B0- and B1-Insensitive Saturation Pulse for Accurate T1 Estimation for First-Pass Perfusion MRI

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Introduction: First-pass myocardial perfusion MRI is potentially a quantifiable method for assessing the severity of coronary artery disease [1]. Perfusion can be estimated, in principle, from T_1-weighted images by converting the signal-time curves to contrast agent concentration-time curves. Typically, T_1-weighting is achieved by saturating the magnetization with a nonselective radio-frequency pulse prior to imaging. Incomplete saturation of magnetization due to static magnetic field (B_0) and radio-frequency field (B_1) inhomogeneities will introduce uncertainties in T_1 estimation. The purposes of this study were: 1) to demonstrate that single-shot, echo-planar imaging (EPI)[2] can be used to image the residual magnetization (M_R) immediately after incomplete saturation due to B_0 and B_1 inhomogeneities in the heart at 1.5T, and 2) to demonstrate that complete saturation of magnetization can be achieved using a composite B_1-insensitive rotation (BIR) pulse.

Background: In quantitative, first-pass perfusion MRI, a nonselective 90° saturation pulse (typically, a square envelope) is generally preferred due to its insensitivity to arrhythmias [3] and to previous history of magnetization for multi-slice 2D imaging (Fig. 1A). The accuracy of perfusion measurements from T_1-weighted images can be heavily dependent on the sensitivity of the effectiveness of the saturation pulse to B_0 and B_1 inhomogeneities. Shimming and calibration methods can be used to compensate for B_0 and B_1 inhomogeneities, respectively, but they are often time consuming and difficult to perform in cardiac imaging. A saturation pulse more robust than a single pulse is a nonselective 90° composite simple pulse, which is comprised of individual pulses that approximately cancel each other's imperfections [4]. Figure 1B shows such a composite pulse, comprised of three pulses ($90°_x$-$180°_y$-$90°_y$) that collectively rotate the longitudinal magnetization into the transverse plane with a higher degree of tolerance to B_0 and B_1 inhomogeneities. Adiabatic pulses are amplitude- and frequency-modulated pulses which sweep over a broad band of frequencies in order to achieve immunity to B_1 inhomogeneity. While an adiabatic half-passage pulse can be utilized as a saturation pulse, it cannot compensate for B_0 inhomogeneity. A more robust saturation pulse is a BIR-4, which is comprised of four adiabatic pulses that collectively provide arbitrary rotation angle and immunity to B_0 and B_1 inhomogeneities [5].

Methods: An EPI sequence was implemented to image the M_R immediately after incomplete saturation due to B_0 and B_1 inhomogeneities in the heart at 1.5T (Fig. 1D). The EPI protocol (scan duration = 19.4 ms) was designed to reduce artifacts due to T_2* relaxation, motion, and B_0 variation and to image (in single-shot mode) with negligible recovery of magnetization after saturation. Imaging parameters included: field of view = 400 x 200 mm^2, acquisition matrix = 64 x 32, in-plane resolution = 6.25 x 6.25 mm^2, slice thickness = 8 mm, TE = 9.2 ms, scan duration = 19.4 ms, imaging flip angle = 90°, and bandwidth = 2790 Hz/pixel. Three saturation pulses were implemented as described above: nonselective single 90°, nonselective composite 90°, and nonselective BIR-4 90°. The pulse durations for single 90°, composite simple 90°, and BIR-4 90° were 1 ms, 3 ms, and 4.1 ms, respectively, and the gradient spoiling duration was 2.6 ms. The nominal 90° was determined as the result of running the manufacturer's routine tune-up procedure. A proton density-weighted (PDW) image was also acquired (without saturation) in order to correct for the receive coil inhomogeneity. All imaging experiments were performed on a 1.5T whole-body MR scanner (Avanto, Siemens Medical Solutions) equipped with a 12-channel phased array RF coil and a gradient system capable of achieving a maximum gradient strength of 45 mT/m and a slew rate of 200 T/m/s.

A spherical phantom (T_1 = 2680 ms) was imaged in 3 orthogonal planes (coronal, sagittal, and transverse) near magnet isocenter. This long T_1 value ensured negligible recovery of magnetization during the time between saturation and imaging. Four healthy human subjects were imaged at 3 short-axis (apical, mid-ventricular, basal) and 2 long-axis (2-Chamber, 4-Chamber) views of the heart. Both electrocardiogram gating and breath holding, though not required for single-shot EPI, were performed for image registration purposes. The M_R was computed as the ratio of image intensity and the corresponding PDW image intensity. The mean and standard deviation of M_R were computed from the entire phantom or left ventricle. Statistical comparison of M_R was performed using ANOVA. In a separate experiment, after an initial standard tune-up procedure, image acquisition using single and composite pulses was repeated with nominal flip angles ranging from 80-100° (0.5° steps) in order to identify an effective flip angle that can best saturate the magnetization.

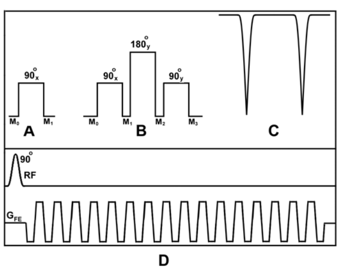

Fig. 1. Schematic diagrams of the three saturation pulses implemented: a) single 90°, b) composite simple 90°, and c) BIR-4 90° (only the amplitude profile is shown). d) A single-shot EPI sequence.

Results: Figure 2 shows representative images of residual magnetization across the phantom in the transverse plane, comparing the performance of the three saturation pulses. In all three planes, mean M_R was significantly different between the three pulses ($M_{R,Single}$ =6.8 ± 4.9; $M_{R,composite}$=2.5 ± 2.7, $M_{R.BIR-4}$=0.4 ± 0.2; $p < 0.001$). Figure 3 shows representative images of residual magnetization in a 4-chamber view of the heart, comparing the performance of the three saturation pulses. In all human subjects, mean M_R was significantly different between the three pulses ($M_{R,Single}$ =10.8 ± 7.8; $M_{R,composite}$=5.1 ± 5.2, $M_{R.BIR-4}$=1.1 ± 0.9; $p < 0.001$). In both phantom and cardiac experiments using single and composite pulses, no nominal flip angle value was able to completely saturate the magnetization across the whole phantom or left ventricle, due to B_0 and B_1 inhomogeneities.

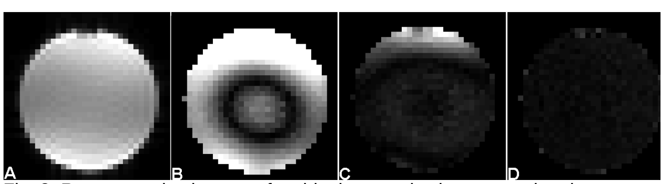

Fig. 2. Representative images of residual magnetization across the phantom, comparing the performance of the three saturation pulses in the transverse plane: a) PDW, b) single, c) composite, and d) BIR-4 pulses [(b-d) displayed with identical intensity scales].

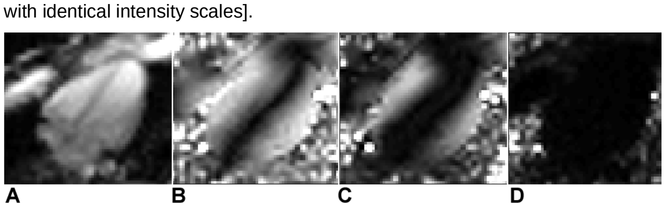

Fig. 3. Representative images of residual magnetization in a 4-chamber view of the heart, comparing the performance of the three saturation pulses. a) PDW, b) single pulse, c) composite pulse, and d) BIR-4 pulse [(b-d) displayed with identical intensity scales].

Discussion: This study demonstrates that a single-shot EPI sequence can be used for imaging the M_R immediately after incomplete saturation due to B_0 and B_1 inhomogeneities in the heart at 1.5T. The RF flip angle inhomogeneity can result in regional variation of the effectiveness of saturation that can potentially compromise T_1 measurements. Using a BIR-4 pulse to perform saturation of magnetization seems very promising for improving the reliability of T_1 estimation for first-pass perfusion MRI.

References

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