Comparison of the Effectiveness of Saturation Pulses for Quantitative First-Pass Cardiac Perfusion MRI at 1.5T and 3T

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Introduction: Effective saturation of magnetization is crucial for accurate quantification of myocardial perfusion from T_1-weighted first-pass contrast-enhanced images. Despite the known limitations of the widely used rectangular radio-frequency (RF) saturation pulse [1], the effectiveness of the saturation pulse has been largely ignored in previous first-pass myocardial perfusion MRI studies. Two saturation pulses more robust than the rectangular pulse are the rectangular RF pulse train [2] and the adiabatic B_1-insensitive rotation (BIR-4) pulse [3,4]. Briefly, the pulse train achieves uniform saturation of magnetization by applying a train of three rectangular 90° RF pulses with crusher gradients in between the RF pulses, where the spoiler gradients are cycled to eliminate stimulated echoes. The BIR-4 pulse achieves uniform saturation of magnetization by sweeping over a broad band of frequencies and phase cycling four adiabatic half-passage pulses. The purpose of this study, therefore, was to assess the relative effectiveness of the rectangular, pulse train, and BIR-4 saturation pulses in the heart at 1.5T and 3T.

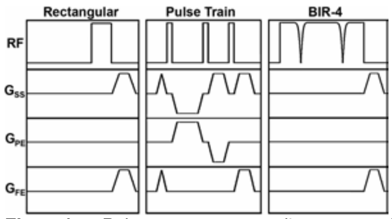

Fig. 1. Pulse sequence diagrams of rectangular, pulse train, and BIR-4 pulses. For the pulse train, the crusher gradients in between RF pulses are cycled to eliminate stimulated echoes. G_{SS}: slice-select gradient; G_{PE}: phase-encoding gradient; G_{FE}: frequency-encoding gradient. The pulse durations are summarized in Table 1.

Methods: Figure 1 shows the pulse sequence diagrams of the rectangular, pulse train, and BIR-4 saturation pulses, which were implemented on 1.5T and 3T whole-body MR scanners (Avanto and Tim Trio, Siemens). The penalties associated with the pulse train and BIR-4 pulses are longer pulse duration and higher RF power deposition than the rectangular pulse. Table 1 summarizes the pulse duration and relative RF energy of the three types of saturation pulses. The residual longitudinal magnetization left behind by the saturation pulse can be measured by performing a saturation-no-recovery experiment, as previously described [3]. In this study, a TurboFLASH sequence with a center-out k-space trajectory was used to achieve good image quality at 3T. The imaging parameters include: FOV = 500 x 250 (phase-encoding) mm, acquisition matrix = 128 x 48, in-plane resolution = 3.9 x 5.2 mm, slice thickness = 8 mm, TE/TR = 1.0/2.35 ms, TD = 2 ms (spoiler gradient duration), image acquisition time = 113 ms, flip angle = 10°, and bandwidth = 740 Hz/pixel. Five healthy human subjects were imaged at 1.5T in 3 short-axis (apical, mid-ventricular, basal) and 2 long-axis (2-chamber and 4-chamber) views of the heart. Six different human subjects were imaged at 3T in the same five cardiac views. Human imaging was performed in accordance with protocols approved by the Human Investigation Committee at our institution; all subjects gave written informed consent. In addition to the three magnetization saturation images, for image normalization, a proton-density (PD) weighted image was acquired with 3° flip angle and no the saturation pulse. Receiver settings were kept unchanged between acquisitions, to permit signal comparisons. For image analysis, the resulting normalized saturation images were multiplied by the factor sin(3°)/sin(10°) to account for the difference in the two flip angle values. A region-of-interest (ROI) was manually drawn for the whole left ventricle per cardiac view. For each ROI, the root-mean-square (RMS) of the residual magnetization was calculated. The reported values represent the mean ± standard deviation of RMS of residual magnetization across ROIs.

Results: In Figure 2, representative normalized magnetization saturation images are shown in three short-axis and two long-axis views of the heart at 1.5T and 3T. The mean residual magnetization was significantly higher for the rectangular pulse than for the pulse train and BIR-4 saturation pulses at 1.5T (0.138 ± 0.039 vs. 0.028 ± 0.006 vs. 0.028 ± 0.005; $p < 0.001$, respectively) and 3T (0.141 ± 0.057 vs. 0.032 ± 0.016 vs. 0.029 ± 0.011; $p < 0.001$, respectively). The RMS of residual magnetization was not different between the pulse train and BIR-4 pulses at both field strengths.

Discussion: This study demonstrates that the (undesirable) residual longitudinal magnetization of the rectangular pulse can be as large as 14% of equilibrium magnetization (M_0), whereas those of the pulse train and BIR-4 pulses are relatively small (~3% of M_0). These findings are significant because a residual magnetization as large as 14% of M_0 can cause significant T_1-weighted signal errors (e.g., pre-contrast baseline signals; contrast-enhanced myocardial signal) in quantitative analysis of first-pass cardiac perfusion MRI. While both the pulse train and BIR-4 pulses are more robust than the conventional rectangular RF pulse, there are costs associated with their benefits. The higher specific absorption rate (SAR) is generally not a serious limitation since the duty cycle of the saturation pulse (6.2-10.2 ms) is relatively low per cardiac perfusion image acquisition (~150-200 ms). However, SAR may be an issue for the BIR-4 pulse at 3T, because its required B_1 to achieve adiabaticity can exceed the SAR limit.

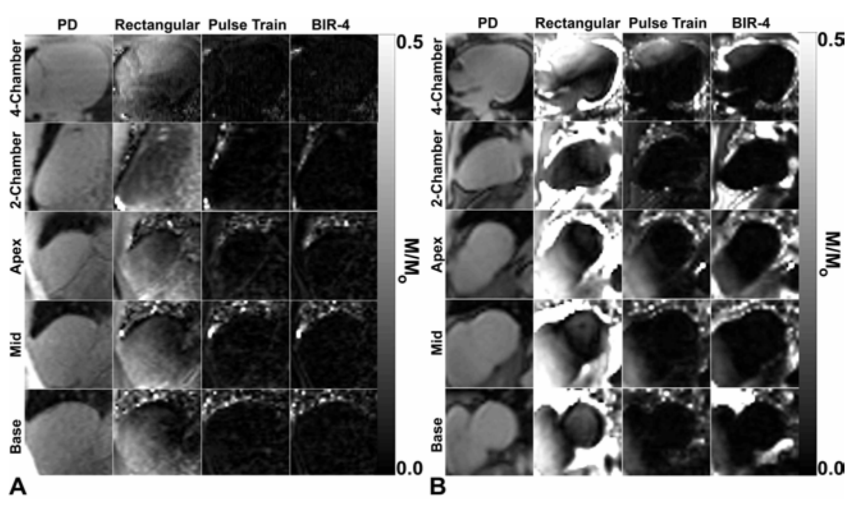

Fig. 2. Representative normalized saturation images in three short-axis and two long-axis views of the heart at (A) 1.5T and (B) 3T. The normalized images are displayed with identically narrow grayscales (0 – 0.5 in dimensionless units). SAX1: apical short-axis view; SAX2: mid-ventricular short-axis view; SAX3: basal short-axis view.

References
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Table 1: Summary of pulse duration and RF energy of the rectangular, pulse train, and BIR-4 saturation pulses at both 1.5T and 3T. The pulse duration excludes the final spoiler gradient duration of 2 ms.

Field	Pulse Attribute	Rectangular	Pulse Train	BIR-4
1.5T	Duration	1 ms	7.5 ms	4.1 ms
	Relative Energy	1	6	64
3T	Duration	2 ms	7.5 ms	8.2 ms
	Relative Energy	1	12	64