Real-time Prospective Adjustment of Inversion Time using Arrhythmia Insensitive Inversion Recovery (AIIR) Algorithm for Delayed Hyper-enhancement MRI

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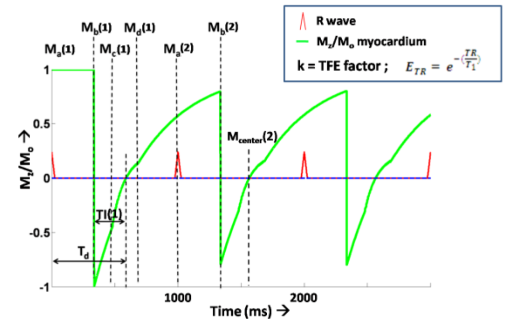
Introduction: Studies have shown that Delayed Hyper-enhancement (DHE) MRI technique can accurately and reproducibly measure the extent of irreversible injury following myocardial infarction[1,2]. DHE sequence is a cardiac gated, inversion-recovery (IR) prepared, multi-shot - gradient recalled echo (GRE) method in which the inversion time (TI) is set to null the signal from the normal myocardium. The combination of differential contrast agent kinetics between normal and infarcted myocardium, as well as the increased distribution volume for extra-vascular contrast in regions of scar, is exploited to make signal intensity of scar brighter than normal myocardium[3]. IR preparation, while providing maximal contrast between normal and scarred myocardium, is sensitive to arrhythmias. This is because, TI prescribed to null signal from normal myocardium is appropriate only when the RR interval is regular. In real-world patients, the RR-intervals are variable leading to fluctuations in the steady-state longitudinal magnetization (M_z) and this variation can create substantial artifacts in the acquired image. The cumulative nature of the drift in M_z with variation in R-R results in significant artifacts, when the acquisition duration is longer, like in cases of 1) 3D or 2) higher spatial resolution acquisitions that are typically acquired using a navigator guided sequence.

Purpose: The purposes of this work are twofold: 1) To develop an arrhythmia insensitive inversion (AIIR) algorithm that can track the magnetization of tissue of interest and can prospectively correct TI for every RR interval of acquisition; 2) To validate the algorithm in simulations, phantoms and in human subjects.

Theory: Equations describing M_z at different temporal points of the acquisition protocol are shown in Figure 1. Same cardiac phase of acquisition in every R-R was used as the constraint for the acquisition. The myocardial M_z is tracked over the R-R intervals and TI is calculated in real-time (just after the arrival of a new R wave) such that application of IR pulse at that time point will ensure that M_z crosses zero at the center of the acquisition window (when center of k-space is filled assuming a linear profile order).



$$M_{center}^{-}(n) = \sum_{l=0}^{k-2} (\cos\alpha)^l E_{TR}^{\ l}(1 - E_{TR})M_o + M_c(n)(\cos\alpha)^{n-1} E_{TR}^{\ n-1}$$

$$M_c(n) = -\frac{\sum_{l=0}^{k-2}(\cos\alpha)^l E_{TR}^{\ l}(1 - E_{TR})M_o}{(\cos\alpha)^{k-1}E_{TR}^{\ k-1}}$$

Conditions:
1) $M_{center} = 0$; 2) Td cannot change

$$TI(n) = T_1 \ \log\frac{M_o + M_{b(n)}}{M_o - M_{c(n)}}$$

Figure 1: The Arrhythmia Insensitive Inversion Algorithm (AIIR) keeps track of the longitudinal magnetization of the tissue of interest (myocardium). Equations were developed to calculate the magnetization at the center of IR-TFE acquisition. By nulling this value, TI value can be prospectively calculated just after a R wave has occurred, that can minimize the artifacts due to variation of heart sinus rhythm. A linear k-space filling profile is assumed here. It can be easily extended to a low-high profile.

Methods: Prior to imaging, simulations were performed using MATLAB™ to confirm the presence of artifacts due to arrhythmia. Various types of arrhythmias (bigeminy, ectopic beats etc.) were simulated, and the effect of AIIR algorithm on these artifacts (for a range of T_1 values) was studied.

Acquisition: The AIIR algorithm was implemented as a software patch on a commercial MR scanner (1.5T, Philips Achieva).

Phantom validation: The real-time AIIR preparation algorithm was tested in gel phantoms with different T_1 (T_1 = 300, 600, 1200 ms) for various types of simulated arrhythmia.

Clinical validation: 16 patients (7 Males, age: 53+/- 20 years) were imaged. All subjects provided written informed consent. After acquisition of initial scout images and around 15 minutes after 0.2 mmol/kg of Gd-DTPA administration, a Look-Locker sequence[4] was performed to determine the myocardial inversion time and estimate the myocardial T_1 value to use for AIIR algorithm. 3D IR-GRE viability images were immediately obtained with and without AIIR algorithm in LV short axis view. Imaging parameters were: TR/TE/flip = 4.8/2.3 ms/15°; FOV ~ 360*360*120 mm; TFE factor = 30; voxel size = 2.0 *2.0 * 8 mm^3; 8-12 slices covering the entire LV. Navigator guidance for respiratory compensation was used (Acquisition time: 90-150 RR intervals including navigator efficiency). After patient images were obtained, an experienced cardiologist (>7 years experience in cardiac MRI) performed a blinded scoring of both sets of images (Score Range: 1-5, 5-excellent, 1-non-diagnostic). A) Overall Image Quality, B) Quality of Scar (if present) and C) Nulling of Myocardium were rated.

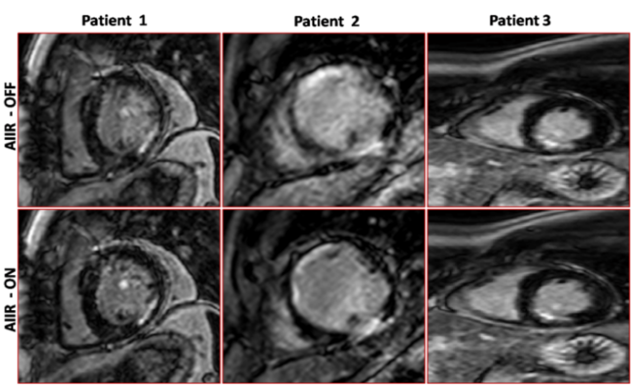


Figure 2: Viability images obtained with AIIR algorithm ON and OFF from three different patients are shown. The sequences were acquired for about 80 seconds long each, using a navigator guided IR-TFE sequence. The scar appears sharper with AIIR ON, while without AIIR an overestimation of scar region occurs.

Results: (a) Simulations showed significant artifact present due to arrhythmia that can be reduced using AIIR algorithm. (b)Phantom results confirmed the theoretical predictions. (c) In all the patients, blinded Image Quality assessment of an experienced CVMR imager found that the overall image quality was improved (4.3±0.7 vs. 3.3±0.8) and nulling of myocardium (4.2±0.7 vs. 3.3±0.8) was consistently better (or equal) with AIIR than without. In 7/16 patients that had scar present, the scar quality with AIIR was consistently better (4.6±0.5 vs. 3.3±0.8). All comparisons were statistically significant ($p<0.02$, paired Student's t-test).

Conclusion: The AIIR algorithm significantly reduces artifacts in viability imaging encountering a higher number of heart beats and/or arrhythmias during acquisition. Clinically, it is useful while imaging patients with a) limited breath-holding capacity, b) severe arrhythmia, and c) with small sub-endocardial scar (or RV wall ablation) that need a higher spatial resolution imaging. This method of magnetization tracking can also be extended to other triggered /gated sequences where TR depends on the heart rate.

Reference: 1. Kim RJ,et al. Circulation 2008;117(5):629-637. 2. Kim HW et al. J Am Coll Cardiol 2009;55(1):1-16. 3. Simonetti OP et al. *Radiology* 2001; 218:215-223; 4. D.C. Look, Locker DR. *The Review of Sci. Instr.* 1970;41:2