

Hybrid Adiabatic-Rectangular Pulse Train for Effective Saturation of Magnetization within the Whole Heart at 3T

D. Kim¹, and K. McGorty¹

¹Center for Biomedical Imaging and Radiology, NYU Langone Medical Center, New York, NY, United States

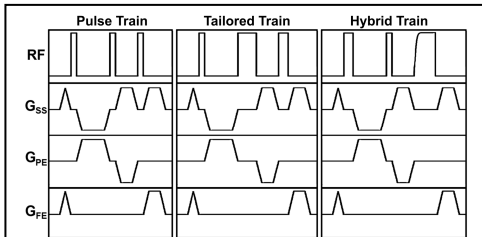


Fig. 1. Pulse sequence diagram of (left) conventional pulse train, (middle) tailored pulse train, and (right) hybrid pulse train.

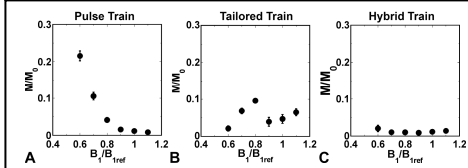


Fig. 2. Plots of M_{ZR} produced by the three saturation pulses as a function of normalized B_1 .

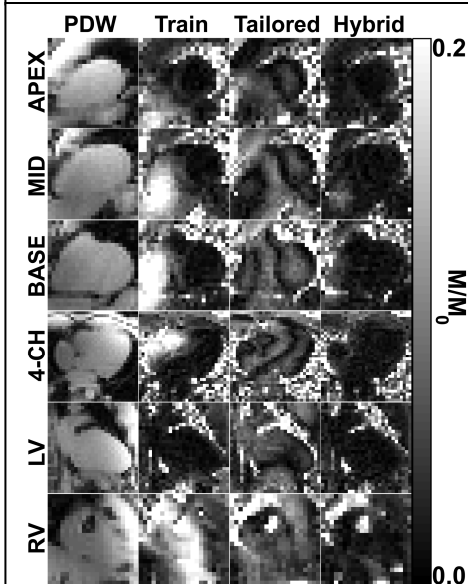


Fig. 3. PDW and normalized saturation images, which are displayed in dimensionless units 0.0-0.2.

Introduction: A recent study showed that the diagnostic performance of first-pass myocardial perfusion MRI at 3T is superior to that at 1.5T for the identification of both single and multiple vessel coronary disease [1]. However, radio-frequency (RF) field (B_1) variations and dielectric effects are comparatively higher at 3T than at 1.5T. These challenging factors make it difficult to perform accurate T_1 -weighting using a nonselective rectangular saturation pulse. Previously reported adiabatic B_1 -insensitive rotation (BIR-4)[2], rectangular RF pulse train [2,3], and tailored rectangular RF pulse train [4] showed significant improvement in the saturation of magnetization at 3T. Unfortunately, none of them achieved effective saturation of magnetization, which we shall define as residual longitudinal magnetization (M_{ZR}) after saturation $< 5\%$ of equilibrium magnetization (M_0), within the whole heart, while remaining within clinically acceptable specific absorption rate limits. The purpose of this study was to develop a hybrid adiabatic-rectangular pulse train that can achieve both of the aforementioned objectives at 3T.

Methods: Figure 1 shows pulse sequence diagrams of a conventional rectangular pulse train, tailored pulse train, and hybrid adiabatic-rectangular pulse train, which includes an adiabatic half-passage pulse (see Table 1 for their characteristics). The three saturation pulses were implemented on a 3T whole-body MR scanner (Tim-Trio; Siemens) equipped with an 12-channel phased array RF coil. M_{ZR} left behind by the saturation pulse was measured by performing a saturation-no-recovery experiment using a TurboFLASH pulse sequence with centric k-space reordering, as previously described [2]. Relevant imaging parameters include: field of view = 340 x 276 mm, acquisition matrix = 64 x 52, slice thickness = 8 mm, TE/TR = 1.1/2.3ms, TD = 3 ms, image acquisition time = 78 ms, flip angle = 10°, GRAPPA parallel imaging acceleration factor = 1.5, and bandwidth = 1002 Hz/pixel. Proton density weighted (PDW) image was acquired using 4° flip angle and without the saturation pulse. Saturation image was divided by the PDW image, in order to correct for surface receiver coil inhomogeneities and M_0 . This image was multiplied by a factor $\sin(4^\circ)/\sin(10^\circ)$ to account for the two flip angles, and the resulting normalized image intensity conveniently has a range of 0 (perfect saturation) and 1 (no saturation) [2]. The breath-hold duration was 8 s, which includes 6 s of wait time for full recovery of magnetization between PDW and saturation-recovery image acquisitions. The RF, receiver scales, and B_0 shim settings were kept identical between the different acquisitions. A spherical oil phantom was imaged in an axial plane at magnet isocenter with the shim setting manually adjusted to produce 130 Hz peak-to-peak B_0 variation, in order to mimic the heart at 3T [5]. The image acquisition was repeated with the reference B_1 manually adjusted from 0.6-1.1 (0.1 steps) of its nominally calibrated value, in order to determine the sensitivity of each saturation pulse to clinically relevant B_1 [6]. For in vivo evaluation, nine adult volunteers (7 males; 2 females) were imaged in 3 short-axis (apical, mid-ventricular, basal) views of the left ventricle (LV) and 3 long-axis views (2-chamber view of the LV, 2-chamber view of the right ventricle (RV), 4-chamber). For image analysis, the LV and RV were segmented manually. Reported data represent the mean and standard deviation over cardiac views. A single-factor ANOVA was used to compare the mean values between the three groups, and the Tukey's multiple comparison test was used to compare between each pair of two groups.

Results: Figure 2 shows plots of M_{ZR} produced by the three pulses as a function of normalized B_1 . Compared with conventional pulse train and tailored train, the hybrid pulse train produced considerably lower M_{ZR} (< 0.03) over the range of 0.6-1.1 reference B_1 . Figure 3 shows representative saturation images of one volunteer. Statistically, the mean M_{ZR} within the LV and RV was different between all three pulse groups and within each pair of pulses (Table 2).

Discussion: This study compared the efficacies of the conventional pulse train, tailored pulse train, and hybrid pulse train for saturation of magnetization within the whole heart at 3T. Only the hybrid pulse train produced $M_{ZR} < 0.03$. The additional RF energy needed to play the hybrid pulse train is inconsequential in the context of multi-slice (> 5) first-pass perfusion MRI at 3T. Effective saturation of magnetization within the whole heart is likely to produce more accurate estimation of cardiac perfusion, particularly for 3D whole heart first-pass perfusion MRI and high spatial resolution imaging for RV perfusion estimation.

References

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Table 1. Summary of pulse characteristics. Each pulse train is preceded by 1 ms long spoiler gradient and followed by 3 ms long spoiler gradient, and the first and second crusher gradient durations are 3 and 2 ms, respectively. Note that the hybrid train includes an adiabatic half-passage pulse.

	Angle (°)	Duration (ms)	B_1 (Hz)	Total Relative Energy	Total Duration (ms)
Pulse Train	90	0.5	500	1	10.5
	90	0.5	500		
	90	0.5	500		
	96	0.6	444.44		
Tailored Train	228	1.3	487.18	1.65	11.7
	141	0.8	489.58		
	140	0.8	486.11		
Hybrid Train	90	0.5	500	2.47	11.8
	Half-Passage	1.54	666.67		

Table 2. Mean M_{ZR} was different between all three pulse groups and within each pair of pulses ($n = 52$; $p < 0.003$).

	Pulse Train	Tailored Train	Hybrid Train
LV	0.021 ± 0.009	0.048 ± 0.009	0.015 ± 0.003
RV	0.090 ± 0.063	0.058 ± 0.015	0.020 ± 0.007

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