Robust non-adiabatic T 2 -preparation using universal parallel- transmit k T -point pulses for 3D FLAIR imaging at 7 Tesla

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Abstract

Purpose: The Fluid Attenuated Inversion Recovery (FLAIR) sequence is a pillar technique to detect brain lesions in MRI. At ultra-high field, the lengthening of T_1 often advocates a T_2-weighting preparation module to regain signal and contrast between tissues, which can be affected by transmit radiofrequency (RF) field inhomogeneity. In this note, we report an extension of a previous FLAIR study that now incorporates the T_2-preparation with parallel transmission calibration-free universal pulses to mitigate the problem.

Methods: The preparation consisted of a 90°-τ-180°-τ-90° module to implement an effective inversion in the cerebral spinal fluid and a saturation in the brain tissues. Care was taken for the pulses to have the desired phase relationship in every voxel by appropriate pulse design. The RF pulse design made use of the k_T-point parametrization and was based on a database of 20 B_1^+ and ΔB_0 maps previously acquired on different subjects at 7T. Simulations and experiments on 5 volunteers, not contained in the database, were performed for validation.

Results: Simulations reported very good inversion efficiency for the preparation module with 8% variation, with respectively four and six times less power and SAR than for the adiabatic version. Experiments revealed FLAIR images free of B_1^+ artefacts.

Conclusion: This work contributes further to the panel of 3D sequences validated and now available with universal pulses at 7T. The drop in power and SAR demand compared to adiabatic pulses in the T_2-preparation leads to more freedom for the design of the readout train.

Introduction

The Fluid Attenuated Inversion Recovery (FLAIR) sequence is of major importance for the detection of cortical lesions (1), e.g. in patients with multiple sclerosis. At ultra-high field (UHF), it has been reported that the increased image resolution enabled by the inherent boost in Signal-to-Noise Ratio (SNR) leads to superior diagnostic capability (2-4). For whole-brain T_2-weighted imaging compatible with clinical routine, the protocol often incorporates variable flip angle readouts to comply with Specific Absorption Rate (SAR) guidelines and power limit issues. But as shown previously (5-7), T_2-weighted sequences at UHF are particularly sensitive to the radiofrequency (RF) field inhomogeneity, making their direct implementation in the Circularly Polarized (CP) mode at 7T highly problematic due to severe signal dropouts. Parallel transmission (pTx) provides to the user a valuable set of degrees of freedom to mitigate the problem but its inherent workflow has been a major obstacle to transpose all the developments made by the community to clinical routine. The approach typically consists of first measuring subject-specific B_1^+ and ΔB_0 maps, post-processing the data and performing on the fly RF pulse design, which altogether can cumulate 10 minutes or more over an entire exam. It requires expertise and it is subject to human and technical errors. Moreover, it is based on field maps that are typically acquired at the beginning of the exam and thus are prone to change if subsequent patient motion occurs. To bypass the calibration procedure while being robust against intersubject/position variability, a calibration-free "universal pulse" (UP) approach, which consists of designing RF pulses offline on a database of good-quality B_1^+ and ΔB_0 maps pre-acquired on different subjects, was first proposed in (8). The concept was successfully tested with home-made and commercial coils at 7T with the MPRAGE (8,9), the 2D GRE (9) and the variable Flip Angle Turbo Spin Echo (vFA-TSE) (7) sequences, yielding good mitigation of the RF inhomogeneity problem at a mild cost in performance compared to a subject-based tailored approach. An inversion pulse prior to the vFA-TSE sequence was also inserted to suppress the Cerebral Spinal Fluid (CSF) signal and implement a 3D SPACE (Sampling Perfection with Application of optimized Contrasts using different flip angle Evolution)-FLAIR sequence (7). However, although the flip angle throughout the brain was uniform, the final images lacked contrast because of the lengthening of the T_1 with field strength. For this reason, it is advocated to insert a T_2-preparation

module (10,11) before the readout to effectively boost the signal and the contrast between white and gray matter while still suppressing the CSF signal (see Fig. 1 for a Bloch simulation illustration (12)). This preparation can consist of an adiabatic half passage, a delay, an adiabatic full passage, another delay and a last adiabatic half passage (11) but can also use up to 4 adiabatic refocusing pulses to be more robust against B_1^+ and B_0 inhomogeneity (10). However, because they are SAR and power intensive, adiabatic approaches can lead to sub-optimal duty cycles, sub-optimal readout trains (RF pulse design, flip angle evolution train) and detrimental magnetization transfer effects (10). Finally, when surrounded by crusher gradients their long durations can lead to flow-induced artefacts.

In this work, we report a whole-brain 3D FLAIR implementation at 7T in which the T_2-preparation module is built from calibration-free universal pulses to mitigate the RF inhomogeneity problem. The design of the pulses for the vFA-TSE readout is similar to a previous work (7) and thus will not be detailed here. Instead, here we report the design of RF pulses tailored to the T_2-preparation, as well as simulations and in vivo experiments on 5 healthy volunteers to validate its design concept.

Theory

The T_2-preparation module is shown in Fig. 2. It consists of a 90° excitation, a delay TE/2, a 180° refocusing pulse (dephased by 90° with respect to the excitation), same delay TE/2 and same 90° excitation. The overall targeted effect is to invert the CSF magnetization and saturate brain tissue uniformly in space, despite heterogeneous B_1^+ and B_0 fields. In terms of RF pulse design, one of the challenges associated with this task is to synthetize the correct rotation matrix at each location in the region of interest (the brain), not just flip angles. For the effects of the 90° and 180° pulses to be coherent over the whole T_2 preparation module, the 90° pulses ideally should yield 90° rotation angles with transverse rotation axis. The latter requirement is strong given the amount of B_1^+ and B_0 inhomogeneity (6) and the peak/average power limits imposed by the hardware and the safety guidelines. This problem was circumvented in (7) for the vFA-TSE readout module by observing that the rotation matrix of a pulse could be well approximated under some circumstances by a free precession, followed by a rotation with purely transverse rotation axis and the same free precession. That way, the free precessions could be "absorbed" in the delays naturally occurring in the MRI sequence while the pulses behaved

effectively as if they were purely transverse rotations. In principle, the leading 90° excitation of the vFA-TSE readout could be used for the T_2-preparation module while the 180° could be synthetized by cascading two such 90° pulses. Let us denote by R the rotation matrix characterizing the 90° pulse. According to the theory (7), this rotation may be rewritten as $R = R_z(\Delta B_0)R_\perp(\theta)R_z(\Delta B_0)$ where R_z and $R_\perp(\theta)$denote rotations about the z and a purely transverse axis respectively. Hence, doubling the waveform would yield the rotation $R^2 = R_z(\Delta B_0)R_\perp(\theta)R_z(\Delta B_0)R_z(\Delta B_0)R_\perp(\theta)R_z(\Delta B_0)$, in general different from the desired rotation $R_z(\Delta B_0)R_\perp(2\theta)R_z(\Delta B_0)$, except if ΔB_0=0. As a result, simply doubling the 90° pulse of the vFA-TSE readout would yield good results for up to moderate ΔB_0 values only. For the refocusing pulse of the T_2 preparation module, we thus propose to design a specific ΔB_0-robust universal k_T-point inversion pulse. We observe that if a 180° flip angle is reached, then the axis of rotation necessarily is transverse (13), and the pulse is refocusing. Denoting by α and β the Cayley-Klein parameters of the rotation matrix, propagating an initial magnetization along z and looking at its projection along –z yields: $[0\ 1]\begin{bmatrix}\alpha & -\beta^* \\ \beta & \alpha^*\end{bmatrix}\begin{bmatrix}1 \\ 0\end{bmatrix} = \beta$. Thus, by unitarity of the matrix ($|\alpha|^2 + |\beta|^2 = 1$), if $|\beta| = 1$ then $\alpha = 0$, i.e. the axis of rotation is transverse. One convenient way to construct a phase-coherent pair of 90° and 180° pulses hence is to design a unique refocusing 180° pulse whose internal structure is the cascade of two identical waveforms. By doing this, the objective function to minimize in this case is simply a flip angle Normalized Root Mean Square Error (NRMSE) with 180° target. Taking the first half of the gradient and RF waveforms then leads to the desired result: a rotation angle halved (90°) and the same, transverse, rotation axis. The proposed approach thus remains in essence as simple as a conventional flip angle NRMSE minimization problem while it *inherently* promotes more phase coherent solutions compared to the approach consisting of designing a 90° pulse and doubling it.

Methods

The 180° rotation of the T_2-preparation module was designed using the k_T-point parametrization (14), under explicit power and SAR constraints (15) and with simultaneous optimization of the k-space trajectory (16). According to the theory above, it consisted of 5 k_T-point pulses applied twice back to

back, leading to a total of 10 k_T-points and a duration of 2 ms (160 µs per sub-pulse and 40 µs gradient blips). The first half of the waveform was extracted to yield the phase coherent 90° pulse. The UPs were designed on a database of 20 subjects whose field maps were acquired in a previous study (age 40 ± 15 years old, 50 % women) as an attempt to cover significant intersubject variability yet with a reasonable number of scans (9). The flip angle NRMSE averaged over the database subjects was the cost function to minimize. The vFA-TSE readout flip angle train was synthetized using Mugler's approach (17) and was built from a single, scalable, refocusing UP (7). The designed pulses were integrated in the T_2-preparation module of the sequence and were implemented on a Magnetom 7T scanner (Siemens Healthcare, Erlangen, Germany) equipped with the Nova 8TX-32RX (Nova Medical, Wilmington, MA, USA) head coil and a SC72 whole body gradient insert (40 mT/m nominal amplitude and 200 T/m/s maximum slew rate). Neither tailored pTx calibration nor online pulse design were performed, just as in single channel mode. The scans were conducted on 5 adult volunteers in the "protected mode" supervision (Siemens step 2.3) with average power limits of 1.5 W per channel and 8 W total at the coil plug. The study was approved by the local ethics committee and the 5 volunteers gave written informed consent. The sequence parameters were the following: TR = 7 s, TI = 2100 ms, TE = 100 ms, 1×1×1 mm^3 resolution, matrix size = 256×208×144, GRAPPA (R = 2×2), total scan time = 9 min 48 s. To demonstrate the gain in contrast brought by the preparation, an additional scan was performed on 2 of the volunteers with the T_2 preparation module replaced by a single UP inversion (3.7 ms duration). Brain images were segmented by using the FSL FMRIB Automated Segmentation Tool (FAST) (18) to confirm contrast quality. After measuring their respective B_1 and ΔB_0 maps, Bloch simulations of the action of the T_2 preparation module were performed for the scanned subjects to verify good inversion and saturation properties for CSF (T_1 = 4.4 s, T_2 = 2 s) and brain tissue (T_1 = 2 s, T_2 = 0.06 s) respectively. For comparison, a similar simulation was performed for the preparation consisting of one hard tip-down 90° pulse, 4-hyperbolic secant adiabatic refocusing pulses (duration = 9 ms, maximum frequency modulation = 706 Hz), one hard tip-up 90° pulse and a final inversion adiabatic pulse (duration = 17.1 ms, maximum frequency modulation = 700 Hz), as proposed in (10) and implemented in (19) with pTx. Analysis of the longitudinal magnetization homogeneity was performed just after the T_2-preparation and just before the vFA-TSE readout, i.e. after magnetization recovery. To gain insight into the importance

of magnetization transfer effects for the UP and the adiabatic-based T_2 preparation modules, the same simulation was performed for the macromolecular protons of the brain tissues with T_1=1.6 s and T_2=10 μs (20). The saturation of the macromolecular pool (21), i.e. the ratio of the longitudinal magnetization at the end of the preparation to the one prior to it, hereby was obtained for the two T_2 preparation techniques. For simplicity, the exchange between the free and macromolecular protons was ignored during the preparation due to its relatively low rate (~2.4 s^{-1} and ~4.3 s^{-1} for gray and white matter respectively (22)) at the time scale of interest (the duration of the T_2 preparation module , i.e. ~100 ms). Given that TI ≫ T_2, it was also neglected during the recovery of the brain tissues to follow the longitudinal magnetization of the same macromolecular protons considered during the T_2 preparation, in the limit that the two proton pools have similar T_1 relaxation times.

Results

The returned average power per channel with the k_T-point UPs was 0.13 W for the whole T_2-preparation, thus requiring ~4 times less power than the adiabatic version[1] (19). Electromagnetic field simulations provided by the coil manufacturer on a head model and validated in the laboratory also returned 6 times less peak 10-g SAR than for the adiabatic approach. The saturation coefficient of the macromolecular pool averaged over the whole-brain amounted to 0.16 and 0.68 for the adiabatic and UP approaches respectively, just at the end of the preparation module, and 0.77 and 0.91 just before the vFA-TSE readout. Intersubject variability was found to be not more than 10%. The flip angle NRMSEs of the 90° and 180° UPs of the preparation module were 7.5 ± 1.5 % and 10.1 ± 1.2 % when evaluated over the 20 database subjects, so better than the 13 % NRMSE obtained at 3T in single channel CP mode (23). The simulated longitudinal magnetization is reported in Fig. 3 for the 5 scanned subjects, for the adiabatic and UP implementations. The preparation effectively results into a saturation for brain tissues while maintaining an inversion for the CSF. Just after the preparation, standard deviations in units of M_0 are 0.10 and 0.23 for the brain tissue and CSF respectively with the adiabatic approach, versus 0.02 and 0.07 with UPs. As shown in (19), and confirmed by our simulations, remaining inhomogeneities at the end of the T_2 preparation largely disappear with the regrowth of the longitudinal magnetization

$(M_z(TI) = M_z(0)e^{-\frac{TI}{T_1}} + (1 - e^{-\frac{TI}{T_1}}))$, making the readout in fact far more critical for signal and contrast homogeneity. After recovery, the numbers above become 0.03 and 0.14 for the adiabatic case, versus 0.01 and 0.04 for the UPs, yielding good homogeneity in both cases.

Fig. 4.a reports the in vivo results on the 5 volunteers. Good contrast was obtained consistently throughout the tests with no apparent B_1^+ artefact. As a reference, for comparison, the result obtained with a single UP inversion instead of the T_2 preparation is provided in Fig. 4.b for volunteer #5. It demonstrates a lack of contrast if a T_2 preparation module is not incorporated. The gain in contrast brought by the preparation translates directly into better segmentation results (see Fig. 5).

Discussion

We have reported the design and implementation of a T_2-preparation module with parallel transmit k_T-point UPs. The phase coherence between the 180° and the 90° excitation pulses was enforced by parametrizing the former with two successive identical waveforms, the first (or second) half constituting the excitation. Smaller, phase coherent, rotations incidentally could be synthetized this way by extrapolating the method. We showed in (9) that universal inversion pulses could reach flip angle NRMSEs less than 5 %. Here the NRMSE obtained across the database subjects for the refocusing pulse was 10.1 ± 1.2 %, thus indicating a small price to pay to achieve phase coherence with this pulse construction. Alternatively, the doubling of the waveforms to achieve 180° could be abandoned, but then at the expense of a more involved and complicated pulse design for the excitation where the phase in each voxel would need to be tracked (6).

A whole-brain FLAIR study with a T_2-preparation module and with pTx was also reported in (19). The pulse design was based on a direct signal control model where each RF pulse in the vFA-TSE readout train made use of a different RF shim setting to target a prescribed signal evolution for a given T_1 and T_2 pair. A UP version, still making use of RF shim pulses, was also successfully implemented, albeit with some moderate loss of performance compared to the subject-based tailored approach. To be more robust against the RF field inhomogeneity inherent to 90° hard pulses, the T_2 preparation used 4 hyperbolic secant refocusing and one inversion, also adiabatic, pulses. Our simulations confirm their

results by showing that the vFA-TSE readout indeed is far more critical for the signal and contrast homogeneity than the T_2-preparation, as imperfections in the preparation largely disappear with magnetization recovery. The main benefit of the proposed k_T-point universal pulse approach hence is the reduced power (×4) and SAR (×6) demands, leading most importantly to more freedom to optimize the readout train. Incidentally, we could also show in simulation significant reduction of the saturation of the macromolecular protons caused by the preparation. Those differences yet again fade after magnetization recovery and do not likely lead to big effects in this particular application. Finally, the shorter duration of the refocusing universal pulses (2 ms versus 9 ms) can be beneficial to limit flow artefacts in the presence of crusher gradients occurring in the T_2-preparation.

Conclusion

We have reported the design and implementation of a T_2-preparation module with pTx universal pulses in the 3D FLAIR sequence at 7T. Simulations and measurements validated the approach, which yields comparable signal homogeneity to the adiabatic version but with significantly less power, SAR and pulse duration. This complements the toolbox of universal pulses already available in 3D sequences and widens the applicability of the technique in general for use in clinical routine. The solutions have also been shown to be robust with respect to inter-site variability (24). They are available upon reasonable request with the appropriate sequences.

Acknowledgements

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Footnote

[1]The 0.34 W indicated in ref (19) is for TR=8 s, and thus becomes 0.39 W for TR=7 s. A private communication with one of the authors revealed that this number did not include the final inversion pulse, necessary to invert the CSF longitudinal magnetization. Given the information provided about that pulse, the overall total power was estimated as 0.58 W.

List of captions

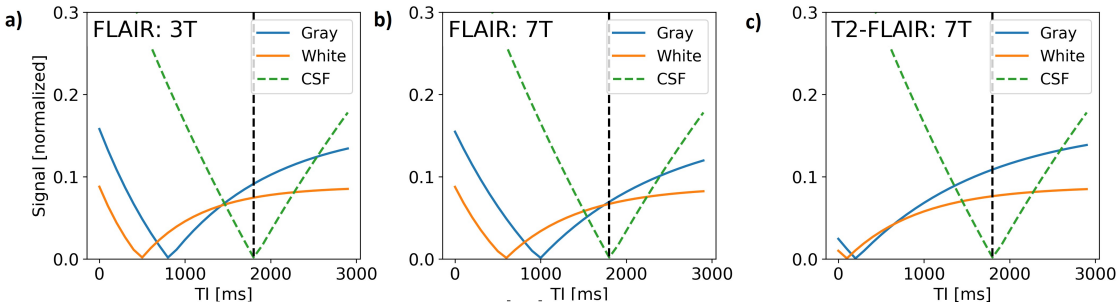

Figure 1. Bloch equation simulation results for the FLAIR. The simulations took literature values for T_1 and T_2 at 3T and at 7T. The simulation results are provided for 3T (a) and 7T (b) with just inversion recovery, c) for 7T with a T_2 preparation module. The lengthening of T_1 from 3T to 7T attenuates the signal and contrast between brain tissues. Inserting the T_2 preparation boosts the contrast between gray and white matter while suppressing the CSF signal.

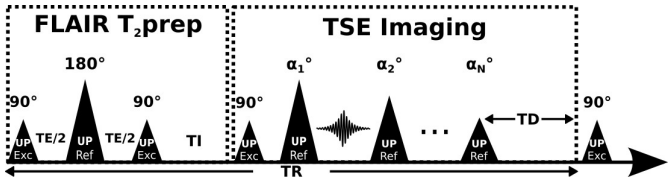

Figure 2. Sequence diagram of the implemented FLAIR sequence with magnetization preparation. The turbo spin echo (TSE) readout train uses variable flip angle refocusing universal pulses (UPs). The T_2-preparation module inverts the CSF signal while saturating brain tissue to regain signal and contrast between grey and white matter. For more optimality, in the proposed work the design of the pulses in the T_2-preparation is independent from the design of the pulses in the readout train.

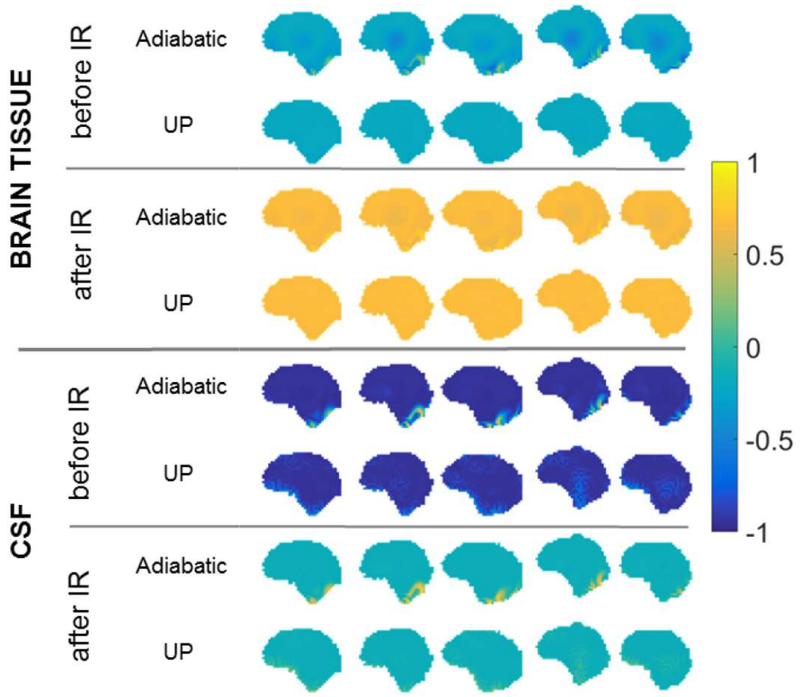

Figure 3. Bloch simulation results of the T_2-preparation module. Assuming perfect spoiling, the result is represented as the longitudinal magnetization (units of M_0) for the brain tissue (top) and CSF (bottom). The distributions are plotted on sagittal slices for the 5 scanned subjects. Comparisons are provided between the UP and the adiabatic pulse implementations, just after the preparation module and just prior to the vFA-TSE readout (i.e. after Inversion Recovery (IR)). Both methods return good homogeneity at the end of the recovery with perhaps little imperfections at the bottom of the brain for the CSF with the adiabatic approach (see also Figure 4 in (19)).

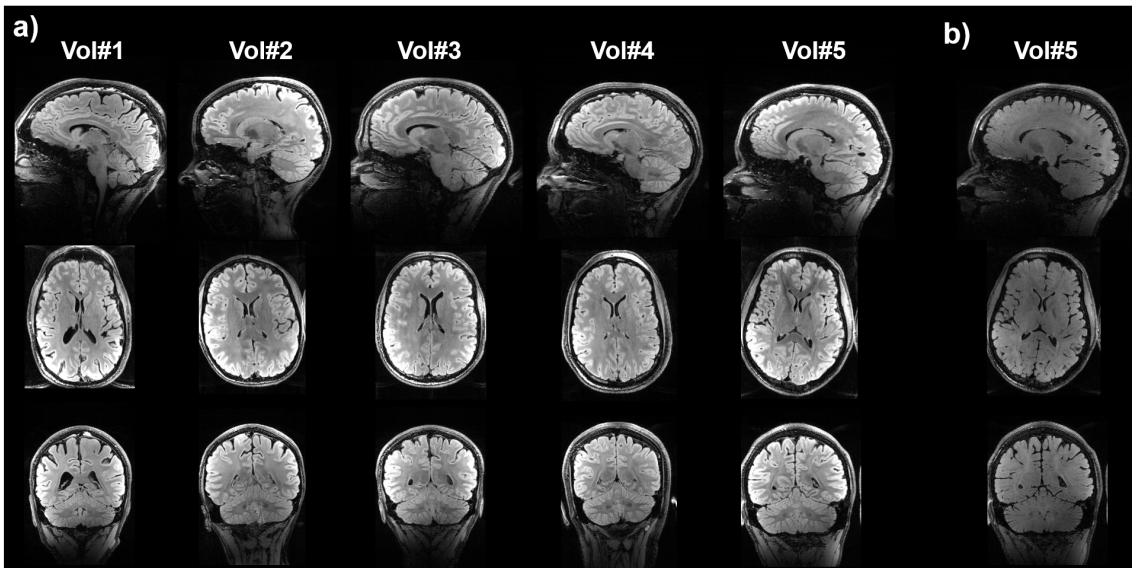

Figure 4. In-vivo FLAIR imaging results at 7T with no bias field correction. a) Sagittal, axial and coronal views obtained with pTx universal pulses on 5 volunteers. The CSF is effectively suppressed throughout the brain while good contrast between white matter and grey matter is obtained. b) Same views for volunteer #5 obtained with a single UP inversion replacing the preparation. Comparison between the two illustrates the contrast gain achieved by means of the T_2 preparation module.

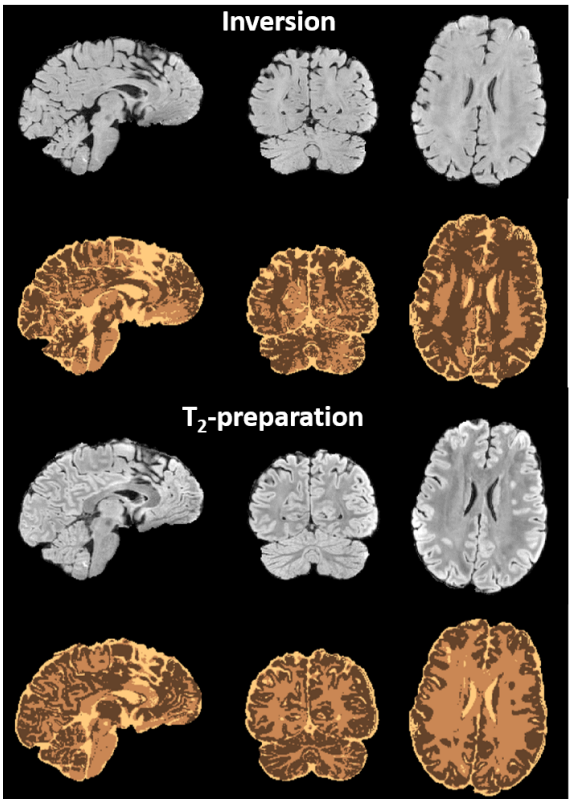

Figure 5. Segmentation results with FSL on volunteer #5. Top: results with the UP inversion only. Bottom: results with the UP T_2-preparation approach. Three tissue-segmentation (three colors) was specified for white matter, gray matter and CSF. In-vivo images were bias-field corrected with FSL.