Published in final edited form as:
J Magn Reson Imaging. 2012 August ; 36(2): 379–386. doi:10.1002/jmri.23662.

Free-Breathing 3D Whole Heart Black Blood Imaging with Motion Sensitized Driven Equilibrium

Subashini Srinivasan, MSc[1,2], **Peng Hu, PhD**[3], **Kraig V. Kissinger, RT**[1], **Beth Goddu, RT**[1], **Lois Goepfert, RN, MS**[1], **Ehud J. Schmidt, PhD**[4], **Sebastian Kozerke, PhD**[2], and **Reza Nezafat, PhD**[1]

[1]Department of Medicine (Cardiovascular Division), Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, MA, USA [2]Institute of Biomedical Engineering, ETH, Zurich, Switzerland [3]Diagnostic Cardiovascular Imaging Section and Department of Radiology, University of California in Los Angeles, CA, USA [4]Department of Radiology, Brigham and Women's Hospital, Harvard Medical School, Boston, MA, USA

Abstract

Purpose—To assess the efficacy and robustness of motion sensitized driven equilibrium (MSDE) for blood suppression in volumetric 3D whole heart cardiac MR.

Materials and Methods—To investigate the efficacy of MSDE on blood suppression and myocardial SNR loss on different imaging sequences. 7 healthy adult subjects were imaged using 3D ECG-triggered MSDE-prep T_1-weighted turbo spin echo (TSE), and spoiled gradient echo (GRE), after optimization of MSDE parameters in a pilot study of 5 subjects. Imaging artifacts, myocardial and blood SNR were assessed. Subsequently, the feasibility of isotropic spatial resolution MSDE-prep black-blood was assessed in 6 subjects. Finally, 15 patients with known or suspected cardiovascular disease were recruited to be imaged using conventional multi-slice 2D DIR TSE imaging sequence and 3D MSDE-prep spoiled GRE.

Results—The MSDE-prep yields significant blood suppression (75-92%), enabling a volumetric 3D black-blood assessment of the whole heart with significantly improved visualization of the chamber walls. The MSDE-prep also allowed successful acquisition of black-blood images with isotropic spatial resolution. In the patient study, 3D black-blood MSDE-prep and DIR resulted in similar blood suppression in LV and RV walls but the MSDE prep had superior myocardial signal and wall sharpness.

Conclusion—MSDE-prep allows volumetric black-blood imaging of the heart.

Keywords

black-blood cardiac imaging; motion sensitized driven equilibrium; 3D imaging

INTRODUCTION

Black-blood imaging techniques (1,2) have been widely used in cardiovascular magnetic resonance (CMR). The suppression of the blood pool allows for better delineation of the cardiac chambers, especially the thinner right ventricular (RV) and atrial walls. Black-blood imaging techniques have also been used to image the aortic valve leaflets (3), atherosclerotic

Correspondence to: Reza Nezafat, Ph.D., Beth Israel Deaconess Medical Center, 330 Brookline Ave, Boston, MA, 02215, Phone: 617-667-1747; Fax: 617-975-5480, rnezafat@bidmc.harvard.edu.

plaques, and the coronary, aortic and carotid artery vessel walls (4-7). T_1- and T_2-weighted black-blood imaging with and without fat saturation are also commonly used in the assessment of cardiac masses, myocardium, pericardium, and fat in arrhythmogenic right ventricular cardiomyopathy (ARVC) (8-10). The enhanced contrast provided by black-blood imaging also enables better quantification of myocardial wall thickness under various pathological conditions (11).

The most common black-blood imaging technique in clinical CMR is double inversion recovery (DIR) (2,12). In DIR preparation sequence, blood signal suppression is due to the inflow of the inverted magnetization into the imaging plane and depends on several factors including the velocity of the inflowing blood, the thickness of the selected slice, and the TI. Additionally, the selective slab thickness is usually 1.5 to 2 times the imaging slab thickness to retain the myocardial spins which might have moved due to cardiac motion. Hence, slow moving and circulating blood or blood remaining in-plane are not well suppressed. Blood suppression by spatial pre-saturation (13) is another black-blood imaging technique that is commonly used by dephasing the flowing spins in two slabs placed on either side of the imaging slab. Quadruple inversion recovery (14) has also been proposed for black-blood imaging, which consists of two DIR pulses with the inversion times adjusted to null the blood signal within a wide range of T_1. These methods also suffer from some of the aforementioned problems such as dependence on flow direction and slab thickness.

To overcome the above limitations, other methods have been investigated. Recently, a flow independent technique based on the differences in T_1 and T_2 between the myocardium and blood was applied to suppress the blood in CMR (15,16). In this method, the preparation sequence consists of a T_2 preparation, followed by an inversion pulse and a delay period. The T_2 preparation time and the inversion delay are adjusted appropriately to maximize the contrast of the myocardium and blood, and inversion delay is set to null the blood. Another method using stimulated echo acquisition mode (17) has also been utilized for black-blood imaging.

Three-dimensional (3D) imaging offers improved spatial resolution (18) which is especially important for black-blood imaging in CMR. Higher spatial resolution could improve the diagnostic ability of CMR in ARVC where the thin free wall of the RV is being assessed. Improved spatial resolution can also benefit imaging of thin atrial walls and measurements of LV wall thickness in patients with hypertrophic cardiomyopathy. Despite these potential advantages for a 3D volumetric black-blood imaging, current techniques do not allow volumetric 3D acquisitions in the heart.

Motion sensitized driven equilibrium (MSDE) (19-21) (also referred to as diffusion prepared) utilizes a pair of gradients and a 180 pulse to dephase the moving magnetization and has been proposed for black blood imaging in carotid, thoracic aortic walls and the heart. MSDE preparation has also been used in imaging of the coronary walls (22). A phantom study (23) demonstrated that MSDE suppresses turbulent flow better than laminar flow. Hence, the complex flow patterns in the carotid and aortic arteries are suppressed better using the MSDE sequence than other techniques. A combination of DIR and MSDE (24) showed improved 3D blood suppression along the carotid wall, by suppressing both the laminar and the complex flow patterns. Although initial studies in the carotid arteries and the aorta demonstrate the feasibility of volumetric 3D acquisition, blood flow in the cardiac chamber is fundamentally different and more complex compared to flow in the carotid arteries or aorta. Additionally, black-blood cardiac assessment requires different contrast weightings which necessitate 3D black-blood spin-echo or gradient-echo imaging sequences and have not been previously evaluated.

In this study we sought to assess the efficacy of MSDE for blood suppression in volumetric 3D whole heart CMR. Imaging was performed in both healthy adult subjects and patients with suspected cardiovascular disease to assess the robustness of the technique.

METHODS

Four studies were performed to investigate the efficacy of MSDE for blood suppression in 3D whole heart imaging. Initially, a pilot study was performed to experimentally determine the optimal MSDE parameters. This was followed by a second study in healthy adult subjects to investigate the myocardial SNR loss and blood suppression resulting from an application of an MSDE pre-pulse. Third, to investigate the feasibility of isotropic 3D black blood imaging, 3D MSDE prep spoiled GRE with isotropic resolution was acquired in a small cohort of healthy subjects. Finally, to examine the image quality of 3D MSDE prep spoiled GRE compared to conventional multi-slice 2D DIR TSE sequence, a pilot study was performed in patients with suspected cardiovascular disease.

Written consent was obtained from the subjects and the protocol was approved by our Institutional Review Board. CMR scanning was performed on a commercial 1.5T MRI system (Achieva, Philips Healthcare, Best, Netherlands) with a maximum gradient of 33 mT/m and a maximum slew rate of 180 mT/m/ms. Subjects were placed supine in the scanner with a 5-channel cardiac array coil as receiver.

Motion Sensitized Driven Equilibrium Sequence

The MSDE preparation sequence (Figure 1) consists of a combination of 90_x-180_y-90_{-x} hard pulses with identical gradient strength around the 180_y pulse, delivered along the slice-, frequency-, and phase-encoding directions. The 180_y pulse is a composite pulse of 90°, 180° and 90° hard pulses with phase shifts of 180°, 270°, and 180°, respectively. This combination of pulses with the gradient results in velocity encoding of the magnetization (23). Blood suppression is due to intra-voxel dephasing, when the encoding introduces larger phase shifts for the spectrum of blood velocities within a voxel. Furthermore, in turbulent flow, the distribution of velocity of the blood magnetization within a voxel increases and improves intra-voxel dephasing.

Imaging Study

Three plane scout images were acquired to position the imaging slab, magnetic-field shimming region-of-interest and the respiratory navigator-echo. The imaging sequence used in this study was an ECG triggered, free breathing, navigator-echo gated 3D imaging sequence. The ECG trigger delay was set to mid-diastole, during which the ventricular wall has the least motion. A respiratory navigator-echo, along with prospective real time correction, was placed over the dome of the right hemi-diaphragm, with an acceptance window of 5-7 mm and a 0.6 slice-tracking ratio.

MSDE Parameter Selection

To determine the MSDE prep parameters, a pilot study was performed. 3D electrocardiogram (ECG) triggered, free breathing, navigator-echo gated, MSDE-prep, axial spoiled GRE sequence was performed on 5 healthy adult subjects (mean age 20.5 yrs, 2 male). The MSDE prep gradient amplitude was experimentally varied between 5-20 mT/m and the MSDE prep echo time (TE_{prep}), the time from the application of the 90_x° to 90_{-x}° pulse, was varied between 5-14 ms. Blood suppression in ventricles, myocardial signal loss were evaluated visually to determine the range of MSDE parameters that allowed sufficient blood suppression without substantial myocardial signal loss.

Blood and Myocardial SNR Assessment with MSDE

7 healthy adult subjects (2 male; 19 to 63 years old,) were recruited to investigate the impact of MSDE for blood suppression in 3D whole heart imaging for two imaging sequences: spoiled gradient echo (GRE) and turbo spin echo (TSE). In each of the 7 subjects, whole heart images were acquired using T_1-weighted (T_1w) TSE and spoiled GRE sequence with and without MSDE prep. The imaging parameters are given in Table 1. The image acquisition was performed in axial slab, analogous to our conventional clinical imaging protocol, covering the entire heart from apex to base to evaluate the performance of the proposed imaging sequence. Parallel imaging was not used to allow for accurate SNR comparison.

Based on the results from MSDE parameter selection study (see results), in all 7 subjects, the MSDE prep gradient amplitude in all three directions along the imaging plane was set to 12-17 mT/m along the three directions of the imaging plane, with a gradient rise time of 0.4 ms, and TE_{prep} of 6-7 ms, producing an effective diffusional attenuation moment (b-value) of ~0.2 s/mm^2. The spoiler gradients were set to an amplitude of 21 mT/m with a duration of 6 ms along all the three directions, in order to spoil the magnetization remaining in the transverse plane after the 90_{-x} pulse. The total preparation time of the MSDE preparation sequence was ~12 ms. In each subject, 4 datasets were acquired: T_1w-TSE's and spoiled GRE imaging sequences with and without MSDE prep.

3D Black-Blood with Isotropic Spatial Resolution

In 6 healthy adult subjects (2 male; 20-55 years old), we investigated the feasibility of acquiring 3D MSDE prep spoiled GRE black-blood imaging with 1.7mm^3 isotropic spatial resolution. The imaging parameters are given in Table 1.

Patient Study

We performed a feasibility study to evaluate the efficacy of 3D MSDE prep spoiled GRE whole heart imaging compared to the conventional multi-slice 2D DIR TSE in patients with known or suspected cardiovascular disease. In 15 patients (9 male; 23 to 68 years old) referred to our center for evaluation of LV function, LV viability, or atrial fibrillation, two additional black-blood image datasets were acquired. 2D ECG triggered multi-slice T_1w TSE DIR imaging sequence was performed at mid-diastole using our clinical imaging protocol with parameters as shown in Table 1. SENSE factor of 2.6 was used and 2 averages were acquired to reduce motion artifacts. Subsequently, the patients were imaged using a 3D MSDE prep spoiled GRE imaging sequence with the same parameters as used in the imaging study (Table 1). To remove user-interaction, we chose to use fixed MSDE parameters for all of our studies, which were MSDE gradient amplitude of 15 mT/m along the three directions of the imaging plane and TE_{prep} of 5 ms. Both scans were performed prior to the administration of contrast agents.

Data and Statistical Analysis

For SNR analysis, the images of the 7 normal subjects, were analyzed using ViewForum software (Philips Healthcare, Best, Netherlands). Regions-of-interest (ROI) was drawn in the lateral wall of the left ventricle (LV), the ventricular septum, and the LV, RV, left atrial (LA) and right atrial (RA) cavities. The ROIs were drawn in the MSDE prep images at 3 different levels of the heart: 2 adjacent slices along the apex of the heart, 2 slices in the mid-ventricular region, and 2 slices at the atrial level. These ROIs were copied to the same locations in images acquired without MSDE prep. The noise was measured in an ROI outside the chest wall. The SNR for each region was then calculated as the ratio of the mean signal intensity to the standard deviation of the noise. The SNR was measured at the

specified levels, at different regions, in both the images with and without MSDE prep. A paired t-test was performed to evaluate the significance between the SNR of the acquisitions with and without MSDE prep. All data is reported as mean ± standard deviation. A two-tailed *P* value <0.05 was considered to indicate significance. Contrast-to-noise ratio (CNR) between the LV and blood pool was also measured. All statistical analysis was performed in Excel 2007 (Microsoft, Redmond, WA).

For the patient study, subjective grading was performed based on a four-point scale (1= poor, 4=excellent) by an experienced reader with over 10 years of experience. Three criteria were considered: blood suppression, myocardial signal loss and blood-myocardium border sharpness. For each chamber, a separate score was given for each criterion. The septum was also scored separately for sharpness. The subjective grading scores from the two methods (i.e. MSDE prep vs. DIR) were compared using a Wilcoxon signed rank test. A two-tailed *P* value <0.05 was considered to indicate significance.

RESULTS

MSDE Parameter Selection

Visual analysis of the blood suppression and myocardial signal loss showed that TEprep in the range of 12-17 mT/m and 6-7 ms, respectively, provided maximum blood suppression and minimum myocardial signal loss for subjects with normal heart rate in the range of 65-75 beats/min. One of the subjects had a high heart rate of 85-95 beats/min and the nominal MSDE gradient of 16 mT/m and TEprep of 6ms resulted in severe myocardial SNR loss. However, with MSDE gradient reduced to about 8mT/m with TEprep of 6ms, good blood suppression and myocardial signal was observed.

Blood and Myocardial SNR Assessment with MSDE

Figure 2 shows a single slice from the 3D volumes of T_1w-TSE and spoiled GRE with and without MSDE prep. The MSDE prep results in excellent suppression of the blood signal in the lumen of the LV and RV, while retaining the signal from the LV and RV myocardium. Example MSDE prep T_1w-TSE images and spoiled GRE from a subject at four different slice locations (from the apex to the base) are shown in Figure 3. The papillary muscles and the LV, RV, RA and LA walls are clearly delineated. Table 2 summarizes the average SNR of all 6 segments at different regions for both imaging sequences with the exception of RA and LA blood, which were measured as the average SNR of the 2 basal segments. The MSDE prep results in significant suppression of blood signal for both sequences and at different luminal regions. The LV, RV, RA and LA luminal blood suppression was significant in all the sequences ($P< 0.005$). The segmental analysis of SNR (data not shown) shows a loss of SNR in the mid-slice of LV and septum using MSDE prep spoiled GRE and MSDE prep T_1w-TSE sequences ($P = 0.03$). Despite these SNR losses, lateral LV and septal regions were visible in all the subjects. Myocardial SNR loss of ~15-17% was observed using MSDE prep spoiled GRE and ~14-20% using MSDE prep T_1w-TSE. SNR measurements were not performed for the atrial and RV walls, due to the limited spatial resolution. The RA wall was not visible in 2 subjects using MSDE prep spoiled GRE and in 1 subject using MSDE prep T_1w-TSE. The CNR calculated between the LV and the blood pool was 101±30 and 83±20 using MSDE prep T_1w-TSE and MSDE prep spoiled GRE respectively.

3D Black-Blood with Isotropic Spatial Resolution

Black blood images with isotropic spatial resolution were successfully acquired in all subjects. Figure 4 shows four multi-planar reformatted images from 3D black blood images

with isotropic spatial resolution. MSDE prep resulted in excellent visualization of all cardiac structures and allows reformatting images in any desired orientation.

Patient Study

Figure 5 shows 3D black blood MSDE prep spoiled GRE images obtained from a patient with chronic pericarditis compared with 2D DIR, with the former showing excellent blood suppression in all chambers. Figure 6 compares the 3D MSDE prep images with 2D DIR in a patient with atrial fibrillation. The MSDE prep suppresses the LV blood better than the DIR; however, the LA blood is not suppressed by either sequence. The dilated LA and LV wall are clearly visible using MSDE prep. Table 3 summarizes the grading of black-blood images in the patient cohort. Blood suppression by 3D MSDE prep spoiled GRE was similar to DIR in the LV and RV, but slightly lower in the LA and RA. DIR resulted in higher signal loss and signal inhomogeneity in the LA, RA, LV and LA. The MDSE images were scored significantly higher in terms of wall sharpness.

DISCUSSION

In this study, we evaluated the MSDE prep sequence for free breathing, navigator-echo gated, 3D whole-heart black-blood imaging with T_1w-TSE and spoiled GRE acquisitions. Conventional black-blood imaging techniques, such as single-, or multi-slice, 2D DIR (25) and pre-saturation slabs are based on the inflow of the blood magnetization. DIR preparation is most efficient when the direction of blood flow is primarily perpendicular to the imaging slab, thereby restricting the appropriate imaging plane orientation. Therefore, the application of DIR in 3D thick slab black blood imaging, or in scenarios where blood flow is primarily in-plane, is limited. 3D black blood-imaging with MSDE prepared SSFP has been previously reported for carotid and aorta imaging (19). The uni-directionality of blood flow in the carotid and aorta allows better blood suppression compared to the complex cardiac chamber flow.

MSDE preparation, a technique independent of the inflow of magnetization through the imaging slice, is sensitive to intra-voxel dephasing caused by the flow sensitizing gradients. Hence, it is useful in 3D black-blood cardiac imaging to acquire data along any plane, utilizing higher or even isotropic resolution. In addition, it may be useful to fine-tune the gradient moment in thin and/or moving anatomy, such as the atrial wall. The duration of the MSDE prep is shorter (~12ms) compared to the other techniques, which would decrease the total scan duration, as well as allow acquisition at any cardiac phase, even in early systole, which is difficult with DIR preparation. The ability of MSDE prep to suppress complex flow patterns could also be an advantage in the assessment of cardiac masses and different cardiac wall pathologies, which often result in complex blood flow patterns.

Although spoiled GRE has the least myocardial SNR loss, it is less versatile in creating different contrasts relative to those achievable with TSE. Therefore, despite the superiority of GRE in terms of myocardial SNR loss, TSE may be the preferred imaging sequence for black-blood cardiac MR. This is also true for black-blood imaging of atherosclerotic plaque in the carotid and descending aorta. T_2 weighted 3D black blood CMR could be performed by applying MSDE prep pulse with longer TE and TR, TSE readout or by using MSDE as both T_2 preparation and blood suppression pulse (with lower amplitude MSDE gradient for a longer duration) and TSE readout. Recently, modified MSDE prep pulse with 3D SPACE sequence, FSD-SPACE (26) has been used for 3D black blood T_2 weighted carotid imaging. T_2 weighted 3D MSDE prep black blood CMR was not studied here and needs further investigation. Whole heart 3D spoiled GRE without MSDE prep suffers from increased inflow saturation and lack of sufficient blood-myocardium contrast (27), which limits its use. But with MSDE prep spoiled GRE, there is excellent depiction of cardiac anatomy.

The blood suppression due to the MSDE prep pulse depends on various subject specific factors like blood velocity distribution, voxel size (23) and heart rate of the subject. Higher gradient moment results in good blood suppression but would also cause myocardial signal loss and vice-versa. Hence the choice of the MSDE parameters for good blood suppression is subject specific. In our study, we varied the MSDE parameters for the subjects manually within the nominal range by visually evaluating the blood suppression and myocardial loss. However, this manual variation was not possible during patient imaging due to time restriction. The selection of the MSDE parameters could be improved by obtaining scout images at different heart levels with various MSDE gradient parameters and choosing the amplitude and TE_{prep} that provides good blood suppression and least myocardial signal loss (28). Further studies are warranted to improve the parameter optimization for MSDE sequence and to optimize the MSDE gradient dephasing direction to match a specific cardiac anatomy for improved blood saturation and minimal myocardial SNR loss.

Our initial pilot study demonstrates the potential of this imaging sequence for black-blood imaging. However, our data also shows this technique is not suitable for all patient populations. As shown, both DIR and MSDE preparation failed to suppress blood in the LA in a patient with irregular rhythm (Figure 6). This might be due to the slow blood flow in the atrium resulting in lesser intra-voxel dephasing of the atrial blood, as the patient was in atrial fibrillation. Further studies in a targeted patient cohort are needed to further investigate this sequence.

Our study had several limitations; the first being the small number of subjects imaged. The blood suppression may vary in patients with other heart diseases (e.g. valvular disease or systolic heart failure with low ejection fraction). Further studies are also needed to evaluate high spatial resolution 3D black-blood imaging in patients. We have compared our black-blood MSDE with GRE imaging sequence to images acquired with 2D DIR with TSE. Because of contrast differences inherent to these two different sequences, no SNR and CNR measurements were presented. Further studies investigating the combination of MSDE with T_1/T_2-weighted images are warranted.

In conclusion, MSDE prep with T_1w TSE or spoiled GRE can be used for 3D whole heart black-blood imaging. The significant blood suppression allows delineation of the LV, RV, LA, and RA walls, along with small features such as the papillary muscles. A black-blood whole heart acquisition with isotropic spatial resolution allows multi-planar reformatting for better assessment of cardiovascular structure.

Acknowledgments

The authors acknowledge grant support from NIH R01EB008743-01A2, AHA SDG-0730339N, and National Center for Research Resources UL1 RR025758-01 (Harvard Clinical and Translational Science Center).

REFERENCES

1. Edelman RR, Chien D, Kim D. Fast selective black blood MR imaging. Radiology. 1991; 181(3): 655–660. [PubMed: 1947077]
2. Simonetti OP, Finn JP, White RD, Laub G, Henry DA. “Black blood” T2-weighted inversion-recovery MR imaging of the heart. Radiology. 1996; 199(1):49–57. [PubMed: 8633172]
3. Arai AE, Epstein FH, Bove KE, Wolff SD. Visualization of aortic valve leaflets using black blood MRI. J Magn Reson Imaging. 1999; 10(5):771–777. [PubMed: 10548787]
4. Crowe LA, Gatehouse P, Yang GZ, et al. Volume-selective 3D turbo spin echo imaging for vascular wall imaging and distensibility measurement. J Magn Reson Imaging. 2003; 17(5):572–580. [PubMed: 12720267]

5. Sirol M, Itskovich VV, Mani V, et al. Lipid-rich atherosclerotic plaques detected by gadofluorine-enhanced in vivo magnetic resonance imaging. Circulation. 2004; 109(23):2890–2896. Epub 2004 Jun 2897. [PubMed: 15184290]
6. Stuber M, Botnar RM, Kissinger KV, Manning WJ. Free-breathing black-blood coronary MR angiography: initial results. Radiology. 2001; 219(1):278–283. [PubMed: 11274570]
7. Amparo EG, Higgins CB, Hoddick W, et al. Magnetic resonance imaging of aortic disease: preliminary results. AJR Am J Roentgenol. 1984; 143(6):1203–1209. [PubMed: 6149679]
8. Kayser HW, van der Wall EE, Sivananthan MU, Plein S, Bloomer TN, de Roos A. Diagnosis of arrhythmogenic right ventricular dysplasia: a review. Radiographics. 2002; 22(3):639–648. discussion 649-650. [PubMed: 12006692]
9. Campos S, Martinez Sanjuan V, Garcia Nieto JJ, et al. New black blood pulse sequence for studies of the heart. Int J Card Imaging. 1999; 15(2):175–183. [PubMed: 10453416]
10. 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(1):38–48. [PubMed: 15220492]
11. Higgins CB. Overview of MR of the heart--1986. AJR Am J Roentgenol. 1986; 146(5):907–918. [PubMed: 3515882]
12. Parker DL, Goodrich KC, Masiker M, Tsuruda JS, Katzman GL. Improved efficiency in double-inversion fast spin-echo imaging. Magn Reson Med. 2002; 47(5):1017–1021. [PubMed: 11979583]
13. Felmlee JP, Ehman RL. Spatial presaturation: a method for suppressing flow artifacts and improving depiction of vascular anatomy in MR imaging. Radiology. 1987; 164(2):559–564. [PubMed: 3602402]
14. Yarnykh VL, Yuan C. T1-insensitive flow suppression using quadruple inversion-recovery. Magnetic Resonance in Medicine. 2002; 48(5):899–905. [PubMed: 12418006]
15. Liu C-Y, Bley TA, Wieben O, Brittain JH, Reeder SB. Flow-independent T2-prepared inversion recovery black-blood MR imaging. Journal of Magnetic Resonance Imaging. 2010; 31(1):248–254. [PubMed: 20027595]
16. Nguyen, TD.; Kawaji, K.; SpinceMaille, P., et al. Three dimensional black blood MRI with extensive cardiothoracic coverage: A feasibility study in healthy volunteers; Proceedings of 18th Annual Meeting of ISMRM; Stockholm, Sweden. 2010; abstract 3650
17. Fahmy AS, Pan L, Osman NF. Artifact-free black-blood cine cardiac imaging in a single breath-hold. Magnetic Resonance Imaging. 2006; 24(10):1303–1310. [PubMed: 17145401]
18. Balu N, Chu B, Hatsukami TS, Yuan C, Yarnykh VL. Comparison between 2D and 3D high-resolution black-blood techniques for carotid artery wall imaging in clinically significant atherosclerosis. Journal of Magnetic Resonance Imaging. 2008; 27(4):918–924. [PubMed: 18383253]
19. Koktzoglou I, Li D. Diffusion-prepared segmented steady-state free precession: Application to 3D black-blood cardiovascular magnetic resonance of the thoracic aorta and carotid artery walls. J Cardiovasc Magn Reson. 2007; 9(1):33–42. [PubMed: 17178678]
20. Wang J, Yarnykh V, Hatsukami T, Chu B, Balu N, Yuan C. Improved suppression of plaque-mimicking artifacts in black-blood carotid atherosclerosis imaging using a multislice motion-sensitized driven-equilibrium (MSDE) turbo spin-echo (TSE) sequence. Magn Reson Med. 2007; 58:973–981. [PubMed: 17969103]
21. Koktzoglou I, Li D. Submillimeter isotropic resolution carotid wall MRI with swallowing compensation: imaging results and semiautomated wall morphometry. J Magn Reson Imaging. 2007; 25(4):815–823. [PubMed: 17345637]
22. Gerretsen, S.; Wang, J.; Maki, JH., et al. Reproducible coronary vessel wall imaging at 3T using improved Motion Sensitized Driven Equilibrium (iMSDE; Proceedings of 18th Annual Meeting of ISMRM; Stockholm, Sweden. 2010; abstract 665
23. Nguyen TD, de Rochefort L, Spincemaille P, et al. Effective motion-sensitizing magnetization preparation for black blood magnetic resonance imaging of the heart. Journal of Magnetic Resonance Imaging. 2008; 28(5):1092–1100. [PubMed: 18972350]

24. Makhijani MK, Hu HH, Pohost GM, Nayak KS. Improved blood suppression in three-dimensional (3D) fast spin-echo (FSE) vessel wall imaging using a combination of double inversion-recovery (DIR) and diffusion sensitizing gradient (DSG) preparations. J Magn Reson Imaging. 2010; 31(2): 398–405. [PubMed: 20099353]
25. Mani V, Itskovich VV, Szimtenings M, et al. Rapid extended coverage simultaneous multisection black-blood vessel wall MR imaging. Radiology. 2004; 232(1):281–288. [PubMed: 15220509]
26. Fan Z, Zhang Z, Chung Y-C, et al. Carotid arterial wall MRI at 3T using 3D variable-flip-angle turbo spin-echo (TSE) with flow-sensitive dephasing (FSD). Journal of Magnetic Resonance Imaging. 2010; 31(3):645–654. [PubMed: 20187208]
27. Nezafat R, Herzka D, Stehning C, Peters DC, Nehrke K, Manning WJ. Inflow quantification in three-dimensional cardiovascular MR imaging. J Magn Reson Imaging. 2008; 28(5):1273–1279. [PubMed: 18972337]
28. Fan, Z.; Bi, X.; Zhou, X., et al. 3D Non-Contrast-Enhanced MRA Using Flow-Sensitive Dephasing (FSD) prepared Balanced SSFP: Identification of the Optimal First-Order Gradient Moment; Proceedings of 18th Annual Meeting of ISMRM; Stockholm, Sweden. 2010; abstract 1410

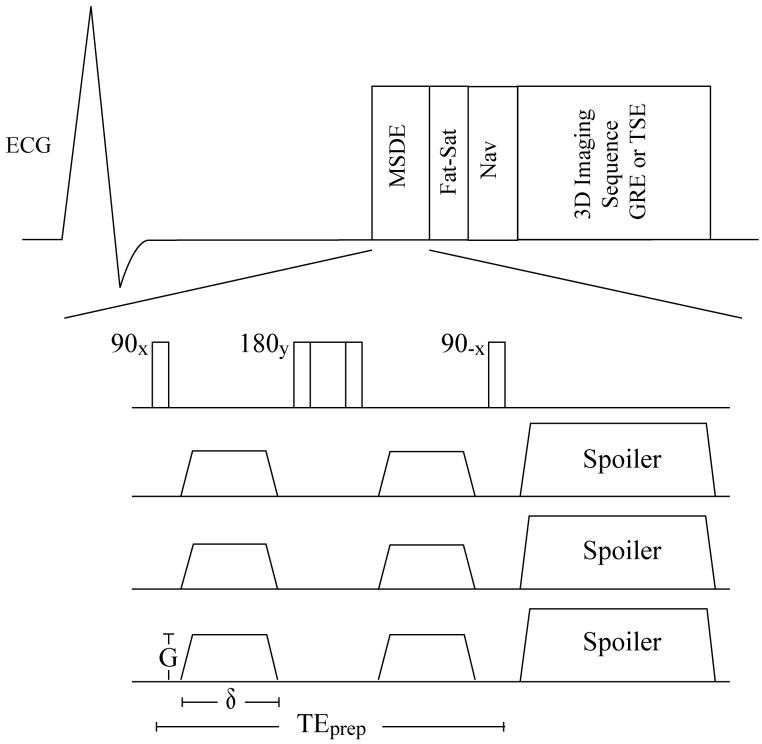

Figure 1.
3D black blood, electrocardiogram (ECG) triggered whole heart imaging sequence (upper) with motion sensitized driven equilibrium (MSDE) preparation (lower). The MSDE preparation sequence is followed by a spectrally-selective fat saturation (Fat-Sat) and respiratory navigator-echo (Nav), prior to the 3D data acquisition. The ECG trigger delay is set to mid-diastole.

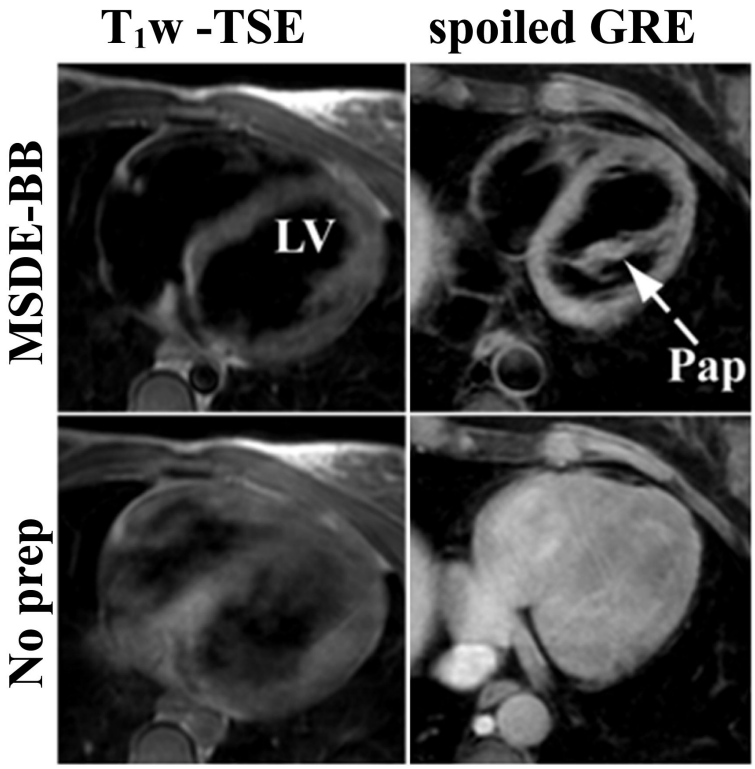

Figure 2.
A single slice from the 3D volume acquired using T_1w-TSE, and spoiled GRE with and without MSDE prep. Significant suppression of the blood signal can be seen in all images acquired with MDSE prep, allowing visualization of the left ventricle (LV) and right ventricle (RV) wall and the papillary (Pap) muscle.

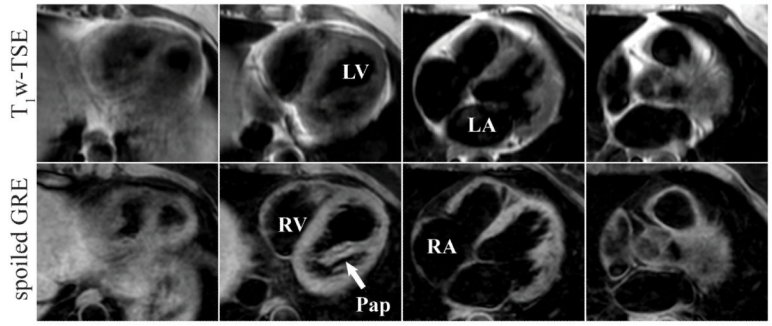

Figure 3.
Four apical to basal level slices from the 3D whole heart black blood images acquired using 3D T_1w-TSE and spoiled GRE with an MSDE prep gradient of 15 mT/m and TE_{prep} of 6ms in all the three gradient directions, demonstrating blood suppression in the LV, RV, right atrium (RA) and left atrium (LA).

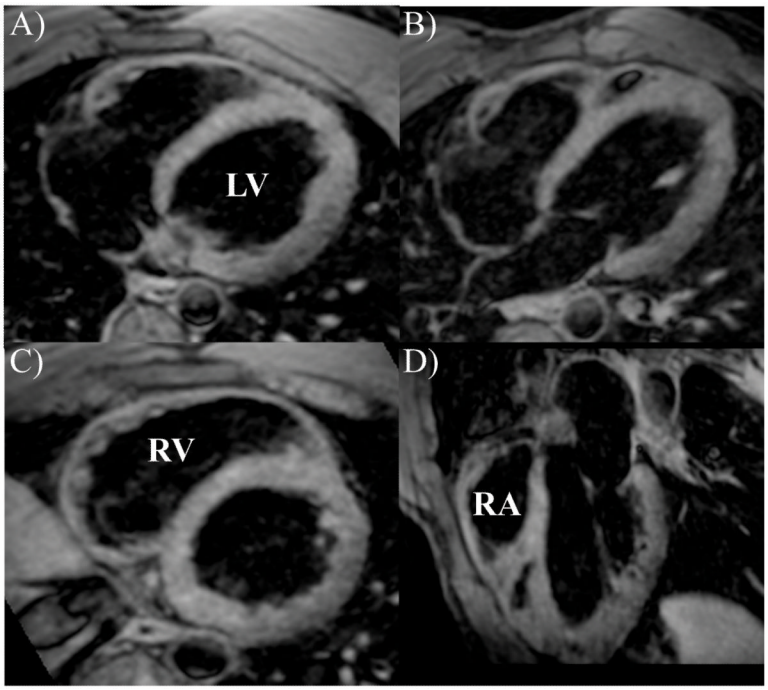

Figure 4.
Four multi-planar reformatted slices from 3D black blood spoiled GRE sequence with MSDE prep acquired with an isotropic resolution of 1.7 mm^3, demonstrating suppression of the blood pool. 3D acquisition with isotropic spatial resolution allows reformatting in any orientation.

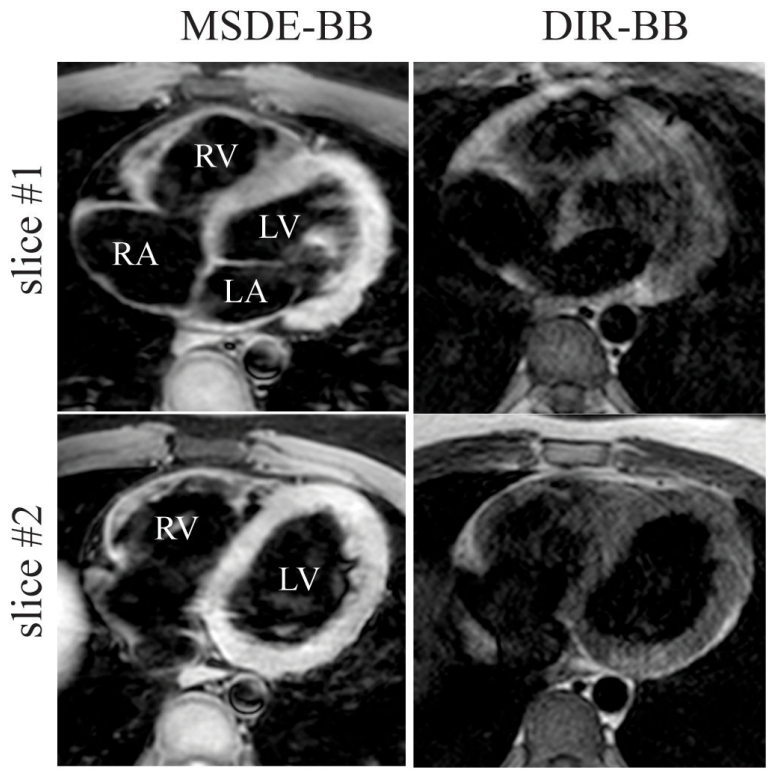

Figure 5.
Two example slices from 3D black-blood dataset acquired using spoiled GRE with MSDE prep in comparison with conventional multi-slice 2D double-inversion (DIR) TSE imaging sequence in a patient with chronic pericarditis and average heart rate of 65 BPM. Good blood suppression can be seen in MSDE-prepared 3D data in all the four chambers.

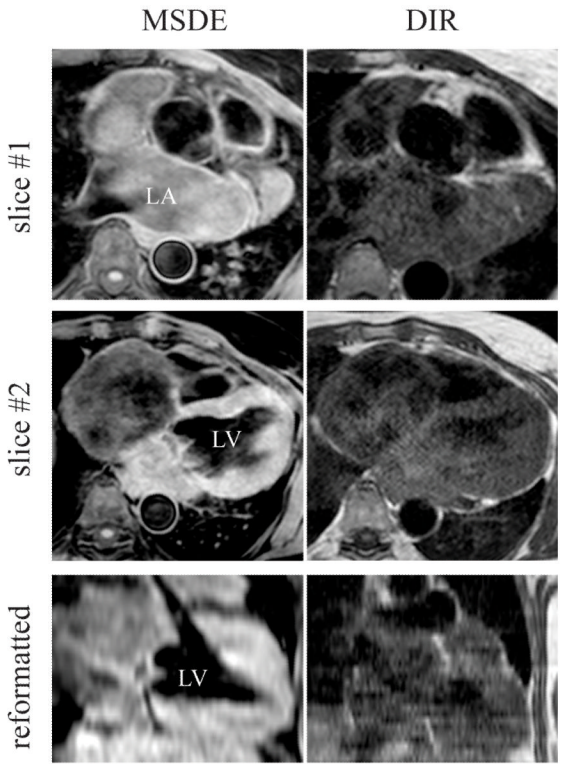

Figure 6.
3D black-blood images acquired using 3D whole heart spoiled GRE with MSDE prep compared with conventional multi-slice 2D-DIR TSE imaging sequence in a patient with history of atrial fibrillation, and was in atrial fibrillation during the exam. While blood in LV is better suppressed with MSDE prep, both sequences fail to suppress the blood in dilated LA. MSDE prep causes slightly better blood suppression in LA and allows visualization of LA wall despite its failure in blood suppression and better depiction of LV wall.

Table 1

Imaging parameters used in the imaging and patient studies.

	3D T_1w-TSE	3D Spoiled GRE	3D Isotropic Spoiled GRE	2D multi-slice TSE DIR
FOV (mm^3)	300-320×300×116	300×300×100	300×300×100.3	320×320
spatial resolution (mm^3)	1.5×1.5×8	1.5×1.5×4	1.7×1.7×1.7	1.5×1.5×5
bandwidth (Hz/px)	714 – 741	287	287	599
TR/TE/α	1 RR/10ms/90°	5.4/2.6 ms/20°	5.4/2.6 ms/20°	800/20ms/90° TI:280ms
fat saturation	No	Yes	Yes	No
acquisition interval (ms)	102-138	100-120	100-120	61
scan time (min) (assuming 50% navigator efficiency)	~7	~8.5	~19	~4

Table 2

mean ± 1 standard deviation of SNR measured over six slices (two apical, two mid and two atrial levels) for all the 7 subjects for the LV wall, septum, LV-blood, RV- blood, RA-blood and LA blood. MSDE-prep causes myocardial SNR loss in the LV of ~15-17% for spoiled GRE and ~14-20% for T_1w-TSE and blood suppression between 75- 78% for T1w-TSE and 88-92% for spoiled GRE. There is significant blood suppression in chambers with MSDE-prep in both imaging sequences.

	T_1w-TSE		**Spoiled GRE**	
	No prep	***MSDE***	***No prep***	***MSDE***
LV wall	157±33	126±35	112±20	95±20
Septum	153±26	131±21	117±19	97±14
LV-blood	98±32	24±8*	110±17	13±3*
RV-blood	96±25	22±7*	119±20	11±1*
RA-blood	98±19	25±10*	135±36	12±2*
LA-blood	90±28	20±5*	128±41	10±2*

* indicates $P < 0.05$

Table 3

mean ± 1 standard deviation of the subjective score of the 15 patients.

Blood Suppression					
	LV	*RV*	*LA*	*RA*	
MSDE	3.4 ± 0.6	3.4 ± 0.6	2.8 ± 0.7*	2.9 ± 0.7*	
DIR	3.3 ± 0.7	3.4 ± 0.7	3.1 ± 0.8	3.3 ± 0.9	
Myocardial Signal Loss					
	LV	*RV*	*LA*	*RA*	
MSDE	4.0 ± 0.0*	3.9 ± 0.4*	3.8 ± 0.6*	3.7 ± 0.6*	
DIR	3.3 ± 0.7	2.9 ± 0.9	2.6 ± 0.7	2.7 ± 0.8	
Blood-Myocardium Sharpness					
	LV	*RV*	*LA*	*RA*	*Septum*
MSDE	3.9 ± 0.4*	3.7 ± 0.6*	3.7 ± 0.6*	3.7 ± 0.6*	3.9 ± 0.4*
DIR	2.9 ± 0.8	2.5 ± 1.0	2.3 ± 1.1	2.3 ± 1.1	2.8 ± 0.9

*indicates $P < 0.05$.