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Contrast enhancement of a magnetization prepared steady state sequence: an optimal control framework

Benoît Vernier^{1, 2}, Eric Van Reeth^{1, 3}, Frank Pilleul^{1, 4}, Oliver Beuf¹, Hélène Ratiney¹

¹ CREATIS, Université de Lyon, INSA Lyon, UCBL Lyon 1, UJM Saint Etienne, Unité CNRS UMR 5220, INSERM U1206, F69621 Lyon, France

² SIEMENS Healthineers, 93210 Saint-Denis, France, ³ CPE Lyon, France, ⁴ Centre Léon Bérard, France

Synopsis

Optimal control in MRI has demonstrated its potential in the design of magnetization preparation in order to enhance relaxation based contrast. However, previous studies require full magnetization recovery between each TR, which induces long acquisition times and restricts its use to specific sequences. Here, a generic optimal control framework that considers a longitudinal steady state is introduced, and applied to a MP-RAGE sequence. *In vitro* and *in vivo* (rat brain) experiments validate the improvement of the contrast-to-noise ratio per unit of time when compared with an inversion-recovery preparation.

Intro

A MP-RAGE sequence is composed of the repetition of segments divided in three steps: (1) a magnetization preparation for contrast control, (2) data acquisition with a short time of repetition (TR) and low flip angle spoiled gradient echo scheme, and (3) a partial recovery step. Short segments and their rapid succession lead to a longitudinal steady state (contribution of transverse magnetization is destroyed). This Flash-type acquisition allows flexible contrasts. MP-RAGE is generally used in combination with an inversion preparation, to generate T1 contrast¹. Nevertheless, it can be anticipated that contrast could be improved by playing both on T1 and T2 relaxations. This requires the optimization of more complex preparation schemes, which cannot be solved straightforwardly. Thus, an optimal control (OC) framework that allows longitudinal steady state is developed, based on the GRAPE algorithm^{2, 3}. The interest of our optimized preparation is quantified and demonstrated *in vitro* and *in vivo* on rat brain, for different segment durations.

Methods

Unlike previously proposed OC preparation schemes that considered full magnetization recovery^{4, 5}, the proposed framework takes into account the formation of a longitudinal steady state.

More precisely, the action of the preparation on the magnetization is modelled by successive matrix multiplications and any transverse magnetization is assumed to be adequately spoiled before and after the preparation. Then the condition of equilibrium gives a general expression of the longitudinal steady state as a function of acquisition parameters and preparation parameters that become variables of the considered optimization problem.

The cost function used in the OC problem aims at maximizing the contrast when acquiring the central line of the k-space:

$$C = \alpha \cdot S_{a,i}^2 - S_{b,i}^2$$

α : a weighting coefficient (10 in our case).

$S_{a/b,i}$: signal intensity of tissue a, to be saturated, or tissue b, to be maximized, after the i^{th} flip angle excitation of the gradient echo acquisition in a cycle, once the macro steady is achieved.

The adequacy between theoretical and experimental contrast results were checked in vitro on tubes (glycerol + NiSO₄). Relaxation times were measured and the optimized sequences were computed and applied on a 11.7T Bruker system to saturate the signal of one sample *a* (T₁/T₂ (ms): 719/76) and maximize the signal of one sample *b* of shorter T₁ and T₂ (T₁/T₂ (ms): 454/25) for different segment durations (from 4s to 0,5s). The matrix size was 128x128x16 pixels, segments of 32 readout were performed with centric encoding, an echo repetition time of 6.5ms and a 13° flip angle.

The sequences to enhance contrast between cortex (T₂/T₁ (ms): 34,2/1945) and corpus callosum (T₂/T₁ (ms): 31,2/1710) in the rat brain were optimized with the proposed OC framework and applied on Brucker 11.7T MRI preclinical scanner, for different segment duration from 3s to 1s. Two rat brains were scans: in coronal (first rat) and axial and coronal slices (second rat). Compared to previous in vitro acquisition, in-plane matrix was resized to 256x256 but other parameters were kept unchanged.

In each case, a preparation scheme of one pulse and two pulses were optimized (refocusing pulses are not counted).

Results

The proposed optimization method finds an inversion-recovery (IR) for one pulse preparation, and a T₂prep-IR for two pulses preparation (referenced as OC-prep), for both in vitro and in vivo experiments.

In vitro, we found a good correlation between the experimental contrast and the numerically predicted contrast for IR and OC-prep for different segment duration, with a contrast match ranging from 73% to 97%. Indeed the experimental contrast was included between 97% and 73% of the numerically predicted contrast.

In vivo an increase of the contrast-to-noise ratio between cortex and corpus callosum was obtained with OC-prep compared to IR prep over the two rats, for the four different segment duration and the different slices orientations (figure 2). The increase is at least 18% and reach 500% for segment duration of 1s, but in this case with a simple IR the signal is so low that is melted into the noise.

The gain in contrast-to-noise ratio of OC-prep compared with IR is larger as segment duration decreases. In vivo, the increase lies between 274% and 83% for a segment duration of 1,5s, against only 18% and 61% for a segment duration of 3s.

Discussion

In this present case, when seeking to maximize signal of short T₁ and T₂ tissues, the optimization results in a T₂prep-IR scheme, which is a known solution that plays on T₂ differences to enhance T₁ contrast. The advantage here is that optimal pulse parameters (timing and flip angles) are computed automatically. Moreover, the proposed framework is generic and allows to optimize a preparation of an arbitrary number of pulses that could be used for more difficult contrast objectives such as involving three different tissues.

Both in vitro and in vivo experiments suggest that the benefit of the CO-prep with respect to IR increases as the TR decreases. The proposed scheme is thus able to generate a better contrast-to-noise ratio in shorter acquisition times due to faster T2 relaxation.

Conclusion

Magnetization preparations optimized by the GRAPE algorithm that use both T1 and T2 relaxations allows to enhance contrast between brain tissues and most importantly in short acquisition times. Other developments are under study to integrate more acquisition parameters (TR, FA) into the optimization.

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Summary of Main Findings (/250c)

A generic optimal control framework for contrast optimization in presence of a longitudinal steady state is presented. *In vitro* and *in vivo* experiments validate the improvement of the contrast-to-noise ratio per unit of time of an MP-RAGE sequence

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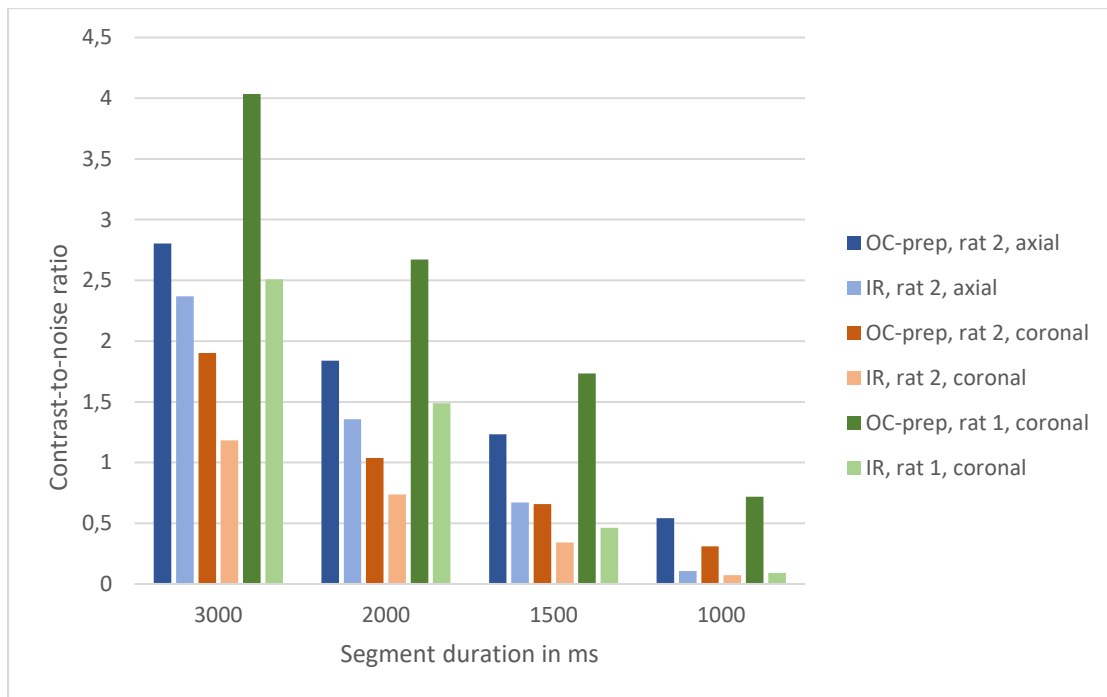
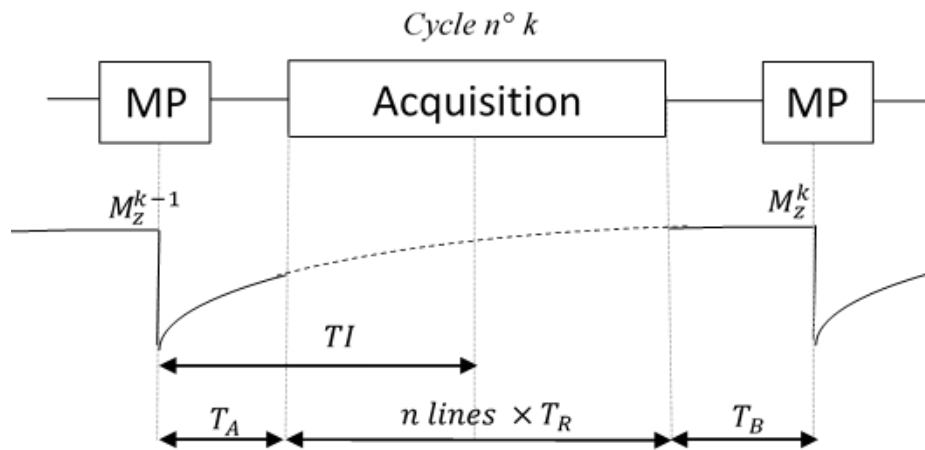


Figure 2 : Contrast-to-noise ratio over the two rats, the four segment duration and the different slices orientations

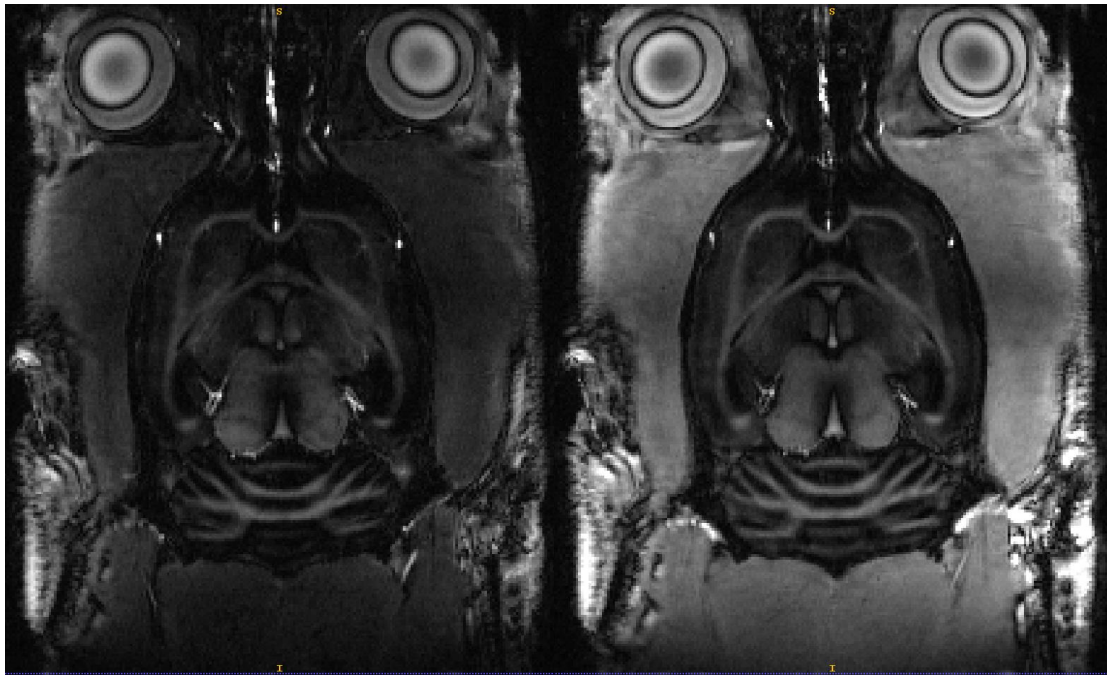


Figure 3: Rat 1, at the left side MP-RAGE with a simple inversion, at the right side MP-RAGE with a T2prep-IR, both optimized with an optimal control framework aiming at enhancing contrast between cortex and corpus callosum. Same acquisition parameters are used (segment duration: 3s, TR: 6.5ms, flip angle: 13°).

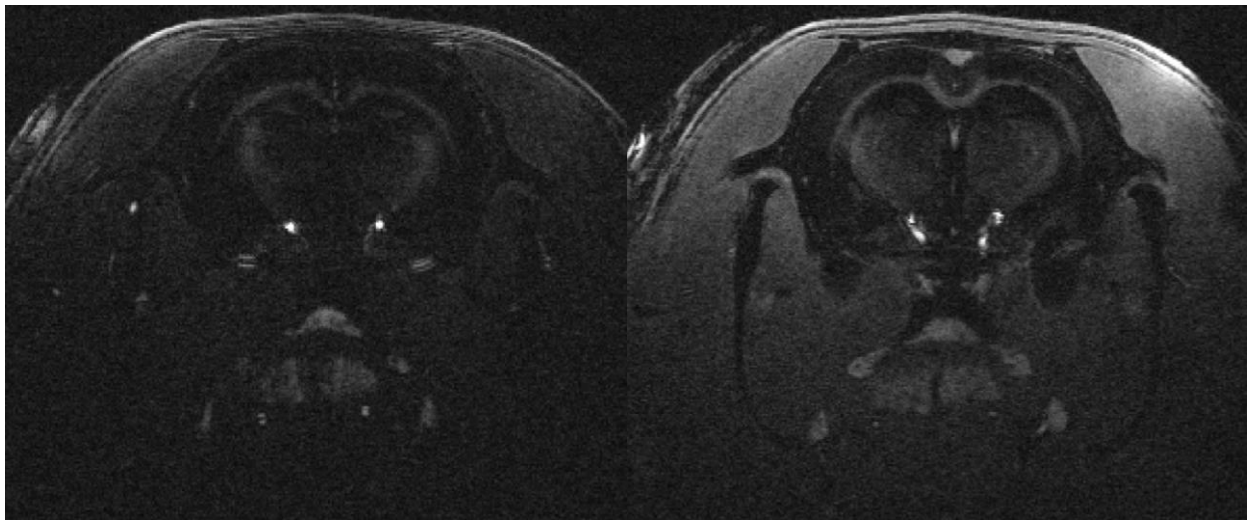


Figure 4: Rat 2, at the left side MP-RAGE with a simple inversion, at the right side MP-RAGE with a T2prep-IR, both optimized with an optimal control framework aiming at enhancing contrast between cortex and corpus callosum. Same acquisition parameters are used (segment duration: 1,5s, TR: 6.5ms, flip angle: 13°).

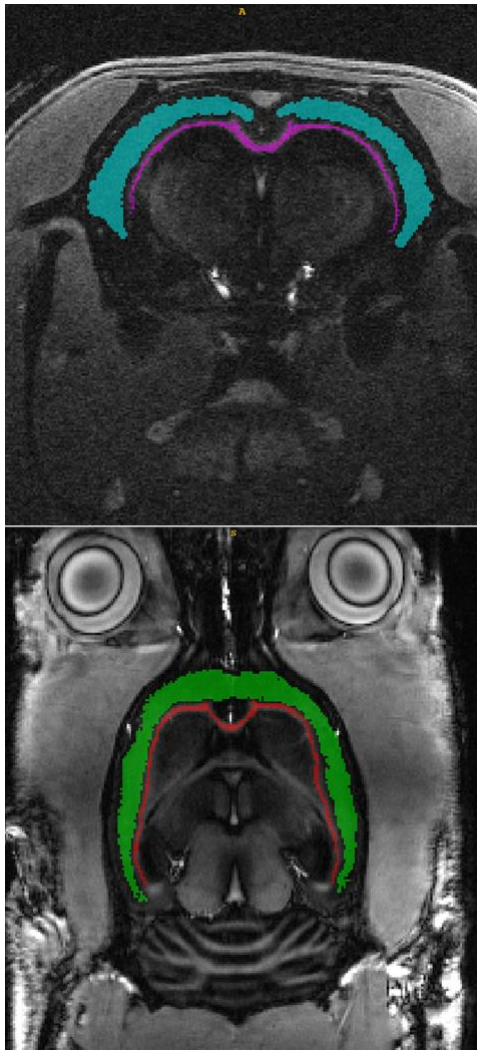


Figure 5 : Example of segmentations used to calculate contrast-to-noise ratio between cortex (in light blue in the top image and in green in the bottom image) and corpus callosum (in purple in the top image and in red in the bottom image) for axial slices of rat 2 (top image) and coronal slices of rat 1 (bottom image).