Single-Shot R1-Mapping Strategies for Dynamic Contrast Agent Quantification

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Introduction - Contrast enhanced MRI has shown significant impact for a wide range of applications, e.g. in the detection of atherosclerotic plaque using Gd-based contrast agents [1,2]. However, the diagnosis can be improved by the dynamic quantification of the contrast agent concentration, i.e. quantification of the uptake rate. This can be achieved by fast – ideally single-shot – R1-mapping exploiting the linear relationship between the relaxation rate R1 (=1/T1) and concentration C. However, the temporal segmentation of a data set, acquired after the inversion or saturation prepulse, consequently comes with severe restrictions in the number and spatial resolution of images. This work discusses two radial acquisition schemes that can overcome these obstacles by the use of contrast preparation filters. The accuracy of the techniques was tested on phantoms for quantification of contrast agent concentrations. In addition, both techniques were evaluated for dynamic R1-mapping of carotids in healthy volunteers.

Methods

According to the Look-Locker sequence, an adiabatic inversion recovery (IR) pulse is followed by a train of N radial low flip angle FE acquisitions. For the reconstruction of a time point Ti on the relaxation curve, the entire single-shot data set is taken into account. However, only those profiles acquired at or close to Ti, contribute to the contrast dominating k-space center. According to the contrast preparation filter, the other profiles are used to complete the undersampled high frequency part of k-space. In particular, two radial acquisition schemes and contrast preparation filters were investigated for multiple image generation from this single-shot data set. 1.) REVERSED BIT PROFILE ORDER (RBPO) as proposed for the KWIC (k-space weighted image contrast) approach [3]: the single-shot data set of N profiles is segmented into P=16 phases, each one consisting of N/16 evenly spaced profiles. The angulation of the subsets with respect to each other is determined by the reversed bit order (RBO): the first profiles $p_{0,0}$, $p_{1,0}$, …, $p_{15,0}$ of the segments 0…15 are angulated by RBO_{16}=[0, 8, 4, …, 15]*π/N, resulting in an "angle bisection scheme". The inner circle of the contrast preparation filter contains the segment acquired around Ti, then, ring by ring, the number of segments doubles. The radii of the rings are determined by the largest angular gap occurring in each ring, so that Nyquist is fulfilled in all k-space regions. Fig. 1 demonstrates the segmentation for N=8 profiles and P=4 phases. 2.) GOLDEN CUT PROFILE ORDER (GCPO): The profiles, acquired after the inversion pulse, are spaced by a fixed angle of 111.25° (Fig. 2), which divides 180° by the golden cut section. A new profile added to a set of profiles then divides the largest angular gap occurring, yielding an optimal profile distribution for any arbitrary number of profiles [4]. It can be shown, that the largest angle increment in a subset of N' profiles changes as soon as N' exceeds a Fibonacci number. As the radius of a filter ring depends on the largest angle increment, the number of profiles in succeeding rings is thus determined by succeeding Fibonacci numbers (2,3,5,8,..), starting with 2 profiles in the inner circle. The images are finally reconstructed by Fourier transform after density correction and regridding to a Cartesian grid.

Results

The above technique was used on a 1.5T whole body system (Philips Achieva) with a 208x208 matrix, FOV=130mm, slice 7mm, flip angle=10°, TR=6.4ms, and a 2 element surface coil (∅11cm) to acquire carotid images from healthy volunteers. To fulfil the Nyquist theorem even in the outmost k-space periphery for a 208x208 image matrix, the RBPO required a total of N=352 (N'=352/16=22) profiles, while the GCPO required N=377 profiles. This resulted in total scan durations of 2.3s (RBPO) and 2.4s. Mapping was done using a non-linear least squares fit. In case of the GCPO, 187 images in a temporal distance of 12.8ms were reconstructed of the single-shot data set. The performance of both techniques was first tested on a phantom, containing Magnevist (Gd-based. Schering, Germany) in different concentrations to mimic high relaxation rates, as they occur invivo in the presence of contrast agent (Table 1).

$R1/s^{-1}$	12.5	6.3	4.3	3.2
RBPO	19.2±38.0	8.7±29.2	4.4±0.4	3.3±0.1
GCPO	17.2±2.4	6.3±0.9	4.2±0.4	3.0±0.2

Table 1. Phantom Experiment: mapping of high R1-values, as they appear in the presence of contast agent.

Fig. 3 and 4 show quantitative maps of healthy volunteer's carotids, overlaid on a TSE image of the same geometry. Both techniques provided accurate mapping results for blood and muscle tissue.

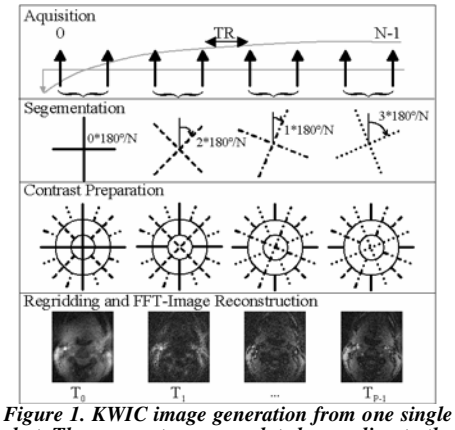

Figure 1. KWIC image generation from one single shot. The segments are angulated according to the reversed bit order (RBO) scheme. The RBO results in an evenly distributed sampling scheme but also in a restricted number of images.

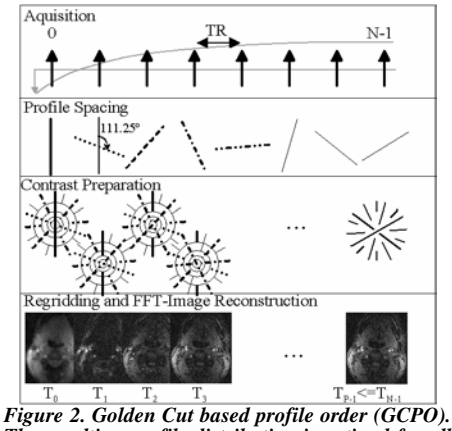

Figure 2. Golden Cut based profile order (GCPO). The resulting profile distribution is optimal for all phases with respect to the distribution of profiles in each filter ring. The GCPO results in an arbitrary number of images at arbitrary time points.

Discussion/Conclusion

Both techniques yielded excellent R1-maps in terms of accuracy and stability for a sub-millimeter in-plane resolution in about 2s. While the RBPO results in an evenly distributed profile scheme but a restricted number of images, the GCPO uses a less homogeneous sampling pattern, but allows the reconstruction of an arbitrary number of images at arbitrary time points. Thus a profile order, based on the golden cut section, is preferable in case of high relaxation rates, as they occur in the presence of contrast agent due to the most flexible time point resolution. We conclude, that a radial sampling scheme combined with a contrast preparation filter satisfies the particularly high requirements for the dynamic quantification of contrast agents in carotid plaque imaging, in terms of spatial and temporal resolution as well as mapping accuracy.

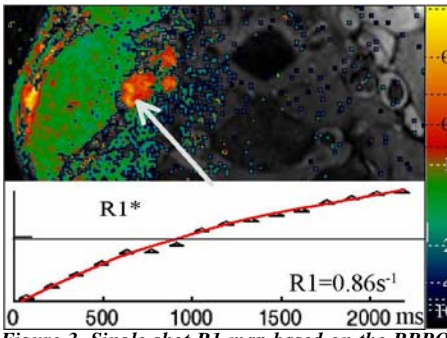

Figure 3. Single-shot R1-map based on the RBPO approach. Blood: R1=(0.86±0.14)s^{-1}, Muscle: R1=(1.19±0.22)s^{-1}.

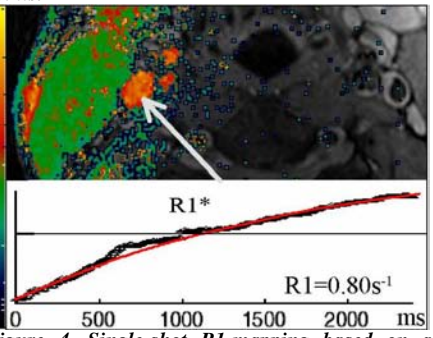

Figure 4. Single-shot R1-mapping based on a GCPO. Blood: R1=(0.80±0.16)s^{-1}, Muscle: R1=(1.10±0.15)s^{-1}.

Literature: muscle – R1=1.15s^{-1}, blood – R1=0.83s^{-1}

References - [1] Yuan C, et al, JMRI 15, 62-67, (2002), [2] Sirol M, et al, Circulation 109, 2890-6, (2004), [3] Song HK, et al, MRM 44, 825-832, (2000), [4] Winkelmann S, et al, Proc. ISMRM 13, 2196, (2005)