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Slice-selective Adiabatic Magnetization T_2 -Preparation (SAMPA) for Efficient T_2 -Weighted Imaging at Ultra-High Field Strengths

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Abstract

Purpose—At high field, T_2 -weighted (T_2w) imaging is limited by transmit field inhomogeneity and increased radiofrequency power deposition. In this work we introduce SAMPA (Slice-selective Adiabatic Magnetization T_2 Preparation) and demonstrate its use for efficient brain T_2w imaging at 7T.

Methods—SAMPA was designed by subsampling an optimized B_1 insensitive rotation (BIR4) waveform with small tip angle linear subpulses. In order to perform T_2w imaging, SAMPA was inserted before a fast gradient echo acquisition. The off-resonance behavior, B_1 robustness and slice selectivity of the novel T_2 preparation module were analyzed using Bloch simulations. The performance of SAMPA for T_2w imaging was demonstrated in phantom experiments as well as in the brains of healthy volunteers at 7T.

Results—Based on simulations, the proposed design operates at peak B_1 of 15 μ T and higher, within a 400 Hz bandwidth. T_2 values were in strong agreement with spin echo-based T_2 mapping in phantom experiments. Whole brain, interleaved multislabs 3D imaging could be acquired with 0.8 mm³ isotropic resolution in 5:36 min per T_2 weighting.

Conclusion—Compared with previous adiabatic T_2 preparation techniques, SAMPA allows for slice-selectivity, which can lead to efficient and robust acquisitions for T_2w imaging at high field.

Keywords

adiabatic; RF pulse; T_2 preparation; multislabs; 3D; T_2 mapping; FLASH; ultra-high field; 7T; 7 Tesla

INTRODUCTION

T_2 weighted (T_2w) imaging is an important constituent of most clinical MR exams. At 1.5T and 3T, multi-echo spin echo sequences are extensively used to generate T_2w images. One of the main drawbacks of spin echo-based sequences is the large radiofrequency (RF) power

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SUPPORTING MATERIAL

Matlab_SAMPA.zip: set of Matlab scripts and functions used to generate and simulate SAMPA pulses. The main document containing SAMPA design is *script_design_SAMPA.m*. For Bloch simulations, the reader needs to download this simulation tool developed by Brian Hargreaves: <http://mrsrl.stanford.edu/~brian/blochsim/>

deposited by refocusing pulses, leading to significant scan time increase in order to remain below specific absorption rate (SAR) limitations at 3T and above. In addition, the inhomogeneous transmit field (B_1) when operating at high field strengths leads to signal loss and variable T_2 contrast across the imaged volume. One alternative to spin-echo-based T_2 w imaging is to play a T_2 magnetization preparation (T_2 -prep) followed by a fast imaging acquisition (1,2). A T_2 -prep is typically composed of a 90° tip-down pulse, at least one refocusing 180° pulse and a 90° tip-up pulse that stores the magnetization on the z-axis for future measurement. Previous studies have shown the advantage of a T_2 -prep approach for coronary imaging (3), black blood imaging (4–6) and more recently, functional MRI (fMRI) (7). In addition, T_2 -prep allows for fast quantitative T_2 measurements using a variable preparation length (8), which has been applied to myelin quantification using multi-exponential models (9,10).

One disadvantage of the T_2 -prep method is its high sensitivity to B_0 and B_1 inhomogeneity, which results in signal loss and banding artifacts due to incomplete refocusing or imperfect tip-down or tip-up projections. Advanced RF pulse designs have been proposed to improve robustness of the T_2 -prep, including MLEV series of refocusing pulses at driven equilibrium (5,6,11), pairs of adiabatic pulses (12), B_1 -insensitive refocusing pulses (BIREF) (13), and B_1 -insensitive rotation pulses (BIR4) (14–16) that operate at null flip angle. However, all these designs perform T_2 weighting in the whole imaged volume, resulting in inefficient acquisitions because of long repetition times required for T_1 recovery. Providing a spatially selective T_2 -prep module would lead to increased flexibility in protocol design and higher efficiency when using interleaved slice or slab acquisitions. Because none of the previously proposed T_2 -prep methods allow for slice selectivity (MLEV uses hard pulses while BIREF and BIR4 quality degrades significantly when played with slice gradients), there is a need for novel pulse designs with the capability of providing slice selectivity in addition to being robust to B_0 and B_1 variations.

In this work we introduce SAMPA (Slice-selective Adiabatic Magnetization PreparAtion), which consists of a BIR4-based T_2 -prep envelope subsampled by slice-selective subpulses. SAMPA uses similar design principles as STABLE pulses proposed previously to achieve B_1 -insensitive excitation in a slice (17,18). We analyze the B_0 and B_1 sensitivity of the proposed T_2 -prep using Bloch simulations, and show that SAMPA can be efficiently applied to brain T_2 w imaging and T_2 mapping at 7T.

METHODS

SAMPA pulse design

The T_2 -prep was designed in three steps:

- **BIR4 pulse design:** an optimized BIR4 pulse was derived from an adiabatic full passage (AFP) 180° pulse generated using the adiabatic Shinnar-Le Roux (SLR) algorithm (19). A linear SLR pulse (20) with time bandwidth 6, passband and stopband ripple 0.01, was created using `firls` function in MATLAB (The Mathworks, Natick, MA). Subsequently,

quadratic phase was overlaid on the spectral domain of the linear RF pulse to induce adiabatic behavior as proposed in (19), as follows:

$$F(\omega) = F_0(\omega) e^{ik\omega^2}$$

With F_0 and F the spectral domains of the linear and adiabatic pulses respectively, and $k = 5.11 \cdot 10^{-4} \text{ s}^2$ the quadratic phase strength. The inverse SLR transform was applied to the Fourier transform of $F(\omega)$ to yield the amplitude and phase of the RF pulse. The pulse was further truncated at 10% of its peak amplitude to improve efficiency, while maintaining an undistorted magnetization profile. The final AFP pulse had a 12 ms duration, 960 Hz bandwidth, and achieved B_1 -independent inversion for B_1 values above a $5.3 \mu\text{T}$ adiabatic threshold. This AFP pulse was then cut in half to yield the adiabatic half passage (AHP) and reverse half passage (rAHP) used to compose the full BIR4 pulse. The resulting BIR4 had a total length of 24 ms and is shown in Fig 1A.

- **SAMPA design:** the previously designed BIR4 envelope was then subsampled with slice-selective linear phase subpulses. 44 subpulses were used over the full 24 ms-long waveform. Such subsampling will result in spectral aliasing occurring at 1.83 kHz, which is larger than the initial BIR4 bandwidth and therefore minimally alters the off-resonance behavior of the initial BIR4 envelope. For the subpulses, Hamming-windowed sinc pulses with a time bandwidth product (TBW) of 1 were found to be an acceptable tradeoff between slice selectivity and peak B_1 . The SAMPA pulse is shown in Fig 1B.
- **Slice selection gradients:** trapezoidal gradients waveforms with alternating polarity were used for slice selection. Two different waveforms were generated depending on the required slice thickness range: 3D slab selection used shorter ramps (82 μs) allowing for slab thickness of 10 mm or higher, while 2D applications required larger ramp times (190 μs) to perform slice selection as thin as 3 mm while operating within the gradient hardware slew rate limit (200 mT/m/ms). For each gradient design, the RF subpulses were reshaped using the VERSE method (21) in order to perform RF excitation during gradient ramps.

Matlab code for generating SAMPA pulses is provided as supporting material.

Bloch simulations

The performance of the T_2 -prep for slice selection and its dependence on B_0 and B_1 variations were analyzed using Bloch simulation programs in Matlab (22). T_1 and T_2 values were set to 1000 ms and 60 ms respectively. The longitudinal component of the magnetization m_z at the end of the T_2 -prep was computed. We performed 3 sets of simulations in order to characterize: 1) The performance of non-selective BIR4 and SAMPA as a function of peak B_1 , 2) the effect of B_1 on SAMPA slice profiles for peak B_1 ranging

15–24 μT (this B_1 range reflects the 23 μT maximum B_1 7T transmit head RF coil), and 3) the effect of T_2 -prep length on the observed signal and contrast.

All simulations used a temporal resolution of 4 μs . We evaluated m_z for 200 frequency points ranging from –500 to 500 Hz and for 200 spatial points ranging from –10 to 10 mm.

SAMPA-FLASH sequence design

The T_2 -prep was combined with a RF-spoiled fast gradient echo sequence with low flip angle (FLASH) (1). Because the FLASH signal is acquired in a transient state following T_2 -prep, center-out acquisition of k-space was implemented. In addition, the acquisition was segmented into shorter trains in order to limit blurring occurring with magnetization-prepared FLASH (23). The excitation pulses used for FLASH were 10° flip angle SLR pulses with TBW=6, 1 ms duration for 2D imaging, and TBW=12, 2 ms duration for 3D imaging. Slice-selection gradients were adjusted to excite a section that was half of the thickness achieved by the SAMPA T_2 -prep, in order to avoid transient contrast occurring at the edges of the SAMPA selection profile (see results section below). The full SAMPA-FLASH sequence diagram is shown in Fig 1C.

Phantom experiments

All imaging experiments were performed on a whole body Magnetom 7T scanner (Siemens, Erlangen, Germany) with 70 mT/m gradient sets (200 mT/m/ms slew rate) and a 1Tx/32Rx head coil (Nova Medical, Wilmington, MA). Second order B_0 shimming was performed on a manually selected volume, and transmitter voltage was adjusted using the Bloch-Siegert technique (24) by calibrating the average flip angle in a 5 cm box placed in the center of the object. The performance of the T_2 -prep was first characterized in a phantom containing 7 vials of various agar concentrations (0.5, 1.0, 1.5, 2.0, 3.0, 4.0 and 6.0 % agar in distilled water). The vials were placed in a plastic container filled with a low permittivity fluid (corn syrup) used to achieve homogeneous B_1 throughout the imaged volume, and to offer a large volume for effective B_0 shim adjustments. T_2 w imaging was performed at 4 different T_2 -prep durations $T_E = 25, 50, 75$ and 100 ms. Additional imaging parameters were: 192 lines, acquired in 4 shots (48 lines per shot), effective $T_R = 8$ s (repetition time between subsequent T_2 -prep), FLASH T_E/T_R 3.2/10.2 ms, resolution $0.7 \times 0.7 \times 2 \text{ mm}^3$, flip angle 10° , bandwidth 130 Hz/pixel, partial Fourier 6/8, 0:32 min acquisition time per measured T_2 weighting. In order to compare T_2 values with standard sequences, spin echo imaging was performed on the same phantom with $T_E = 25, 50, 75$ and 100 ms, $T_R = 4$ s, resolution $0.7 \times 0.7 \times 3.5 \text{ mm}^3$, bandwidth 200 Hz/pixel, partial Fourier 6/8, 9:30 min acquisition time per T_2 weighting.

T_2 maps were derived offline using custom scripts written in Matlab, by fitting the decay curves for each pixel using linear regression. Following map reconstruction, T_2 values were measured in each agar vial by placing a rectangular region of interest on the T_2 maps. The T_2 values obtained with spin echo and SAMPA methods were compared using linear regression and Pearson correlation.

In vivo studies

Two volunteers were scanned at 7T after giving informed consent. In the first volunteer, we evaluated SAMPA against 3 other T_2 -prep strategies: 1) MLEV4 with four 90° - 180° - 90° modules, using rectangular pulses of 0.8 and 1.6 ms duration for the 90° and 180° respectively; 2) twice-refocused adiabatic using SLR-designed full passage adiabatic pulses of 4 ms duration and rectangular tip-down and tip-up pulse of 0.5 ms duration; 3) BIR4 using the pulse envelope described in previous sections. Because these T_2 -prep modules are not slice-selective, a long repetition time $T_R = 4$ s was used to acquire 2D slices sequentially. T_2 -prep length was set to 50 ms. FLASH imaging parameters were similar to the phantom experiments, except for parallel imaging acceleration $R = 2$ (GRAPPA), resolution $0.8 \times 0.8 \times 3.5$ mm³, 3 shots per slice (36 lines per shot) resulting in a FLASH readout duration of 259 ms per SAMPA cycle, bandwidth 400 Hz/pixel, and FLASH TE/TR 2.82/7.20 ms. Given T_1 values of brain tissues at 7T (25), such a short readout will lead to minimal blurring of the T_2 -weighted acquisition (23).

To further demonstrate the potential of SAMPA for achieving efficient acquisition, a multislabs 3D protocol was designed for whole brain T_2w imaging at 0.8 mm³ isotropic resolution. 11 slabs, each of 9.6 mm thickness, were acquired in interleaved fashion with an interleaved $TR = 12$ s (one slab acquired every 1.09 s). Each slab contained 12 partitions, resulting in effective slice resolution of 0.8 mm. All remaining protocol parameters were similar to 2D imaging previously described. Total imaging time for the multislabs acquisition was 5:36 min per T_2 weighting. This acquisition time was limited by SAR constraints, the minimum achievable imaging time being 1:53 min without considering SAR. Four volumes were acquired in a healthy volunteer at $T_E = 25, 50, 75$ and 100 ms, resulting in a 22:24 min total acquisition time.

RESULTS

B_1 response of BIR4 and SAMPA T_2 -prep

Figure 2A shows the simulation results for longitudinal magnetization following a 25 ms T_2 -prep, as a function of applied peak B_1 and off-resonance frequency. Both BIR4 and SAMPA show similar oscillating patterns at low B_1 and for frequencies outside a 500 Hz band. Such oscillatory patterns have been reported previously (15,16). The B_1 threshold for occurrence of oscillations is higher for SAMPA (10.5 μ T) than for BIR4 (4.3 μ T), which is due to the reduced power efficiency of the SAMPA pulse as a result of subsampling the waveform with subpulses. Therefore, the power required to operate SAMPA in the adiabatic regime is higher than for BIR4 pulses. When increasing T_2 -prep duration to 50 ms (Fig. 2B), similar B_0 - B_1 operating range is observed, the main difference being a decreased space between oscillatory patterns that lie outside the operating range.

SAMPA slice selectivity

Figure 3 shows the spatial and frequency dependence of SAMPA for different applied peak B_1 amplitudes. There is a well-defined center slice within a 500 Hz frequency band, surrounded by similar oscillatory patterns as in Fig. 2 on the edges of the slice. This can be interpreted as follows: when played with a selection gradient, the subpulses apply a given B_1

profile that has a peak in the center of the selected slice and falls down to zero at the edges of the slice. When B_1 inside the slice decreases below the adiabatic threshold (10.5 μT for SAMPA), BIR4 oscillations are encountered on either sides of the selected slice. In practice, extra care needs to be taken to perform the imaging within the center slice, excluding the oscillatory regions. This can be performed in a T_2 -prep sequence by adjusting the FLASH slice selection gradient to excite the inner slice that has T_2w signal.

The signal within the SAMPA slice has similar intensity at different B_1 values ranging from 15–24 μT , which reflects the adiabatic behavior of the BIR4 envelope. There is a slight increase in slice thickness with increasing B_1 value, which is due to the fact that slice profiles with higher applied B_1 will push the transition regions further away from the center of the slice.

Figure 4 shows the effect of T_2 -prep duration (increased by inserting pauses between rAHP, AFP and AHP pulse sections) on SAMPA slice selectivity and off-resonance behavior, for an 18 μT peak B_1 . There is decreased signal for increasing T_2 -prep length, driven by T_2 decay, while the slice intensity profile appears similar for all T_2 -prep durations. T_2 weighting occurs in a 400 Hz frequency band, and is altered for frequencies larger than ± 200 Hz.

Phantom experiments

Figures 5A and 5B show the comparison between SAMPA-FLASH and spin echo acquisitions in the agar phantom. Similar T_2w images and T_2 maps were observed between both acquisitions. There was a high correlation between T_2 values measured with SAMPA compared to spin echo imaging ($R^2 = 0.999$), and linear regression showed a linear coefficient of 1.04 and offset of 5.95 ms (95% confidence intervals 0.99–1.09 for slope and 1.37–10.52 ms for offset) (Fig. 5B).

In Fig. 5C, the slice profile achieved by SAMPA is shown for various slice selection gradients (10, 20 and 30 mT/m). T_2 contrast can be observed within the selected slice while FLASH contrast dominates outside the selected slice. For our pulse design, a maximum of 35 mT/m gradient could be achieved before slew rate limitations, which corresponds to a total slice thickness of 5 mm (including oscillatory bands) and an effective inner slice thickness of 3 mm available for T_2w imaging.

In vivo comparison of different T_2 -prep methods

Figure 6 shows a comparison of MLEV4, twice-refocused adiabatic, BIR4 and SAMPA T_2 -prep modules acquired at three different slice locations in a healthy subject. Large artifacts are visible for MLEV4 and twice-refocused adiabatic modules near the prefrontal cortex and in regions close to the ear canals. BIR4 and SAMPA lead to similar image quality and increased robustness to artifacts in these regions of large B_0 inhomogeneity.

Interleaved multislabs acquisitions for whole brain T_2w imaging

Full brain isotropic 0.8 mm³ T_2w acquisitions are shown in Fig. 7. Using isotropic resolution led to high quality reformatted images in coronal and sagittal orientations. Residual artifacts are visible near areas of large B_0 inhomogeneity such as the temporal lobe and prefrontal

cortex. Interslab artifacts due to FLASH readout excitation are also visible on the reformatted series. Derived T_2 maps are shown in Fig. 8A. Fast measurement of T_2 allows for more quantitative analysis of tissue properties in different regions of the brain. It has been reported that grey matter in different regions of the brain has different T_2 (26). T_2 was measured using segmentation-grown regions of interest placed in the frontal grey matter, occipital grey matter, and white matter (ROIs are shown on Fig. 7E) leading to values of 62.8, 51.7 and 46.5 ms respectively. Finally, Fig 8B shows a recomposed CSF-suppressed image derived by excluding higher T_2 components ($T_2 > 100\text{ms}$) from the $T_E = 50\text{ ms}$ volume.

DISCUSSION

We have presented the design principles and performance of SAMPa, a new class of T_2 -prep pulses providing slice selectivity while addressing the limitations of T_2 -prep techniques regarding B_0 and B_1 variations. We found that subsampling a BIR4 envelope with slice-selective subpulses leads to a T_2 -prep that retains the adiabatic and off-resonance characteristics of BIR4 pulses, while offering slice selectivity at the cost of moderately increased power requirements. Furthermore, our SAMPa design results in a well-defined $T_2\text{w}$ slice with adiabatic behavior over 15 μT peak B_1 , and off-resonance robustness in a 400 Hz frequency band. SAMPa had similar behavior as BIR4 *in vivo* in the presence of inhomogeneous B_0 and B_1 fields, while providing superior quality compared to commonly used methods such as MLEV4 and twice-refocused adiabatic T_2 -prep. Finally we demonstrated how the spatial selectivity of SAMPa can be leveraged to achieve fast whole brain, interleaved multislab acquisitions which were previously not available with common T_2 -prep methods that lack spatial selectivity.

An important application for T_2 -prep is to provide faster T_2 measurements in tissues compared to spin-echo based techniques (10,27,28), with possibly reduced power deposition and increased robustness to field inhomogeneity. We have found that a segmented SAMPa-FLASH acquisition allows for accurate T_2 estimates compared to spin-echo imaging in phantoms, and that high resolution *in vivo* T_2 mapping can be achieved in acceptable scan time. The bias in T_2 quantification observed when comparing SAMPa-FLASH to spin echo imaging could be due to T_1 recovery during the FLASH readout, spin-locked relaxation during the adiabatic pulses or diffusion effects, all of which have not been taken into account in our analysis. Compared to turbo spin echo imaging and multi-echo spin echo T_2 mapping, multislab SAMPa-FLASH can provide isotropic resolution with lower power deposition and within faster acquisition time. Although FLASH readouts, as used in this study, may suffer from B_1 inhomogeneity leading to inhomogeneous signal, the contrast offered by SAMPa-FLASH is in theory robust to B_1 inhomogeneity and may lead to efficient quantitative T_2 imaging. SAMPa has potential to further increase the efficiency of T_2 mapping and may lead to even faster acquisitions when combined with advanced acceleration techniques such as non-Cartesian sampling (29), compressed sensing (30) and parallel imaging (31,32). In addition, the scan times reported in this work are imposed by SAR limitations. At lower field strength such as 3T, lower achievable repetition time can lead to more efficient acquisition, down to 1:53 min acquisition time per $T_2\text{w}$ volume for our 0.8 mm³ isotropic resolution protocol.

To our knowledge, this is the first fully adiabatic slice-selective T_2 -prep proposed. In a previous work, a twice-refocused T_2 -prep was modified in order to achieve slice selection using the tip-down and tip-up pulses (33), however the presence of conventional 90° pulses reduces the B_1 robustness of such T_2 -prep. Slice-selective B_1 -insensitive pulses (STABLE) derived from BIR4 designs have also been proposed to achieve adiabatic excitation at high field (17,18). STABLE pulses were designed to replace traditional excitation pulses, while SAMPA is designed specifically as a preparation pulse. The requirement for null flip angle as well as waiting periods between the pulse sections of SAMPA lead to different waveform designs proposed in this work. There is a large number of possible applications for SAMPA, which can be combined with a variety of readouts including balanced SSFP (34), spiral (10) and SPACE (35). In addition, slice selectivity can be leveraged to increase the efficiency of applications such as diffusion-prepared imaging (23,36), FLAIR (37,38) and T_2 -prepared BOLD (7).

This study has some limitations. First, the FLASH imaging readout used to acquire T_2 -prepared signal is also sensitive to B_0 and B_1 inhomogeneity, and could benefit from further protocol optimization. In particular, it may be beneficial to perform parallel transmit to achieve homogeneous excitation in the FLASH readout, leading to even more homogeneous SAMPA-FLASH acquisitions. Second, interleaved multislab acquisitions are highly sensitive to slab selection profiles and can lead to signal loss at the edges of each slab, which was visible on reformatted images. Such multislab acquisitions can be improved by performing overlapping slab (39) or sliding slab (40) acquisitions. Third, the effect of magnetization transfer and rotating-frame relaxation in SAMPA T_2 -prep need to be further evaluated in order to improve accuracy of the technique. Finally, although the proposed pulse presents sufficient B_0 and B_1 robustness for most 3T applications (similar to previously reported range for non-selective modules (13,15)), its performance could be affected by the larger field variations observed at 7T. Further flexibility can be gained by tailoring the RF pulse to specific application needs. When designing SAMPA pulses, there is a trade off between B_1 sensitivity (lower adiabatic threshold can be achieved at the cost of reduced bandwidth) and B_0 robustness (higher bandwidth can result in increased pulse power). In multislice or multislab acquisition, the pulse design may be adjusted on a slice-by-slice basis, depending on local B_0 - B_1 requirements. Alternatively, the operating frequency of SAMPA may be modified to match local average B_0 conditions, without modifying the pulse design. We plan to explore such options in future studies. In addition, the local susceptibility artifacts seen near the sinus and ear canals can be further reduced by using advanced shimming method such as 3rd order shimming or local shim arrays (41,42), leading to improved B_0 homogeneity for whole brain applications.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

RF pulse and sequence design for SAMPA. A: BIR4 envelope designed using the adiabatic SLR algorithm; B: SAMPA pulse, derived from the BIR4 pulse using with 44 subpulses; amplitude and phase of the RF pulses are shown on top and bottom diagrams respectively. C: pulse sequence for T_2 -prepared FLASH imaging. Waiting periods have been inserted between SAMPA sections to achieve a given echo time T_E and a spoiler gradient has been inserted after SAMPA to suppress residual transverse magnetization.

Figure 2.

Characterization of B_1 and off-resonance behavior of BIR4 (left) and SAMPA (right) for T_2 -prep length of 25 ms (A) and 50 ms (B). Similar patterns are observed for SAMPA and BIR4, however the threshold for adiabatic behavior is higher for SAMPA (10.5 μT compared with 4.3 μT for BIR4).

Figure 3.

Off-resonance characterization of slice-selective SAMPA pulses under different B_1 conditions ($B_1 = 15, 18, 21$ and $24 \mu\text{T}$, simulated for $T_E = 25 \text{ ms}$, $T_2 = 60 \text{ ms}$). Intensity profiles along the slice selection axis at the center frequency are shown on the right. There is moderate increase in slice thickness for increasing B_1 .

Figure 4.

Characterization of slice selectivity and off resonance profiles of SAMPA pulses at different echo times ($T_E = 25, 50, 75$ and 100 ms, simulated using $T_2 = 60$ ms and $B_1 = 18 \mu\text{T}$). T_2 values derived from the multi-TE simulations are shown in the top right map. Intensity profiles along the slice dimension at the center frequency are shown in the bottom right graph.

Figure 5.

Phantom experiment on agar gels of different concentrations (0.5, 1, 1.5, 2, 3, 4 and 6 % agar). A: evaluation of SAMPa-FLASH for T_2 measurement against spin echo acquisition ($T_E = 25, 50, 75$ and 100 ms). From left to right: T_2 w from spin echo ($T_E = 50$ ms), T_2 map from spin echo, T_2 w from SAMPa ($T_E = 50$ ms), T_2 map from SAMPa. B: excellent correlation was observed for T_2 measurement when compared with spin echo imaging ($R^2 = 0.999$). C: slice selectivity at 10, 20 and 30 mT/m gradient strength, measured by setting the SAMPa slice gradient orthogonal to the FLASH slice gradient.

Figure 6.

comparison of different T₂-prep methods acquired in the brain of a healthy subject. From left to right: MLEV4, twice-refocused adiabatic, BIR4 and SAMPA, shown at 3 different slices. Both MLEV4 and twice-refocused adiabatic modules suffer from B₀ and/or B₁ field inhomogeneity in inferior regions of the brain (arrows). Using SAMPA and BIR4 leads to recovered signal in these regions, as shown in the signal intensity profiles.

Figure 7.

3D multislab T_2w imaging acquired at $T_E = 25, 50, 75$ and 100 ms (A, B, C and D respectively) with 0.8 mm^3 isotropic axial acquisition, along with coronal and sagittal reformats. Full brain coverage was obtained in 5:36 min acquisition per T_2 weighting. Residual artifacts are visible near areas of large off-resonance such as the prefrontal cortex and ear canals. E: ROI placement for T_2 measurement of frontal grey matter (FGM), occipital grey matter (OGM) and white matter (WM).

Figure 8.

A) T₂ maps derived from 0.8 mm³ isotropic resolution T₂-weighted acquisitions shown in Fig. 7. B) Reconstructed fluid-suppressed T₂-weighted image at T_E = 50 ms, derived by excluding regions with T₂ > 100 ms.