice. In the superior slice, no major deviations in the measured fields are seen and the rFOX generated by the tailored pulse remained intact (**Figures 6c and 6d**).

Discussion

This study has been performed as a proof of principle to show that subject specific multidimensional selective excitation can be performed with VFA-TSE and GRE acquisitions. The acquisitions with rFOX were accelerated using rSENSE: instead of reducing the prescribed FOV, the SENSE reconstruction is improved by the reduced number of voxels that require unfolding.

Earlier work that featured tailored excitation in combination with VFA-TSE [10] used interferometrically acquired B_1^+ maps of which the phase-implications are not described. We speculate that the sensitivity maps are pre-calibrated with respect to default excitation mode and the transceive phase, explaining the successful TSE experiments.

For phase-matching, the phases of any B_1^+ -mapping method or other combination of signals can be used, provided that the transmit phase is the only phase contribution that varies between the individual signals. The presented method is developed from a PTX point-of-view, but is equally valid for single channel systems. However, transmit phase maps are no longer required here and the transmit phase and target phase could simply be defined as, respectively, zero and $\pi/2$ at every location. The phase can't be ignored completely (as in a pure magnitude least squares optimization), since this would violate the CPMG conditions.

A 90° flip angle was not always accomplished. RF amplitude-limiting techniques such as VERSE [17] may be used to reduce the amplitude, and possibly also the length [18], of the tailored pulses. The RF amplitude needed to excite the same rFOX was reduced when the target phase was matched to quadrature mode, compared to a constant target phase. This reduction is a noteworthy advantage over an improperly chosen target phase and advocates the use of phase-matching even for non-TSE imaging. We did not systematically investigate the possible improvements of existing TSE protocols, and for TSE imaging the benefits of using rFOX remain to be seen – applications could include imaging near structures in motion.

Although the pulses were designed on a 2D plane, the efficacy of the phase matched tailored pulses was quite robust in other slices. Only in areas with large B_0 variations compared to the

targeted slice the CPMG conditions could no longer be satisfied. This degradation due to ΔB_0 effects might be avoided by increasing the bandwidth of the pulses [19,20] or by considering three dimensional field information during phase-matched pulse design.

In conclusion, phase matched excitation pulses allow VFA-TSE imaging with standard refocusing pulses. This was achieved by using phase information from a signal that is acquired as part of conventional B1+-mapping. The applicability of these pulses remained uncompromised in GRE sequences, allowing coil sensitivity mapping of the same rFOX, and ultimately rSENSE acceleration of the TSE acquisition.

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Figure legends

Figure 1. Sequence diagram showing tailored excitation and VFA-TSE refocusing train. The excitation pulse shown here was used to create an rFOX in Experiment 3. The refocusing pulses ($\alpha_1, \alpha_2, \dots \alpha_N$) are nonselective, of variable flip angle, and depicted with an echo spacing of 2.5 ms. FE: frequency encoding direction, PE1, PE2: first and second phase encoding direction, ADC: analog to digital converter to indicate signal recording.

Figure 2. Experiment 1: Full brain excitation. Measured B_1^+ maps for both channels, **a,b**: amplitude and **c,d**: phase from the stimulated echo (STE) signal. **e,g**: Target magnetization phase pattern masked by the shape of the target magnetization amplitude, for the phase matched (**c**) and spatially constant phase pattern (**g**). Corresponding PTX RF amplitude waveforms (**f,h**).

Figure 3. Experiment 1, full brain excitation. The orange line in the sagittal images marks the position of the slice that is used for tailored pulse design. The transverse images are displayed at this position. **a-f**: 3D VFA-TSE images acquired using different excitation pulses in combination with nonselective refocusing pulses. **a,d**: Non-selective standard excitation pulse, **b,e**: quadrature phase matched tailored pulse with full brain target, **c,f**: constant phase tailored pulse with nearly full brain target. **a-c**: (native) sagittal orientation. **d-f**: transverse reconstructions at the position of the target slice, where the measured information was used in RFPD. **g,h**: Simulated difference between the phase of the tailored pulse and the phase pattern prescribed by CPMG, at the same transverse slice. Note that the in **h** the full range of values is shown, while in **g** the window of values is reduced to $1/4^{\text{th}}$ to show any contrast. The pattern (marked with arrowheads) of locations with a large phase deviation (**h**) is similar to the signal loss in the TSE images in **f**. In the transverse plane, it mainly manifests as a ring-like structure, and extends in the feet-head direction, as can be seen in **c**. **i,j**: Ratio maps of the VFA-TSE images obtained with different excitation strategies. When a constant-phase excitation design is used, the same band structure as in 2f is seen. The phase-matched excitation avoids these signal gaps and even increases signal levels in the temporal lobes. The <1 values on the outer edge are the result of prescribing the target area slightly smaller than the brain tissue.

Figure 4. Experiment 2, excitation of the visual cortex. The yellow lines in the sagittal images mark the position of the transverse slice used for tailored pulse design, which is also used in the transverse images of this Figure. **a,b,c,d**: Low resolution GRE images used for receive coil sensitivity mapping. **e,f,g,h**: TSE images using a 3D VFA acquisition and (r)SENSE acceleration. **a,c**: GRE with standard excitation for whole brain, **b,d**: GRE with phase matched rFOX, **e,g**: TSE with phase matched rFOX, **f,h**: TSE with standard excitation. **Top row**: sagittal (native) view, **middle row**: transverse (reformatted) view. **Bottom row**: zoomed-in sections of **g,h**. **i**: Phase matched rFOX, **j**: standard excitation.

Figure 5. Experiment 3, excitation of the temporal lobe with high resolution imaging. **a,d**: Low resolution GRE coil reference scan, **b,e**: T2* GRE-EPI at $(0.35 \text{ mm})^3$, **c,f**: T2 VFA-TSE at $(0.6 \text{ mm})^3$. **g,h,i,j**: Zoomed versions of the high resolution images (**b,c,e,f** respectively). **Top row**: standard excitation, **bottom row**: phase-matched rFOX.

Figure 6. Experiment 3: zoomed images of the temporal lobe in transverse slices at positions superior and inferior to the target slice for RFPD. The position of the slices are shown in **the upper image**. **Middle row:** Zoomed images at 21 mm superior to the target slice, **bottom row:** 21 mm inferior to the target slice. **From left to right:** standard excitation GRE-EPI with T_2^*w , standard excitation VFA-TSE with T_2w , rFOX GRE-EPI with T_2^*w , rFOX VFA-TSE with T_2w , ratio of measured B_1^+ maps compared to the target slice, difference in B_0 maps compared to the target slice, simulated Flip Angle in the slice, simulated phase difference between the tailored excitation and the CPMG-prescribed phase pattern. A signal void is observed in the rFOX TSE image in the inferior slice (**h**, arrow head). The same region shows a strong offset in B_0 (**n**) and a deviation from the CPMG-phase (**p**). The simulated Flip Angle (**o**) is reduced to approximately 45 degrees in this region.

Table 1. Scan parameters

	TSE Exp. 1 & 2	TSE Exp. 3	GRE Exp. 3	Receive coil mapping
Scan type	3D VFA-TSE T2	3D VFA-TSE T2	3D GRE-EPI T2*	3D spoiled GRE
FOV (P x RL x FH) (mm ³)	250 x 191 x 250	220 x 190 x 150	229 x 200 x 150	300 x 300 x 450
Scan orientation	sagittal	sagittal	Sagittal	transverse
Resolution (mm)	1 x 1 x 1	0.6 x 0.6 x 0.6	0.35 x 0.35 x 0.35	4.7 x 4.7 x 4.7
Undersampling factor	1.2 x 2.8	2.3 x 3.3	2.5 x 2.5	-
Excitation flip angle (°)	40 ^A / 85 ^B / 90 ^C	90	22	1
Shot length	213	162	9	-
TSE echo spacing (ms)	2.3	3.5	-	-
TSE VFA range (°)	[10,90]	[10,90]	-	-
TE (ms)	281 (effective)	295 (effective)	27	0.79 ^E / 0.71 ^F
TR (ms)	3,158	3,158	66 ^E / 65 ^F	8 ^E / 39 ^F
Fat Suppression	SPAIR ^D	SPAIR ^D	-	-
Signal averages	2	2	1	2 ^G
Scan time (m:s)	9:45.6	10:16	7:20 ^A / 7:17 ^B	5:24

A: Experiment 1, rFOX and standard excitation

B: Experiment 2, rFOX

C: Experiment 3, standard excitation

D: SPAIR: Spectral Attenuated Inversion Recovery

E: When a standard excitation pulse is used

F: When a tailored rFOX pulse is used

G: Two scans with different receive coil setups

Highlights

- Phase-matched RF pulse design allows for TSE imaging with a personalized 2D-selective excitation in combination with fast, non-selective refocusing pulses.
- In-vivo experiments at 7T confirmed that the CPMG conditions for the excitation phase were observed
- Phase information from conventional B1+ maps was used, no additional measurements were required
- Phase-matched RF pulses created the same 2D excitation in gradient echo and spin echo sequences

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6