Delayed Enhancement Imaging with Increasing Flip Angles: Reducing Signal Changes during the Acquisition Window

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Introduction: Delayed hyperenhancement (DE) imaging (1) is a valuable technique in cardiovascular MR (CMR) and has recently been applied to very small regions of hyperenhancement, e.g. vessel wall inflammation (2,3,4), thrombus (5), and pulmonary vein ablation scar (6) imaging. For high resolution DE-CMR applications, an important variable that has not been fully addressed is the evolution of image contrast (increasing signals and decreasing contrast for data collected later) that occurs during the 100-200ms acquisition windows, and may result in artifactual enhancement or blurring. Here these effects are analyzed and an increasing flip angle method (optimized flat flip angle method) for achieving fewer artifacts for DE-CMR is presented.

Methods: The Bloch equations were used to calculate a series of flip angles (optimized flat flip angle method) which provides the largest constant signal for a known target T1 (estimated using Refs. 7-9), and a given TI time, TR, heart rate, and views per segment. The flatness constraint is $Mz_i \cdot \sin(\theta_i) = Mz_{i+1} \cdot \sin(\theta_{i+1})$, where θ_i and θ_{i+1} are successive flip angles. The calculation includes effects of inversion, delay, RF pulses, and T1 regrowth between RF pulses and between heart-beats. This calculation is iterative, and has been described by others (10). A "ramp up" series used on our scanner and a constant flip method (15º) were also investigated. All simulations were performed in Matlab. The signal evolution was calculated using each flip angle series, for T1 values of 290 (target T1), 360 and 400ms. Heart-rate of 65bpm, TI=230ms and imaging parameters given below were used. The signals were used to weight synthetic k-space. All imaging was performed on a Philips 1.5T MR scanner (Gyroscan ACS-NT, Philips Medical Systems, Best, NL). The pulse sequence was modified to automatically calculate the optimized flat flip angle series for the user-provided target T1, and scan/input parameters: TR, heart-rate, views per segment. Alternatively, the ramp-up flip series was used. DE-CMR was performed in phantoms and patients (0.2mmol/kg imaged 20 minutes post injection). Typical parameters were for low resolution: 2D spoiled gradient echo, inversion recovery, ECG-gated to late diastole, breath-held, 32 x 32 cm FOV, 10 mm slice, TR/TE/θ = 4ms/1.1ms/15º, 160 x 160 Ny, optimal TI, 24 views per segment, centric view-order. For high resolution, the protocol was the same except: 3D, TR/TE/θ = 4.3ms/2.1ms/15º, 224 x 224 Ny, 5 mm slice, 24 Nz, free-breathing, navigator gated.

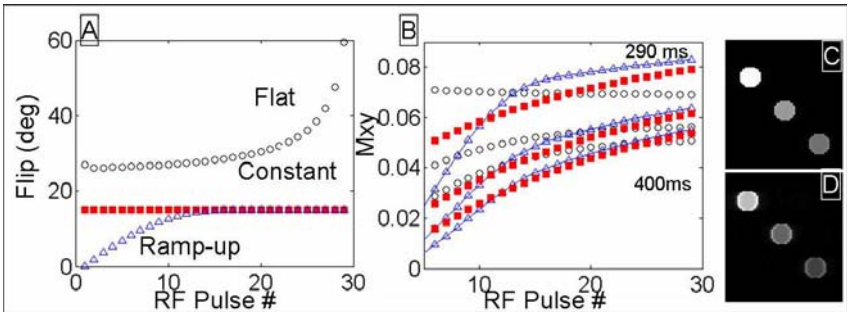

Figure 1: Simulation results, (A) showing the flip angles used for constant, ramp-up and optimized flat flip angle methods, (B) resulting signal changes within the data acquisition window for each method for T1s of 290, 260 and 400 ms, where symbols are identified in (A). Synthetic images were created assuming a centric acquisition, by weighting input objects by the signals of (B). Synethetic images show less edge-enhancement using optimized flat (C) vs. constant flips (D).

Figure 2: 2D DE images of bottles/ phantom (T1=400, 360, 290 ms) using (A) ramp up flip angles and (B) optimized flat flip angles. Note reduced edge-enhancement in (B) (arrow).

Results: Figure 1A compares constant flip angles (15º), the ramp up flip angle series, and the optimized flat flip angle series. Figure 1B shows the resulting signal evolution during the acquisition window for the 3 T1 values using each flip angle series. For a constant flip angle, for the 400, 360, and 290 ms T1s, the signal increases by 250%, 140% and 60% respectively between the 6th and 29th RF pulse; for optimized flat flip angles, the signal changes are 72%, 36%, and -2% respectively. Figure 1C and 1D show the resulting synthetic images for optimzed flat and constant flip angle methods. The ramp-up flip series provides very large signal changes. Figure 2 compares a phantom imaged on the scanner with the 2D DE technique and ramp up flip angle series (A), vs. the optimized flat flip angle series (B). Edge enhancement is evident in A, but is unobservable in B. Figure 3 shows a high-resolution 3D DE-CMR study of a patient, where artifactual edge enhancement using the ramp-up flip series is reduced (long arrow), but true valvular enhancement remains (short arrow).

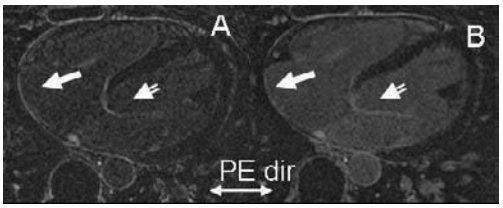

Figure 3: Post-contrast 3D DE-CMR with (A) ramp up and (B) optimized flat flip angles. Note the real enhancement of the valves (short arrows), and artifactual (long arrows) enhancement of the right atrium.

Discussion and Conclusions: Under typical imaging situations, the constant flip angle and ramp-up methods provide signal increases during the acquisition window, especially for "nulled" tissues. The optimized flat series provides less signal evolution, especially for the target T1. This investigation highlights an important challenge to high resolution DE-CMR.

References: 1) RJ Kim, NEJM 2000:343:1445-53. 2) BA Wasserman, *Radiology*. 2002;223:566-73. 3) WP Ingkanisorn, JCMR 2004 (5) 376. 4) SB Yeon, JCMR 2005 (1), 413. 6) RM Botnar, *Circulation*. 2004;109:2023-9. 6) DC Peters, SCMR 2006. 7) JW Goldfarb, MRM 2005;53:367-71. 8) C Klein, JMRI, 2004;20:588-93. 9) F Weinmann. *Physiol Chem Phys Med NMR*. 1984;16:167–172. 10) LO Johansson, JMRI 1999 (9) 552-6.