Published in final edited form as:

J Magn Reson Imaging. 2013 February ; 37(2): 484–490. doi:10.1002/jmri.23779.

Improved Fat Water Separation with Water Selective Inversion Pulse for Inversion Recovery Imaging in Cardiac MRI

Lukas Havla, MS^{1,3}, Tamer Basha, PhD¹, Hussein Rayatzadeh, MD¹, Jaime L. Shaw, BS¹, Warren J. Manning, MD^{1,2}, Scott B. Reeder, MD, PhD⁴, Sebastian Kozerke, PhD³, and Reza Nezafat, PhD¹

¹Department of Medicine, Harvard Medical School and Beth Israel Deaconess Medical Center, Boston, MA, USA ²Department of Radiology, Harvard Medical School and Beth Israel Deaconess Medical Center, Boston, MA, USA ³Institute for Biomedical Engineering, University and ETH Zurich, Switzerland ⁴Department of Radiology, University of Wisconsin, Madison, WI, USA

Abstract

Purpose—To develop an improved chemical shift-based water-fat separation sequence using a water-selective inversion pulse for inversion-recovery 3D contrast-enhanced cardiac MR.

Materials and Methods—In inversion-recovery sequences, the fat signal is substantially reduced due to the application of a non-selective inversion pulse. Therefore, for simultaneous visualization of water, fat, and myocardial enhancement in inversion-recovery based sequences such as late Gadolinium enhancement imaging, two separate scans are used. To overcome this, the non-selective inversion pulse is replaced with a water-selective inversion pulse. Imaging was performed in phantoms, 9 healthy subjects and 9 patients with suspected arrhythmogenic right ventricular cardiomyopathy plus 1 patient for tumor/mass imaging. In patients, images with conventional turbo-spin echo (TSE) with and without fat saturation were acquired prior to contrast injection for fat assessment. Subjective image scores (1=poor, 4=excellent) were used for image assessment.

Results—Phantom experiments showed a fat SNR increase between 1.7 to 5.9 times for inversion times of 150 and 300ms, respectively. The water-selective inversion pulse retains the fat signal in contrast-enhanced cardiac MR, allowing improved visualization of fat in the water-fat separated images of healthy subjects with a score of 3.7 ± 0.6 . Patient images acquired with the proposed sequence were scored higher when compared with TSE sequence (3.5 ± 0.7 vs. 2.2 ± 0.5 , $p < 0.05$).

Conclusion—The water-selective inversion pulse retains the fat signal in inversion-recovery based contrast-enhanced cardiac MR, allowing simultaneous visualization of water and fat.

Keywords

water-fat separation; cardiac MRI; coronary MRI; late gadolinium enhancement

INTRODUCTION

Obesity and visceral fat are associated with a variety of cardiovascular diseases including coronary artery disease, cerebral vascular disease, and stroke (1-5). Pericardial fat volume is

associated with coronary atherosclerotic plaque burden in asymptomatic individuals (6). The thickness of epicardial adipose tissue is an emerging biomarker strongly associated with the likelihood of having detectable carotid atherosclerosis (7). The presence of fatty infiltration is also a hallmark pathological feature of arrhythmogenic right ventricular cardiomyopathy (ARVC) (8-11). Fatty infiltration has been observed in transplanted hearts in regions of healed myocardial infarction, with higher fat volumes in patients with a history of coronary bypass grafting (12). The three-dimensional distribution of epicardial fat is also important in percutaneous epicardial mapping because of its correlation with the electroanatomical voltage attenuation maps (13). Pericardial fat volume is highly associated with paroxysmal and persistent atrial fibrillation (AF) (14). For these reasons, the non-invasive imaging assessment of the presence of fatty infiltration and the quantification of epicardial fat thickness has important prognostic value in cardiovascular disease. Multi-detector computed tomography (MDCT), echocardiography, and magnetic resonance imaging (MRI) all have the ability to image fat. Conventional approaches based on fat suppression in MRI are established techniques for the assessment of the presence or absence of fat (15). Fast spin echo (FSE) sequences, although providing good suppression of the ventricular blood pool and high signal from fat, are not optimal due to the resulting image blurring from the long echo train (16). Chemical shift-based water-fat separation methods (17-26), in which multiple echoes are acquired, can also be used to reconstruct simultaneous fat and water images, thereby improving the sensitivity of fat detection using a positive fat contrast.

Quantification of the fat volume surrounding the heart and coronary vasculature is more frequently performed using MDCT because of its higher spatial resolution and volumetric coverage. Chemical shift based water-fat separation methods or spin-echo imaging with or without fat sat are performed using multi-slice 2D acquisitions, which has limited spatial resolution, especially in through plane that limits the accuracy of fat quantification. 3D imaging approaches can be utilized with chemical shift based water-fat suppression to better assess the fat surrounding the heart and coronaries (27,28). The inflow saturation in large slab 3D whole heart acquisitions necessitates a high-resolution steady-state free-precession (SSFP) sequence with use of T_2 magnetization preparation (29-31). However, multi-echo SSFP sequence with long TR is associated with banding artifacts and not suitable for fat-water separation reconstruction techniques. Therefore spoiled gradient echo (GRE) imaging sequence with use of exogenous contrast agents for 3D volumetric coverage is needed. In 3D contrast-enhanced whole heart GRE, an inversion pulse (32,33) is used to improve the contrast. While an inversion pulse improves the contrast, it will decrease the fat signal because of short available recovery time. Therefore, for 3D whole heart coverage of fat, methods to improve the fat signal to noise ratio (SNR) are needed.

The presence of fatty infiltration in chronic myocardial infarction using multi-echo chemical shift-based water-fat separation methods have also been demonstrated recently (34-38). In these studies, two scans are typically performed: one in which a fat sensitive imaging sequence (i.e. multi-echo chemical shift-based water-fat separation methods) is used to image the fat prior to contrast administration and a second scan in which a late gadolinium enhancement (LGE) imaging sequence (39) at the same orientation is acquired 15-20 min after contrast infusion. This usually requires two separate scans, which may be prone to slice misregistration in addition to increasing the scan time. Kellman et al. (38) evaluated a combined approach in which an LGE sequence is combined with a multi-echo chemical shift-based water-fat separation acquisition. In this study, the SNR of pre-contrast, multi-echo, fat-separated images was approximately 2.6 times that of post-contrast LGE (38). Similar to whole heart GRE with inversion pulse, this signal loss is mainly associated with application of an inversion pulse (IR) (40) and incomplete fat signal recovery in the LGE sequence.

In this study, we propose and evaluate an improved three-dimensional (3D) inversion recovery based water-fat separation sequence in which the fat signal is retained during the imaging by the application of a spectrally selective water inversion pulse. We hypothesize that this approach allows simultaneous visualization of fat and water in post-contrast data acquisition with minimal SNR penalty for fat.

MATERIALS AND METHODS

All images were obtained using a 1.5-T Achieva magnet (Philips Healthcare, Best, the Netherlands) with a 5-channel phased-array coil. The acquired MR data were transferred to a stand-alone computer and the image reconstruction was performed off-line using Matlab (MathWorks, Natick, MA). All *in vivo* studies were approved by our institutional review board and all subjects provided written consent prior to study participation.

Imaging Sequence

Figure 1 shows the schematic of the 3D imaging sequence used in this study. A 3D free breathing and ECG-triggered multi-echo gradient-echo (GRE) imaging sequence was implemented. To selectively invert the water signal, a water selective inversion RF pulse, tuned to the resonance frequency of water, was applied prior to data acquisition. To allow imaging with higher spatial resolution and full coverage of the heart, a respiratory navigator with a 5 mm acceptance window was used for respiratory motion compensation (41,42). All imaging was performed in the diastolic rest period.

Image Reconstruction

Water-fat separation was performed offline using the iterative decomposition with echo symmetry and least-squares (IDEAL) technique (20). In this technique, alternative iterations between fat, water signal estimate, and field map are used to solve non-linear signal equations and simultaneously reconstruct fat and water images and a field map. A region growing process, which correlates the estimation among neighboring pixels, was used to avoid convergence to incorrect field map solutions (23). The field map is estimated from a low-resolution dataset prior to the IDEAL reconstruction assuming the single peak spectral model of fat without T_2^* correction.

Phantom Experiment

To investigate the impact of a water-selective inversion pulse for different ranges of T_1 s and fat, a phantom experiment was performed. The phantom contains multiple vials containing gadolinium doped water with different T_1 s and a vegetable oil vial. Analogous to *in vivo* studies, a simulated-ECG triggered, 3D GRE sequence with three echoes was used. For each choice of inversion time, two sets of images were acquired: one with non-selective IR and one with water-selective IR. The imaging parameters were as follows: 3D multi-echo GRE $TR/TE_1/TE_2/TE_3/\alpha = 8.0/1.5/4.0/6.5/15^\circ$, $FOV = 300 \times 300 \times 100 \text{ mm}^3$, true spatial resolution $1.5 \times 1.2 \times 2.0 \text{ mm}^3$ interpolated to $0.6 \times 0.5 \times 2 \text{ mm}^3$ through zero-filling, and TIs from 150 ms to 300 ms with 50 ms interval. Raw k-space data were transferred to a stand-alone computer, where fat-water separation was performed. The image reconstruction was identical for both phantom and *in vivo* measurements. Regions-of-interest (ROIs) were drawn in the three mid-slices for each vial in water-selective IR. These ROIs were copied to the same locations in the images acquired with non-selective IR. The noise was measured in an ROI outside the phantom. The SNR for each region was then calculated as the ratio of the mean signal intensity to the standard deviation of the noise.

In Vivo Imaging

Healthy Subjects—Nine healthy subjects (6 female, 3 male, mean age 26.1 ± 7.7 years) were recruited for contrast-enhanced whole heart multi-echo GRE with water selective IR. 0.2 mmol/kg of gadobenate dimeglumine (Gd-BOPTA; MultiHance; Bracco Imaging SpA, Milan, Italy) was injected intravenously using 2 ml/s bolus infusion, followed by 20 ml of saline at the same injection rate. A Look-Locker sequence was used to visually determine the optimal inversion time (TI). A 3D free-breathing ECG-triggered, navigator-gated multi-echo GRE sequence was performed. A water selective inversion pulse with the optimal TI was used to suppress myocardial signal. The imaging parameters were TR/TE₁/TE₂/TE₃ = 8.0/1.53/4.03/6.53ms, flip angle = 15°, field of view = 270×270×100 mm³, number of phase-encode lines per heartbeat = 15, and spatial resolution = 1.5×1.2×2 mm³. Total scan time for the *in vivo* studies was 9 minutes, assuming a navigator efficiency of 50%. Because of changes in the contrast level in the blood and myocardium that directly impact SNR, only one scan using water-selective IR was performed. In a subset of four subjects, imaging was repeated using a non-selective IR pulse in a different imaging visit at least one month after the first scan. Raw k-space data were transferred to a stand-alone PC where water-fat separation using IDEAL was performed.

Patient Study—In a prospective study performed to demonstrate the utility of the proposed imaging sequence, we recruited ten patients. Nine patients (3 female, 6 male, mean age 57 ± 11 years) were referred for evaluation of ARVC and one patient (female, 56 years) was referred for evaluation of mass/tumor in the left atrium. Prior to contrast injection, each subject was imaged using a standard clinical free-breathing turbo-spin echo (TSE) imaging sequence with and without fat saturation with TE: 10 ms, TR: 1 heartbeat, TSE factor: 17-23 based on the heart rate, echo spacing: 6ms, asymmetric k-space profile order, bandwidth (BW): 741 Hz/pixel, FOV: 300×300×116 mm³ and spatial resolution: of 1.5×1.5×8 mm³. All patients received 0.2 mmol/kg gadobenate dimeglumine (Gd-BOPTA; MultiHance; Bracco Imaging SpA, Milan, Italy) or Gd-DTPA (Magnevist, Berlex Laboratories, Wayne, New Jersey) intravenously using 2 ml/s bolus infusion followed by 20 ml of saline chaser at the same injection rate. A Look-Locker sequence was used to visually determine the optimal TI prior to data acquisition that nulls LV myocardium signal. Subsequently, each subject was imaged using the proposed water-selective IR multi-echo GRE sequence. All imaging was performed 15-25 minutes post-contrast injection. A free-breathing ECG-triggered navigator-gated multi-echo GRE sequence with a water-selective IR was used for acquisition. The imaging parameters were identical to the ones used for experiments performed in healthy subjects. Since 3D acquisition was used for chemical-shift water/fat separation sequence, a higher through-plane resolution of 2 mm was used compared to 2D TSE sequence which has 8 mm through-plane resolution.

Image Analysis

For all subjects, qualitative assessment of the images reconstructed using IDEAL was performed by two experienced readers in terms of visualization of the fat using a four-point scale system: 1, indicating poor; 2, fair; 3, acceptable; and 4, excellent water and fat visualization. Due to the limited number of subjects with repeat visits, no statistical comparison was performed. For all patients, separate subjective scores were given to TSE images acquired with and without fat saturation and a Wilcoxon Signed-Rank test was performed for comparison between images acquired with TSE and inversion-recovery based sequence. All measurements are presented as mean $\pm$ one standard deviation and a *p*-value of 0.05 was considered statistically significant.

RESULTS

Phantom

Figure 2 shows a representative slice from the phantom experiment, comparing images acquired using non-selective (top row) and water selective inversion (bottom row) with different inversion times of 150 ms, 200 ms and 300 ms. The fat signal is significantly decreased in images acquired with non-selective inversion; however, the use of a water-selective inversion retains fat signal allowing robust water-fat separation. Figure 3 shows quantitative SNR improvements for fat. As expected, the SNR gain depends on the choice of the inversion time. For shorter inversion times, fat recovery is incomplete; therefore, SNR gain is higher. We have chosen different ranges for inversion time with two main applications in mind, contrast-enhanced coronary MRI and LGE. While for the former, a short inversion time (i.e. 150-200 ms) is used, for the latter a longer inversion time (i.e. 250-300 ms) is needed. Results also show minimal impact on SNR of the other two vials. The latter reflects other tissues in order to compare their SNR loss opposed to fat and water.

In Vivo Imaging

Healthy Subjects—Fat water separation was successfully performed in all subjects with a score of 3.7 ± 0.6 . Figure 4 shows an example slice in a subject that was imaged in two visits, one using water-selective and one with non-selective IR sequence. Both images were acquired using IDEAL sequence with 3-echoes using the same imaging protocol and timing after contrast injection. The images show superior fat visualization in images acquired with the water-selective inversion. There are some residual respiratory motion artifacts from the chest wall due to insufficient respiratory motion gating of respiratory navigator for 3D free-breathing scan.

Patient Study—Imaging and reconstruction was successfully performed in all patients with a subjective score of 3.5 ± 0.7 . Figure 5 shows images from the water-fat acquisition and reconstruction from a patient with suspected ARVC. Fatty infiltration in the RV free wall is well visualized, which may significantly increase the confidence level of its presence. Due to the improved spatial resolution and 3D coverage of the heart, the presence of fat was confirmed in all neighboring slices. The images acquired with the proposed sequence were scored higher than the ones acquired using TSE with and without fat saturation (3.5 ± 0.7 vs. 2.2 ± 0.5 , $p < 0.05$). Images from the patient with a suspected mass/tumor demonstrate the presence of fatty mass in the left atrium.

DISCUSSION

In this study, an improved inversion recovery sequence for water-fat separation was proposed and evaluated. By selectively inverting the water protons, the fat does not experience any inversion; therefore, no SNR penalty is imposed on the fat signal. The IDEAL technique is then applied to separate the water and fat components in the images.

The proposed spectrally selective inversion pulse is not expected to affect the calculations of the standard IDEAL algorithm because it only affects the magnitude of the signal while the IDEAL algorithm is based on the phase difference between the water and fat signals resulting from the off-resonance frequency shift between the two species. Other water-fat separation techniques could also be used with similar gain (21,25,26,43) but were not studied here and warrant additional investigation.

A direct application of the proposed sequence is to image the fatty infiltration in chronic myocardial infarction. In contrast to the conventional approach that requires two separate

scans, the proposed sequence provides the water-fat separation using only one scan. In addition to decreasing the scan time to almost half, the proposed sequence eliminates the spatial misregistration problem between the two scans and variation in fat signal suppression in LGE images.

Another application for the proposed sequence is for conventional LGE sequences at high magnetic fields, where fat suppression is challenging. Even with different fat suppression techniques that are deployed during LGE imaging, the recovering signal emanating from fat due to its short T1 relaxation time during the acquisition can hardly be avoided. The proposed sequence is well suited for such a problem because the fat signal remains almost constant during the acquisition and then is separated retrospectively from the water signal. During the study, we noticed that the fat signal was always easy to localize even before the water-fat reconstruction, which is attributed to the high SNR of the fat signal and the intentional suppression of the myocardium signal in LGE images.

Contrast-enhanced coronary MRI is emerging as the state-of-the art approach for non-invasive imaging of the coronary arteries (32,44,45), especially at high magnetic fields where SSFP imaging sequences suffers from banding artifacts. An inversion recovery-based acquisition is always used in this application. Although the combination of an inversion pulse with spectrallyselective fat suppression will reduce the fat signal, the suppression is not usually uniform and is prone to field inhomogeneities. Therefore, the proposed approach has potential benefits for contrast-enhanced coronary MRI at high-field imaging.

Over the duration of data acquisition for 3D data, the contrast level in the blood pool will change. This will impact the optimal inversion time and could potentially result in imaging artifacts. We have chosen MultiHance (Gd-BOPTA; Bracco Imaging SpA, Milan, Italy) for our experiment which has favorable T1 kinetics over other imaging contrast agents (45).

Our study has several limitations. We did not perform a quantitative SNR/CNR analysis in subjects with and without a water-selective inversion. This is due to the need for re-scanning the subjects in separate visits, which is inconvenient for the subjects and not feasible for this study. We did not optimize the water-selective RF pulse; better pulse design to address inhomogeneity should be focused on especially for high field imaging. We have only shown example images of the improvement achieved with the use of water-selective inversion. Further evaluation is needed in a larger patient population with suspected ARVC to evaluate the impact of this approach for improving the sensitivity and specificity.

In conclusion, the water-selective inversion pulse improves visualization of the fat signal in inversion-recovery based water-fat separation.

Acknowledgments

The authors acknowledge grant support from NIH R01EB008743-01A2. Lukas Havla was supported by a fellowship from Bayer Science & Education Foundation.

References

1. Hubert HB, Feinleib M, McNamara PM, Castelli WP. Obesity as an independent risk factor for cardiovascular disease: a 26-year follow-up of participants in the Framingham Heart Study. *Circulation*. 1983; 67:968–977. [PubMed: 6219830]
2. Ding J, Kritchevsky SB, Harris TB, et al. The association of pericardial fat with calcified coronary plaque. *Obesity (Silver Spring)*. 2008; 16:1914–1919. [PubMed: 18535554]

3. de Vos AM, Prokop M, Roos CJ, et al. Peri-coronary epicardial adipose tissue is related to cardiovascular risk factors and coronary artery calcification in post-menopausal women. *Eur Heart J*. 2008; 29:777–783. [PubMed: 18156138]
4. Walker SP, Rimm EB, Ascherio A, Kawachi I, Stampfer MJ, Willett WC. Body size and fat distribution as predictors of stroke among US men. *American Journal of Epidemiology*. 1996; 144:1143–1150. [PubMed: 8956626]
5. Greif M, Becker A, von Ziegler F, et al. Pericardial adipose tissue determined by dual source CT is a risk factor for coronary atherosclerosis. *Arterioscler Thromb Vasc Biol*. 2009; 29:781–786. [PubMed: 19229071]
6. Miao C, Chen S, Ding J, et al. The association of pericardial fat with coronary artery plaque index at MR imaging: The Multi-Ethnic Study of Atherosclerosis (MESA). *Radiology*. 2011; 261:109–115. [PubMed: 21846753]
7. Nelson MR, Mookadam F, Thota V, et al. Epicardial fat: an additional measurement for subclinical atherosclerosis and cardiovascular risk stratification? *Journal of the American Society of Echocardiography*. 2011; 24:339–345. [PubMed: 21185148]
8. Vermes E, Strohm O, Otmani A, Childs H, Duff H, Friedrich MG. Impact of the revision of arrhythmogenic right ventricular cardiomyopathy/dysplasia task force criteria on its prevalence by CMR criteria. *JACC Cardiovasc Imaging*. 2011; 4:282–287. [PubMed: 21414577]
9. Tandri H, Macedo R, Calkins H, et al. Role of magnetic resonance imaging in arrhythmogenic right ventricular dysplasia: insights from the North American arrhythmogenic right ventricular dysplasia (ARVD/C) study. *Am Heart J*. 2008; 155:147–153. [PubMed: 18082506]
10. Castillo E, Tandri H, Rodriguez ER, et al. Arrhythmogenic Right Ventricular Dysplasia: Ex Vivo and in Vivo Fat Detection with Black-Blood MR Imaging1. *Radiology*. 2004; 232:38. [PubMed: 15220492]
11. Tandri H, Castillo E, Ferrari VA, et al. Magnetic resonance imaging of arrhythmogenic right ventricular dysplasia: sensitivity, specificity, and observer variability of fat detection versus functional analysis of the right ventricle. *J Am Coll Cardiol*. 2006; 48:2277–2284. [PubMed: 17161260]
12. Su L, Siegel JE, Fishbein MC. Adipose tissue in myocardial infarction. *Cardiovasc Pathol*. 2004; 13:98–102. [PubMed: 15033159]
13. Desjardins B, Morady F, Bogun F. Effect of epicardial fat on electroanatomical mapping and epicardial catheter ablation. *Journal of the American College of Cardiology*. 2010; 56:1320–1327. [PubMed: 20888522]
14. Al Chekatie MO, Welles CC, Metoyer R, et al. Pericardial fat is independently associated with human atrial fibrillation. *Journal of the American College of Cardiology*. 2010; 56:784–788. [PubMed: 20797492]
15. Delfaut EM, Beltran J, Johnson G, Rousseau J, Marchandise X, Cotten A. Fat suppression in MR imaging: techniques and pitfalls. *Radiographics*. 1999; 19:373–382. [PubMed: 10194785]
16. Castillo E, Tandri H, Rodriguez ER, et al. Arrhythmogenic right ventricular dysplasia: ex vivo and in vivo fat detection with black-blood MR imaging. *Radiology*. 2004; 232:38–48. [PubMed: 15220492]
17. Dixon WT. Simple proton spectroscopic imaging. *Radiology*. 1984; 153:189–194. [PubMed: 6089263]
18. Glover GH, Schneider E. Three-point Dixon technique for true water/fat decomposition with B0 inhomogeneity correction. *Magnetic Resonance in Medicine*. 1991; 18:371–383. [PubMed: 2046518]
19. Szumowski J, Coshov WR, Li F, Quinn SF. Phase unwrapping in the three-point Dixon method for fat suppression MR imaging. *Radiology*. 1994; 192:555–561. [PubMed: 8029431]
20. Reeder SB, Wen Z, Yu H, et al. Multicoil Dixon chemical species separation with an iterative least-squares estimation method. *Magnetic Resonance in Medicine*. 2004; 51:35–45. [PubMed: 14705043]
21. Hernando D, Haldar JP, Sutton BP, Ma J, Kellman P, Liang ZP. Joint estimation of water/fat images and field inhomogeneity map. *Magnetic Resonance in Medicine*. 2008; 59:571–580. [PubMed: 18306409]

22. Reeder SB, Pineda AR, Wen Z, et al. Iterative decomposition of water and fat with echo asymmetry and least-squares estimation (IDEAL): application with fast spin-echo imaging. *Magnetic Resonance in Medicine*. 2005; 54:636–644. [PubMed: 16092103]
23. Yu H, Reeder SB, Shimakawa A, Brittain JH, Pelc NJ. Field map estimation with a region growing scheme for iterative 3-point water-fat decomposition. *Magnetic Resonance in Medicine*. 2005; 54:1032–1039. [PubMed: 16142718]
24. Ma J. Breath-hold water and fat imaging using a dual-echo two-point Dixon technique with an efficient and robust phase-correction algorithm. *Magn Reson Med*. 2004; 52:415–419. [PubMed: 15282827]
25. Eggers H, Brendel B, Duijndam A, Herigault G. Dual-echo Dixon imaging with flexible choice of echo times. *Magn Reson Med*. 2011; 65:96–107. [PubMed: 20860006]
26. Ma J. Dixon techniques for water and fat imaging. *J Magn Reson Imaging*. 2008; 28:543–558. [PubMed: 18777528]
27. Shah S, Bi X, Hernando D, et al. Coronary MRA at 3 T using 3d multi-interleaved multiecho acquisition with varpro fat-water separation. *J Cardiovasc Magn Reson*. 2010; 12(Suppl 1):P42.
28. Koken, P.; Eggers, H.; Beck, G.; Bornert, P. Water/Fat resolved Whole-Heart Imaging for Coronary MRA. Proceedings of the 19th Annual Meeting of ISMRM; Montréal, Québec, Canada. 2011. (abstract 117)
29. Brittain JH, Hu BS, Wright GA, Meyer CH, Macovski A, Nishimura DG. Coronary angiography with magnetization-prepared T2 contrast. *Magnetic Resonance in Medicine*. 1995; 33:689–696. [PubMed: 7596274]
30. Botnar RM, Stuber M, Danias PG, Kissinger KV, Manning WJ. Improved coronary artery definition with T2-weighted, free-breathing, three-dimensional coronary MRA. *Circulation*. 1999; 99:3139–3148. [PubMed: 10377077]
31. Nezafat R, Stuber M, Ouwerkerk R, Gharib AM, Desai MY, Pettigrew RI. B1-insensitive T2 preparation for improved coronary magnetic resonance angiography at 3 T. *Magn Reson Med*. 2006; 55:858–864. [PubMed: 16538606]
32. Bi X, Carr JC, Li D. Whole-heart coronary magnetic resonance angiography at 3 Tesla in 5 minutes with slow infusion of Gd-BOPTA, a high-relaxivity clinical contrast agent. *Magn Reson Med*. 2007; 58:1–7. [PubMed: 17659628]
33. Hu P, Chan J, Ngo LH, et al. Contrast-enhanced whole-heart coronary MRI with bolus infusion of gadobenate dimeglumine at 1.5 T. *Magn Reson Imaging*. 2011; 66:392–398.
34. Goldfarb JW. Fat-water separated delayed hyperenhanced myocardial infarct imaging. *Magnetic Resonance in Medicine*. 2008; 60:503–509. [PubMed: 18727051]
35. Goldfarb JW. Fat deposition in the myocardium of the left ventricle. *J Cardiovasc Magn Reson*. 2007; 9:605–606. [PubMed: 17365242]
36. Goldfarb JW, Roth M, Han J. Myocardial fat deposition after left ventricular myocardial infarction: assessment by using MR water-fat separation imaging. *Radiology*. 2009; 253:65–73. [PubMed: 19703860]
37. Kellman P, Hernando D, Arai AE. Myocardial Fat Imaging. *Curr Cardiovasc Imaging Rep*. 2010; 3:83–91. [PubMed: 20401158]
38. Kellman P, Hernando D, Shah S, et al. Multiecho dixon fat and water separation method for detecting fibrofatty infiltration in the myocardium. *Magnetic Resonance in Medicine*. 2009; 61:215–221. [PubMed: 19097213]
39. Kim RJ, Fieno DS, Parrish TB, et al. Relationship of MRI delayed contrast enhancement to irreversible injury, infarct age, and contractile function. *Circulation*. 1999; 100:1992–2002. [PubMed: 10556226]
40. Simonetti OP, Kim RJ, Fieno DS, et al. An improved MR imaging technique for the visualization of myocardial infarction. *Radiology*. 2001; 218:215–223. [PubMed: 11152805]
41. Wang Y, Riederer SJ, Ehman RL. Respiratory motion of the heart: kinematics and the implications for the spatial resolution in coronary imaging. *Magnetic Resonance in Medicine*. 1995; 33:713–719. [PubMed: 7596276]
42. Danias PG, Stuber M, Botnar RM, Kissinger KV, Edelman RR, Manning WJ. Relationship between motion of coronary arteries and diaphragm during free breathing: lessons from real-time

- MR imaging. *AJR American Journal of Roentgenology*. 1999; 172:1061–1065. [PubMed: 10587147]
43. Hernando D, Kellman P, Haldar JP, Liang ZP. Robust water/fat separation in the presence of large field inhomogeneities using a graph cut algorithm. *Magnetic Resonance in Medicine*. 2010; 63:79–90. [PubMed: 19859956]
44. Yang Q, Li K, Liu X, et al. Contrast-enhanced whole-heart coronary magnetic resonance angiography at 3.0-T: a comparative study with X-ray angiography in a single center. *J Am Coll Cardiol*. 2009; 54:69–76. [PubMed: 19555843]
45. Hu P, Chan J, Ngo LH, et al. Contrast-enhanced whole-heart coronary MRI with bolus infusion of gadobenate dimeglumine at 1.5 T. *Magn Reson Med*. 2011; 65:392–398. [PubMed: 21264933]

Figure 1.

Schematic of the free-breathing, ECG-gated multi-echo chemical shift based water-fat separation acquisition. A water selective inversion pulse is applied to selectively invert the water signal. A respiratory navigator (NAV) restore pulse selectively restores magnetization of the right hemi-diaphragm. NAV gating is used for respiratory motion suppression. A three-echo acquisition with flyback readout is used for data acquisition.

Figure 2.

The raw images (i.e. prior to IDEAL reconstruction) acquired using non-selective (top row) or water-selective inversion (bottom row) with different inversion time of 150 ms, 200 ms and 300 ms. The fat signal is decreased in images acquired with non-selective inversion; however use of a water-selective inversion retains the fat. (V1, V2 are Gd-doped water tubes with different concentration)

Figure 3. SNR increase between non-selective and water-selective IR for sample vials of V1 and V2 (arrows in Figure 2) and fat (vegetable oil) for different inversion times.

Figure 4.

Fat and water images reconstructed, using IDEAL with three echoes, post-contrast injection in a subject using non-selective inversion (top row) and water selective inversion (bottom row). Images were acquired on two different imaging visits with identical imaging protocols and scan timing after contrast injection. Water-selective inversion leads to improved visualization of the fat signal around the heart (shown by arrows). The water image reconstructed using water-selective inversion sequence shows artifacts from breathing of the subject.

Figure 5.

A) first echo, (B) water and (C) fat images from a suspected ARVC patient acquired using a water-selective IR. The presence of fatty infiltration in the RV free wall can be easily visualized in the water and fat images (highlighted in the magnified images). The fat signal can also be visualized in the first-echo images prior to water-fat separation.