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Optimal Control of the contrast in a MP-RAGE sequence: an application on the pelvis

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Synopsis:

MRI contrast enhancement by Optimal Control is a new approach to design optimal magnetization preparation. This allows to maximize the contrast between target tissues characterized by their relaxation times. Recent numerical implementations have made possible the optimization of such preparation in a steady state sequence without full recovery between each repetition. This abstract demonstrates the contrast flexibility offered by this approach when combined with a MP-RAGE sequence on pelvis imaging at 3T.

Introduction:

MP-RAGE¹ is a 3D sequence composed of: a magnetization preparation for contrast control; acquisition of multiple k-space lines with a short time of repetition (TR) and low flip angle spoiled gradient echo scheme; and a partial recovery step. This rapid and high spatial resolution sequence allows T1-weighted brain images thanks to an inversion recovery preparation^{2,3,4}. For other clinical applications (such as for cancer imaging), other weightings could be developed. However, contrasts achievable with a preparation using both T1 and T2 relaxation times are hard to predict due to the formation of an equilibrium state. In this context, we developed an Optimal Control (OC) framework based on the GRAPE algorithm^{5,6,7}, that considers the full magnetization dynamics of the steady state, in order to optimize a complex preparation in this sequence. In the present work, we investigate the possibilities offered by our method when combined with a MP-RAGE to reach different contrasts between pelvis tissues on a clinical MRI scanner. Four different optimized contrast images are acquired on a healthy volunteer to demonstrate the versatility and efficiency of the proposed sequence design.

Methods:

The proposed method relies on an adaptation of the GRAPE algorithm which enables the optimization of an OC preparation composed of an arbitrary number of pulses in a MP-RAGE⁷. The approach is based on the general expression of the longitudinal steady state as a function of all the parameters of the sequence (acquisition and preparation). Then, the normalized signal in the k-space center is derived. The optimization problem is:

$$\begin{cases} \underset{u}{\text{minimize}} C = |S_{a,i}| - |S_{b,i}| \\ \text{subject to } |S_{a,i}| = 0 \text{ and } TS = 2 \end{cases}$$

Where:

- Optimization variables vector composed of angles, phases and delays : $u \in \mathbb{R}^{N \times 3 + 1}$
- Signal intensity of tissue a, to be saturated, or tissue b, to be maximized, after the i^{th} gradient echo acquisition of the readout, once the steady state is achieved : $S_{a/b,i}$
- Time of a segment: TS (s)

The cost function is iteratively minimized using gradient based approach specific to the GRAPE formalism. The cost function aims at maximizing the tissue B while saturating tissue A at k-space central line (e.g. $i=1$ for centric reordering). Here, preparations containing more than one pulses (2 to 5) were optimized in order to play both on T1 and T2 relaxation times.

T1 and T2 of a healthy volunteer were measured with respectively: two VIBE sequences with two different flip angles ($2^\circ, 10^\circ$) and B1 correction, a CPMG train with 8 TE from 10ms to 60ms. Results were compared and harmonized with the literature⁸ (Table 1,A) .

This relaxation times were used to optimize different contrasts between tissues : (A) fat enhancement with internal obturator (io) muscle saturation*, (B) io-muscle enhancement with fat saturation, (C) io-muscle enhancement with prostate saturation, (D) io-muscle enhancement with both bladder and fat saturation. (D) is more complex since two tissues were saturated.

Acquisition parameters remained unchanged between the different solutions (Table 1, B). The four optimized sequences were applied on the healthy volunteer on a 3T Magnetom Vida (Siemens Healthineers, Erlangen). SNR in each region of interest was measured and compared to expected values from the theoretical model.

*Note that for the optimization A, the set of pulses angles was fixed.

Results:

Optimizations resulted in the four preparation modules as below:

(A) : 1256ms – 90° – 15ms – 180° – 15ms – $90^\circ_{\varphi=180^\circ}$ – 330ms– acquisition

(B) : 10ms – 90° – 18ms – 180° – 18ms – $90^\circ_{\varphi=180^\circ}$ – 1320ms– 180° – 250ms –acquisition

(C) : 1202ms – 90° – 30ms – 180° – 30ms – $90^\circ_{\varphi=180^\circ}$ – 354ms– acquisition

(D) : 520ms – 90° – 50ms – 180° – 50ms – $90^\circ_{\varphi=180^\circ}$ – 768ms– 180° – 228ms –acquisition

The first line of Figure 2 shows the longitudinal magnetizations' evolution along a cycle for all four optimized contrasts. The second line illustrates the normalized signal intensity in the center of a k-space as a function of T1/T2 values. Figure 3 and 4 confirms the good saturation of io-muscle, ischiorectal fat, prostate, ischiorectal fat and bladder respectively for optimizations (A), (B), (C) and (D). Figure 5 shows SNR of each tissue and demonstrates that four contrasts objectives are reached.

Discussion:

The results presented are a proof of concept of the proposed contrast optimization method. The OC framework can be extended to the joint optimization of preparation and detection parameters. Increasing the number of preparation pulses gives more degrees of freedom to realize more challenging contrasts or involving a higher number of tissues, such as acquisition D. It is remarkable that preparations A and C are closed to existing preparation schemes (T2Prep-IR⁹). Finally, this method allows to achieve different contrasts preserving the advantages of a given detection scheme (such as spatial resolution and coverage, motion robustness).

Conclusion:

A generic optimal control framework was applied to optimize the preparation of a MP-RAGE sequence. Different contrasts are obtained on a 3T clinical MRI on the pelvis using similar acquisition parameters. Future works will investigate the benefit of this approach in the context of post-radiotherapy rectum MRI.

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Figures:

A - Relaxation times				
	Prostate	Fat	Muscle	Bladder
T_2 (ms)	80	140	35 (internal obturator)	450
T_2 (ms)	1500	380	1300	3500

B - Parameters of the sequence	
Time of a segment	2000ms
Time of repetition	6ms
Flip angle	12°
Time of echo	3.2ms
Lines acquired per segment	64
Matrix size	256x256x32
Orientation	axial
Dummy Cycles	4
Voxel size	1.172x1.72x2.5mm ³
Bandwidth per pixel	940Hz
Time of acquisition	4min24

Table 1: A - Relaxation times for the optimizations. B - Parameters of the sequence.

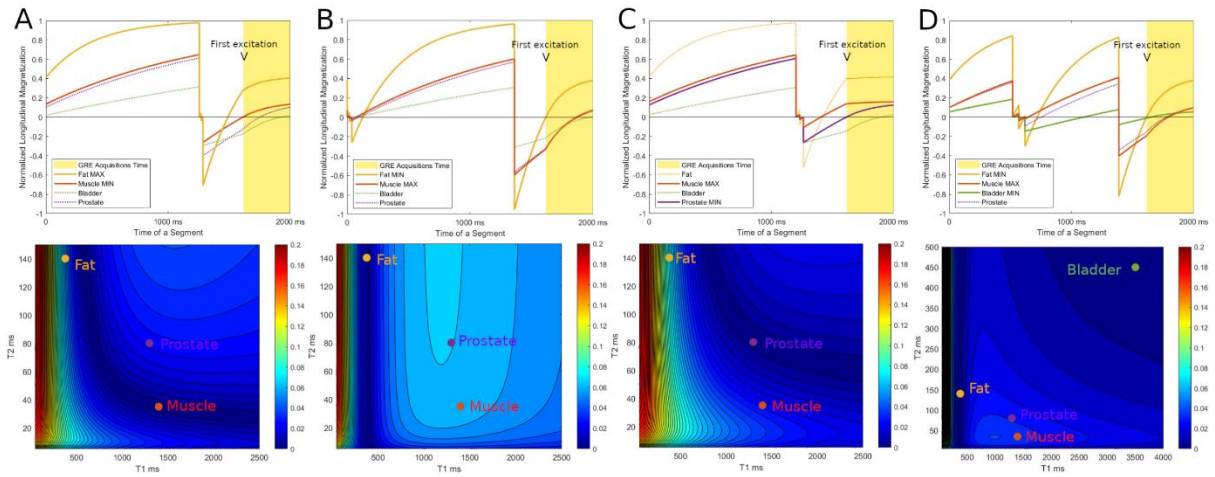


Figure 2: Upper images represent longitudinal evolution of the magnetizations over a cycle for fat, muscle, bladder and prostate. In each optimization (A, B, C, D), solid lines represent the longitudinal magnetizations of the tissues targeted in each optimization (maximized or minimized). Dotted lines represent the longitudinal magnetizations of the other tissues that are not considered in the optimization. Lower images represent transverse magnetization in the center of the k-space (i.e. after the first excitation of the acquisition time in a cycle) in the (T1/T2)-space.

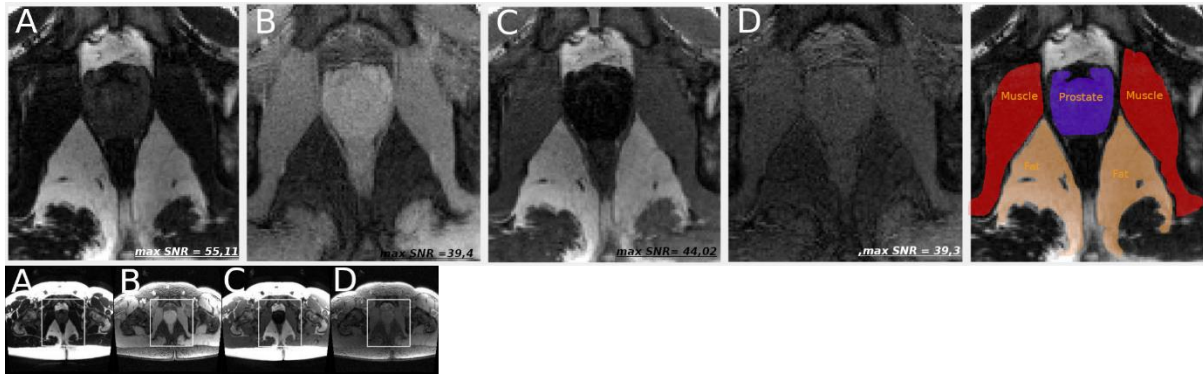


Figure 3: Results of the optimized sequences on a healthy volunteer for the four different preparation modules and the same acquisition scheme. Upper images are zoomed in the prostate area. At the right, ROI segmentations used for signal intensity measurement of the internal obturator muscle (red), the prostate (purple), the fat tissue of the ischiorectal fossa (yellow). Maximum SNR is indicated on each images.

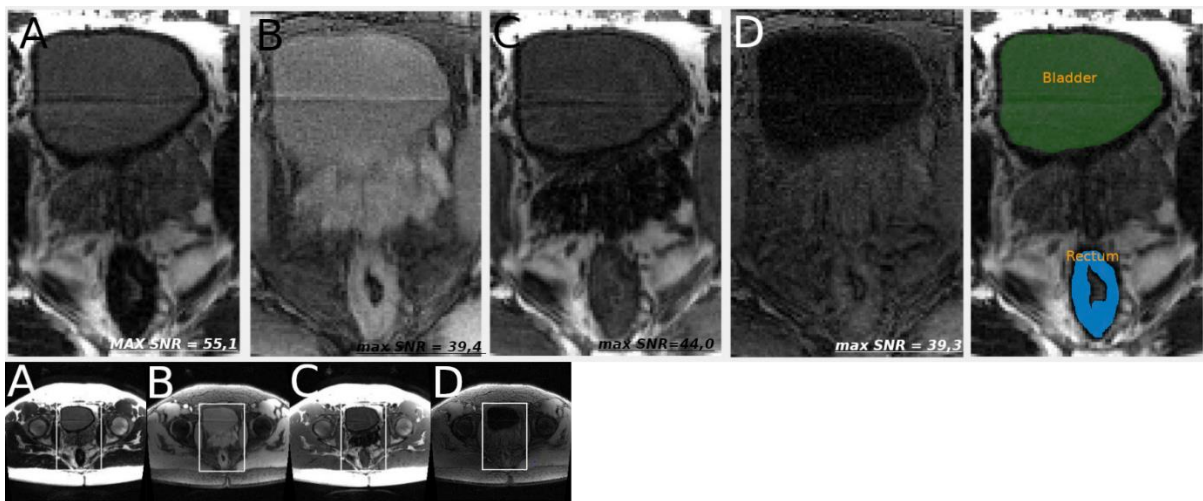


Figure 4: Results of the optimized sequences on our healthy volunteer for the four different preparation modules and the same acquisition. Upper images are zoomed in a plane containing the bladder and the rectum. At the right, segmentations of the bladder (green) and rectum (blue). Maximum SNR is indicated on each images.

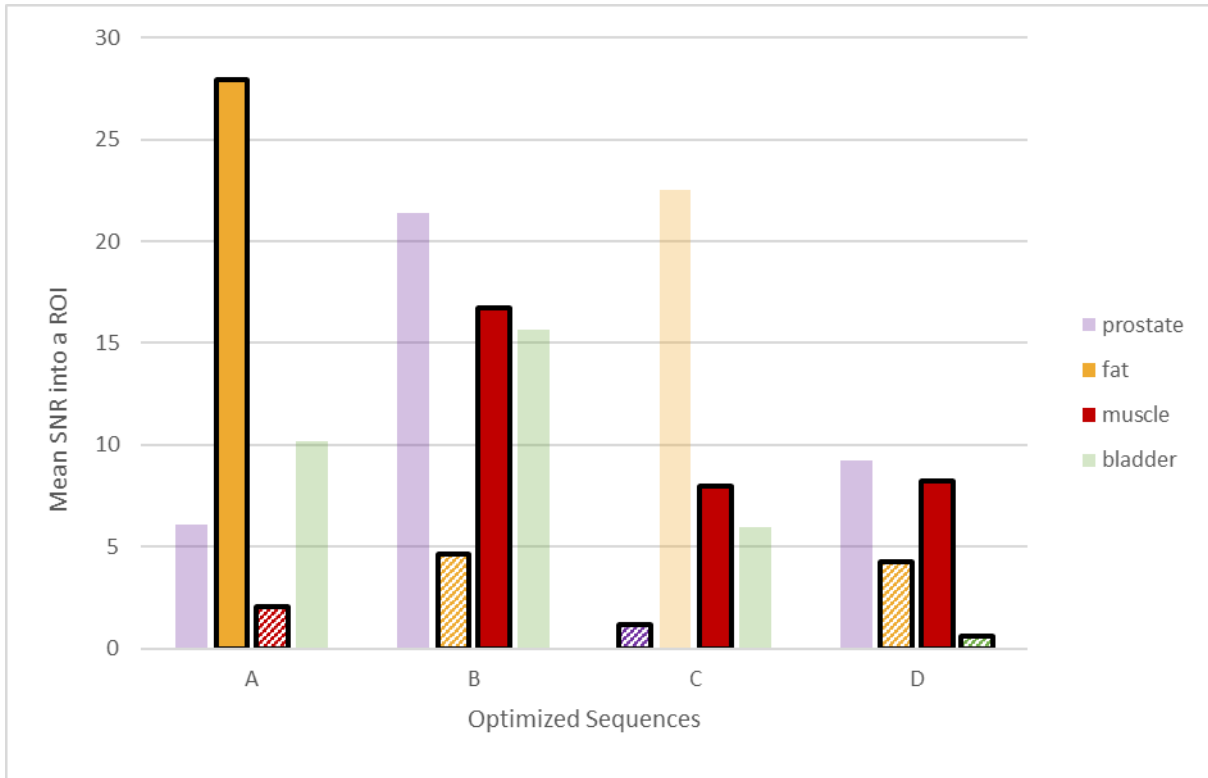


Figure 5 : Bars surrounded by a black border represents the averaged SNR of targeted tissues in each optimization (A,B,C,D). Striped bars refer to the SNR of tissues expected to be minimized, fully colored bars refer to the signal of tissues expected to be concomitantly maximized. Semi-transparent bars represent the resulting signal of other tissues, not targeted in the optimization.