First-Pass Cardiac Perfusion MRI with 50%-Reduced Contrast Agent Dosage

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***Introduction*:** While first-pass cardiac perfusion MRI is a promising modality for the assessment of coronary artery disease [1], it also has several areas that need improvement. One area of improvement that will be addressed by this study is safety concerns associated with Gadolinium-based MRI contrast agents, especially in patients with renal insufficiency (www.fda.gov/cder/drug/advisory/gadolinium_agents.htm). One strategy to reduce the contrast agent dosage is to achieve maximal myocardial contrast-to-noise ratio (CNR) through pulse sequence optimization, as well as high field imaging (≥3T), and trade off a portion of CNR to reduce contrast agent dosage. A previous study has shown that a gradient echo (GRE) pulse sequence with reverse centric k-space trajectory can produce higher CNR than that with linear k-space trajectory [2]. The purpose of this study is to further optimize the pulse sequence with reverse centric k-space trajectory by employing variable flip angles, in order to achieve comparable image quality at 50%-reduced dosage to that produced by a conventional pulse sequence with linear k-space trajectory at standard dosage.

***Methods*:** A computer simulation was conducted to design and evaluate the pulse sequence optimization at 3T. According to the Bloch equation, the magnetization (M) of a saturation-recovery GRE pulse sequence can be mathematically described as $M(k_y) = (1-e^{-TD/T1})(E_1 \cos\theta)^{ky} + (1-E_1)(1-(E_1 \cos\theta)^{ky})/(1-E_1 \cos\theta)$, where TD = time delay between the end of saturation and the beginning of readout, $E_1 = e^{-TR/T1}$, θ = flip angle, equilibrium magnetization (M_0) =1, and k_y = phase-encoding line. Typical imaging parameters at 3T were considered: field of view = 320 x 320 mm, acquisition matrix = 160 x 160, spatial resolution = 2.0 x 2.0 mm, TE/TR = 1.3/2.4 ms, temporal resolution = 128 ms, TSENSE parallel acceleration factor = 3, TD = 20 ms, and bandwidth = 1000 Hz/pixel. Note that the only relevant parameters for simulation are total phase-encoding lines = 54, TD, flip angle, and TR. For each k-space trajectory, the optimal flip angle was calculated to achieve maximal myocardial CNR. Specifically, the transverse magnetization (M_{xy}) at pre-contrast was calculated assuming T_1^{pre} = 1150 ms [3]. Next, M_{xy} at peak wall enhancement was calculated assuming concentration of Gd-DTPA = 0.1 mM for standard dosage of 0.1 mmol/kg [4]. The corresponding T_1 value was calculated assuming fast water exchange [5]: $R_1 = r_1 \cdot [\text{Gd-DTPA}] + R_1^{pre}$, where $R_1 = 1/T_1$, r_1 = 3.7 L/mmol/s [6], and $R_1^{pre} = 1/T_1^{pre}$. The myocardial signal contrast, as defined as $M_{xy}^{peak} - M_{xy}^{pre}$, was plotted as a function of flip angle and k_y. Map of $M_{xy}^{peak} - M_{xy}^{pre}$ can be evaluated along k_y = 27 and k_y =54 to determine the optimal flip angle for the linear k-space trajectory and reverse centric k-space trajectory, respectively. For the reverse centric k-space trajectory, the flip angle was incrementally increased at the tail end of the RF train using a modified Hanning window such that the last RF pulse angle was 38°. This variable flip angle approach was implemented to achieve higher M_{xy} near the center of k-space compared with that by the constant flip angle approach. Two different acquisitions were evaluated: linear k-space trajectory with constant flip angle at [Gd-DTPA] = 0.1 mM (i.e., standard dosage = 0.1 mmol/kg) and reverse centric k-space trajectory with variable flip angles at [Gd-DTPA] = 0.05 mM (i.e., 50%-dosage = 0.05 mmol/kg). Their corresponding amplitude weighting functions (i.e., $M_{xy}^{peak} - M_{xy}^{pre}$) were applied on a template first-pass perfusion MR image. Specifically, the k-space representation of the template image was multiplied by the calculated amplitude weighting function. After performing the inverse Fourier transform of this product, the mean intensity within the whole heart, as defined by manual segmentation of endo- and epi-cardial contours, was calculated. To estimate the penalty in terms of blurring, the point spread function (PSF) in the phase-encoding direction was calculated as the inverse Fourier transform of the amplitude weighting function (i.e., $M_{xy}^{peak} - M_{xy}^{pre}$), and the full width at half maximum (FWHM) of the PSF was calculated with using linear interpolation.

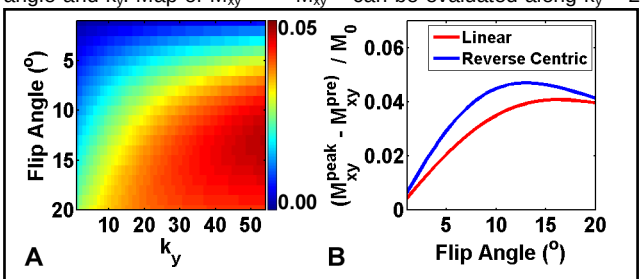

Fig. 1. (A) Map of $M_{xy}^{peak} - M_{xy}^{pre}$ at [Gd-DTPA] = 0.1 mM as a function of flip angle and k_y. Plots of $M_{xy}^{peak} - M_{xy}^{pre}$ as a function of flip angle for (B) linear trajectory and (C) reverse centric trajectory. Center k_y = 27.

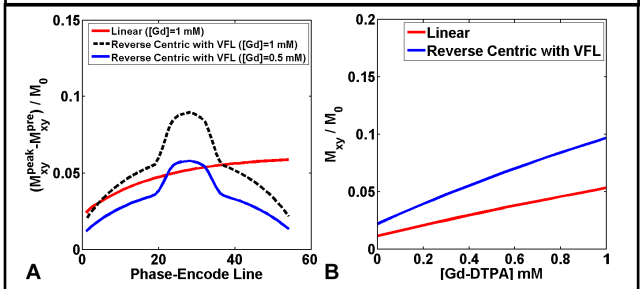

Fig. 2. (A) Plots of $M_{xy}^{peak} - M_{xy}^{pre}$ as a function of k_y. (B) Plots of M_{xy} as a function of [Gd-DTPA]. Center k_y = 27. VFL: variable flip angles.

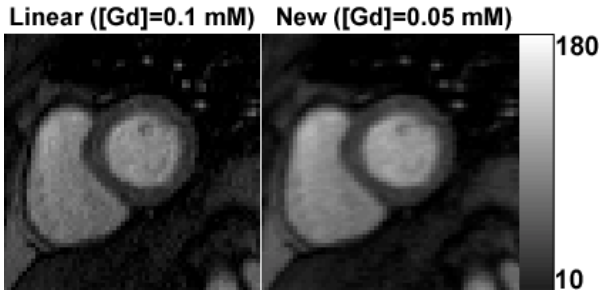

Fig. 3. Amplitude modulated images of the heart: (left) linear k-space trajectory image at [Gd-DTPA] = 0.1 mM after baseline correction and (right) reverse centric k-space trajectory image with variable flip angles at [Gd-DTPA] = 0.05 mM after baseline correction. Images are displayed with identical grayscales (10-180 of a.u.).

***Results*:** Figure 1 shows a map of $M_{xy}^{peak} - M_{xy}^{pre}$ as a function of flip angle and k_y. The optimal flip angles for the linear and reverse centric k-space trajectories were 16° and 13°, respectively. Figure 2 shows plots of $M_{xy}^{peak} - M_{xy}^{pre}$ as a function of k_y and M_{xy} as a function of [Gd-DTPA] for the two different acquisitions. These plots show that the reverse centric k-space trajectory with variable flip angles at 50%-reduced dosage can achieve comparable myocardial CNR to that by the linear k-space trajectory at standard dosage. Figure 3 shows amplitude modulated images produced by the two different acquisitions. Compared with the linear k-space trajectory at standard dosage, the reverse centric k-space with variable flip angles at 50%-reduced dosage yielded 12% higher myocardial signal contrast, but the expense of 22% higher FWHM in the phase-encoding direction.

***Discussion*:** This study has shown that a GRE pulse sequence with reverse centric k-space trajectory and variable flip angles can be used to achieve comparable myocardial CNR at 50%-reduced dosage compared with the linear k-space trajectory at standard dosage. The ability to reduce the contrast agent dosage is clinically relevant, because a lower dosage reduces examination costs and may decrease the likelihood of adverse reactions to the contrast agent, particularly in two-injection (rest-stress) protocols. This new method should be compatible with viability imaging at 3T, because two injections of 0.05 mmol/kg of Gd-DTPA should be sufficient to achieve adequate delayed enhancement of scar.

References

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