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Whole-Heart Chemical Shift Encoded Water–Fat MRI

Valentina Taviani^{1,*}, Diego Hernando¹, Christopher J. Francois¹, Ann Shimakawa², Karl K. Vigen¹, Scott K. Nagle^{1,3,4}, Mark L. Schiebler¹, Thomas M. Grist^{1,3,5}, and Scott B. Reeder^{1,3,5,6}

¹Department of Radiology, University of Wisconsin, Madison, Wisconsin, USA

²Global Applied Science Lab, GE Healthcare, Menlo Park, California, USA

³Department of Medical Physics, University of Wisconsin, Madison, Wisconsin, USA

⁴Department of Pediatrics, University of Wisconsin, Madison, Wisconsin, USA

⁵Department of Biomedical Engineering, University of Wisconsin, Madison, Wisconsin, USA

⁶Department of Medicine, University of Wisconsin, Madison, Wisconsin, USA

Abstract

Purpose—To develop and evaluate a free-breathing chemical-shift-encoded (CSE) spoiled gradient-recalled echo (SPGR) technique for whole-heart water–fat imaging at 3 Tesla (T).

Methods—We developed a three-dimensional (3D) multi-echo SPGR pulse sequence with electrocardiographic gating and navigator echoes and evaluated its performance at 3T in healthy volunteers (N = 6) and patients (N = 20). CSE-SPGR, 3D SPGR, and 3D balanced-SSFP with chemical fat saturation were compared in six healthy subjects with images evaluated for overall image quality, level of residual artifacts, and quality of fat suppression. A similar scoring system was used for the patient datasets.

Results—Images of diagnostic quality were acquired in all but one subject. CSE-SPGR performed similarly to SPGR with fat saturation, although it provided a more uniform fat suppression over the whole field of view. Balanced-SSFP performed worse than SPGR-based methods. In patients, CSE-SPGR produced excellent fat suppression near metal. Overall image quality was either good (7/20) or excellent (12/20) in all but one patient. There were significant artifacts in 5/20 clinical cases.

Conclusion—CSE-SPGR is a promising technique for whole-heart water–fat imaging during free-breathing. The robust fat suppression in the water-only image could improve assessment of complex morphology at 3T and in the presence of off-resonance, with additional information contained in the fat-only image.

Keywords

chemical shift encoding; water; fat; free-breathing; 3D

Introduction

Chemical-shift-encoded (CSE) cardiac MR (CMR) imaging has been previously proposed to characterize pericardial disease (e.g., pericarditis) and cardiac masses (1–4) as well as to improve coronary artery visualization (5). Because of the excellent contrast between fat and water and the ability to detect very small amounts of fat, CSE methods have also been suggested as an alternative to conventional fat suppression to detect and characterize fibrofatty infiltration of the myocardium (3,6), a condition that has been recently associated with sudden cardiac death, arrhythmogenic right ventricular dysplasia (ARVD) (7), chronic myocardial infarction (8), and other nonischemic cardiomyopathies (9).

Conventional frequency-selective fat saturation methods and spectral-spatial pulses (10) are sensitive to field inhomogeneities and susceptibility variations often found in the thoracic cavity (11), especially in those who have undergone prior sternotomy or coronary stent placement. Fat suppression techniques based on short tau inversion recovery (12) are characterized by low signal-to-noise-ratio (SNR) and have limited applicability in contrast-enhanced imaging. On the other hand, CSE methods are robust to off-resonance (i.e., uniform fat suppression over the entire field of view) and have high SNR efficiency (4). CSE methods can also be used to visualize pericardial inflammation (13,14). Furthermore, these methods permit discrimination between myocardial infarcts and pericardial fat in late gadolinium enhancement imaging. These two tissues are often difficult to distinguish from one another using conventional viability imaging due to their similar T_1 values after gadolinium-based contrast agent administration (15). Another important advantage of CSE methods is that they generally provide better contrast between water and fat when compared with other fat suppression techniques, making it possible to identify small fat deposits within the myocardium (e.g., fibrofatty infiltration) and provide additional information, contained in the fat-only image, which might be useful to characterize fat accumulation around the heart (16). There is increasing evidence that an increased volume of epicardial fat is associated with coronary artery disease (17,18) and atrial fibrillation (19,20). In this case, positive contrast provided by the fat-only image may add prognostic value over the fat-suppressed, water-only image alone. It has also been noted that the fat-only image may also aid in the assessment of coronary vessel conspicuity because of the stark contrast between the vasculature and surrounding epicardial fat (5).

The acquisition of spectroscopic information for water–fat decomposition, together with the need to synchronize the acquisition to the QRS complex and diaphragm position to minimize cardiac and respiratory motion artifacts requires long acquisition times. Most cardiac imaging sequences, including most of the CSE techniques previously proposed for water–fat resolved imaging of the heart, acquire a series of two-dimensional (2D) slices with each slice obtained during a single breath-hold (3,4,21). This typically requires many breath-holds, i.e., very long scan times to cover the whole heart, and can only be applied to cooperative patients. 3D acquisitions are highly desirable for patients who are unable to consistently and repeatedly hold their breath, as they are usually performed during free-breathing. In addition, the acquired 3D datasets can be re-sliced at arbitrary angles, so that a single free-breathing 3D acquisition could replace multiple series of 2D scans performed in different planes over multiple breath-holds.

Several methods involving the acquisition of two or more echoes with more or less flexible echo times have been shown to provide robust estimates of field map, water and fat for cardiac applications (3–5,21). In general, two-point methods are faster, but require more sophisticated reconstruction techniques and specific echo times to provide robust water–fat separation (22–25). Multi-echo methods (3 points or more) require higher acceleration factors and generally longer scan times but allow more flexible echo times (26–28). In this work, we propose a 3D RF-spoiled, gradient-echo, multi-echo CSE acquisition with electrocardiographic (ECG) gating and navigator echoes for whole-heart water–fat imaging during free-breathing. A comparison against conventional fat-suppressed techniques for 3D CMR performed in healthy volunteers as well as our initial clinical experience in patients undergoing CMR examinations are reported and discussed.

Methods

All imaging was performed on a 3.0 Tesla (T) whole-body imaging system (GE MR750, GE Healthcare, Waukesha, WI) using the body coil for transmission and a 32-channel receive-only phased array coil for signal reception. All subjects gave written informed consent and were enrolled prospectively according to a local institutional ethics board approved protocol.

Pulse Sequence

We developed a 3D RF-spoiled, gradient echo, multi-echo pulse sequence for whole-heart water–fat imaging during free-breathing. Four echoes were acquired in two interleaves with fly-back gradients (Fig. 1a). A repetition time of 1 R-R with mid-diastolic data acquisition synchronized to the cardiac R wave was used. A T_2 preparation pulse (effective echo time = 48 ms) was played every R-R interval to improve contrast between the blood pool and the myocardium (29). Navigator echoes were acquired once per R-R after data acquisition using a pair of orthogonal slice-selective 90° – 180° pulses (Fig. 1b); 1D projections of a column of magnetization centered around the dome of the liver were obtained using the following parameters: 10 cm profile length, 256 readout points, and ± 31 kHz bandwidth. Histogram analysis of navigator echoes acquired over an initial monitoring period of 24 R-R intervals gave the most frequent end-expiration diaphragm position. During the actual acquisition period, if the diaphragm position recorded by the navigator echo fell outside the ± 2 mm acceptance window set during the initial monitoring period, the corresponding data were rejected and the same views were reacquired until the diaphragm position fell within the prescribed tolerance. Both the threshold and width of the acceptance/rejection window could be updated in real time during the scan to account for eventual drifts in the respiratory waveform and/or significant changes in the breathing pattern.

Image acquisition was accelerated by using corner cutting (80% partial $k_r = (k_y^2 + k_z^2)^{0.5}$) (30) and an autocalibrated data-driven parallel imaging method (ARC, Accelerated Reconstruction for Cartesian imaging) (31). A nominal acceleration factor of 2 in both the phase and slice encoding directions and a 28×28 circular calibration region were used. A segmented acquisition scheme with center-out view ordering within each segment and a data acquisition (DAQ) window $\sim 10\%$ R-R interval were used (Fig. 2). Data acquisition started at the minimum k_z . All corresponding k_y views were acquired starting from the innermost

segment before stepping to the next k_z value. For each k_z , dummy acquisitions were performed in the outermost segment when the number of views required for this segment was less than that in the corresponding inner segments.

Image Reconstruction

Source images were reconstructed for each coil element using ARC and a $3 \times 7 \times 7$ reconstruction kernel. Complex coil combination was performed as described by Walsh (32). A 3D graph cut algorithm was used to obtain a first estimate of field map, water and fat (33). Complex fitting was subsequently performed at each pixel using a nonlinear gradient-based least squares algorithm (lsqnonlin, Matlab, The MathWorks, Natwick, MA) using the water, fat, and field map estimates obtained from graph cut as initial solution. A multi-peak fat spectrum was included in the signal model (28). The total reconstruction time was approximately an hour (Matlab-based reconstruction; 2.3 GHz AMD Opteron processor; 128 GB of RAM; no parallel computing).

Comparative Study in Healthy Volunteers

Six healthy volunteers were scanned with the proposed CSE SPOiled Gradient echo (SPGR) technique, a conventional 3D SPGR pulse sequence and 3D balanced Steady-State Free Precession (SSFP). No contrast agent was given. Both SPGR and balanced SSFP were cardiac gated and used the same navigators and T_2 preparation pulse as CSE-SPGR. SPECIAL (SPECTral Inversion At Lipids) fat suppression (chemically selective 90° pulse), VAST (Variable Asymmetric Sampling in Time) segmentation (34) across 2 R-R intervals and an ASSET (Array Spatial and Sensitivity Encoding Technique) acceleration factor of 2 in the phase encoding direction were used for both 3D SPGR and 3D balanced SSFP. The following imaging parameters were the same for the 3 acquisitions: field of view (FOV) = 40 cm; phase FOV = 70–80%; slice thickness = 3 mm; matrix size = $256 \times 160 \times 50$; receiver bandwidth = ± 143 kHz; trigger window = 10%; trigger delay = $\sim 70\%$ R-R interval. Echo time (ms), repetition time (ms) and flip angle ($^\circ$) were echo time/repetition time/ α ($TE/TR/\alpha$) = 1.2/6.4/15, 0.9/2.5/15, 1.4/3.1/90 for CSE-SPGR, SPGR and balanced SSFP, respectively. Four echoes (two interleaves) were acquired in CSE-SPGR, with echo spacing 1 ms. The average DAQ window duration was 73 ms for CSE-SPGR (~ 12 views per segment). A similar DAQ duration was used for SPGR and balanced SSFP (50–110 ms). Scan time (assuming a 100% navigator efficiency) was 4.1 ± 0.4 , 2.2 ± 0.8 , and 2.1 ± 0.6 min for CSE-SPGR, SPGR, and balanced SSFP, respectively.

All images were reviewed by consensus by two cardiovascular radiologists with 12 and 13 years of experience in cardiac MRI for overall image quality, level of residual artifacts and quality of fat suppression. Overall image quality was graded using a four-point Likert scale (0: poor, non diagnostic; 1: fair, some diagnostic information; 2: good, diagnostic; 3: excellent, diagnostic). The level of residual artifacts was also scored using 4 different categories (0: severe artifacts, nondiagnostic; 1: some artifacts, may interfere with diagnostic information; 2: few artifacts, does not interfere with diagnostic information; 3: minimal/no artifacts). The quality of fat suppression in the heart and mediastinum was also evaluated according to a four-point scale with 0 denoting “complete failure” and 3 “excellent fat suppression”. Paired Student t-tests were used to compare the performance of CSE-SPGR

with respect to SPGR and balanced SSFP in terms of overall image quality, level of residual artifacts and goodness of fat suppression under the assumption of numerical ratings.

Preliminary Evaluation in Patients

Twenty patients (12 men, 8 women; mean age = 48.5 years; range = 19–80 years) undergoing clinical CMR examinations including conventional pulse sequences for morphology, function, and viability imaging were prospectively enrolled in this study. The proposed CSE pulse sequence was added at the end of the routine clinical protocol, approximately 15–20 min after contrast injection [0.15 mmol/kg of gadobenate dimeglumine (Multihance, Bracco Diagnostics, Princeton, NJ)]. Indications for CMR included: known or suspected hypertrophic cardiomyopathy (n = 4); sarcoidosis (n = 3); infiltrative heart disease not otherwise specified (n = 3); congenital heart disease (n = 2); abnormal ventricular function (n = 2); ventricular septal defect (n = 1); lymphoma with suspected myocardial invasion (n = 1); coronary artery disease (n = 1); pericarditis (n = 1); suspected mass (n = 1); myocardial infarction (n = 1). Of the 20 patients who enrolled in the study, 3 had sternal wires, 1 had spinal hardware, and 1 had a prosthetic mitral valve. The following imaging parameters were used, adjusted for body habitus: FOV = 34–40 cm; phase FOV = 65–90%; slice thickness = 2.4–4 mm; matrix size = 256×160 ; number of sections = 44–50; true resolution = $1.3 \times 1.5 \times 3 \text{ mm}^3$, $1.6 \times 2.1 \times 3 \text{ mm}^3$ (interpolated to $1.3 \times 1.3 \times 1.5 \text{ mm}^3$, $1.6 \times 1.6 \times 1.5 \text{ mm}^3$); TE₁ = 1.2–1.4 ms; TE = 1.0–1.2 ms; TR = 6.4–7.4 ms; flip angle = 15°; receiver bandwidth = $\pm 143 \text{ kHz}$; DAQ duration = 64–130 ms (10–18 views per segment); trigger window = 10%; trigger delay = $\sim 70\%$ R-R interval. Total scan time was approximately 8–12 min, depending on the spatial coverage, breathing pattern and navigator efficiency (30–40%).

Images were evaluated for overall image quality and level of residual artifacts by the same two radiologists who performed the qualitative evaluation for the comparative study performed in healthy volunteers. The same four-point Likert scale was used.

Results

Comparative Study in Healthy Volunteers

Diagnostic images were successfully acquired in all volunteers with all pulse sequences. CSE-SPGR performed similarly to SPGR with fat saturation in terms of overall image quality, level of residual artifacts and quality of fat suppression (Table 1). When evaluated over the whole FOV, fat saturation resulted in incomplete fat suppression of subcutaneous fat. Although fat saturation and CSE resulted in similar ratings in terms of residual artifacts, probably due to the small amount of subcutaneous fat found in this small cohort of healthy volunteers, incomplete fat suppression within the chest wall can lead to increased levels of ghosting due to respiratory motion in the presence of significant fat deposits. Balanced SSFP performed worse than CSE-SPGR in all three categories (Table 1), probably due to imperfect shimming and increased sensitivity to off-resonance. Figure 3 shows representative CSE-SPGR, SPGR, and balanced SSFP images acquired in a healthy volunteer.

Preliminary Evaluation in Patients

Images of diagnostic quality were successfully acquired in all patients. Representative water-only (a, c) and fat-only (b) images acquired in a 19-year-old patient with single ventricle and Fontan repair are shown in Figure 4. Uniform fat suppression was obtained over the whole FOV, including the two areas of severe off-resonance produced by the sternal wires and spinal hardware shown in Figure 4a (white arrows). In this case, a true resolution of $1.3 \times 1.5 \times 3 \text{ mm}^3$ (interpolated to $1.3 \times 1.3 \times 1.5 \text{ mm}^3$) provided excellent delineation of the anatomy irrespective of the plane of reformat. Figure 5 shows representative water-only images acquired in a 37-year-old patient with hypertrophic cardiomyopathy (a) and a 51-year-old patient with a prosthetic mitral valve (b). In both cases, good fat suppression can be observed around the heart, thus providing clear anatomical depiction. Oblique (a,b) and curved (c,d) reformats of the right coronary artery of a 38-year-old patient evaluated for CAD performed on water-only (c) and fat-only images (d) are shown in Figure 6. In this case, the almost binary contrast in the fat image provides improved visualization and characterization of the right coronary artery, complementing the information contained in the water-only image.

Good water–fat separation was obtained in all cases. In five cases, small, clinically insignificant water–fat swaps were observed at the very edge of the FOV, in proximity to tissue–air interfaces. Excellent fat suppression was obtained in proximity to all metallic implants. Overall image quality was graded as either good or excellent in all but one case characterized by extensive motion artifacts due to a marked increase of the heart rate during the scan (Fig. 7). Significant artifacts occurred in 5 of 20 cases. The two most common artifacts were residual motion artifacts due to irregular heart rate during the scan and signal drop-out in proximity of the lateral wall of the left ventricle due to residual B_1 shading. Of note, these artifacts did not disrupt the quality of the water–fat separation in any case.

Discussion

In this work, we describe the development of a 3D multi-echo SPGR pulse sequence with ECG gating and navigator echoes for whole heart water–fat imaging during free-breathing. This method allows for flexible use of echo times with variable number of echoes, as well as the use of spectral modeling of fat and R_2^* correction.

Furthermore, we evaluated its performance in healthy volunteers and patients undergoing clinical CMR examinations. In healthy volunteers, CSE-SPGR performed similarly to SPGR with fat saturation in terms of overall image quality, level of residual artifacts and quality of fat suppression around the heart. However, CSE-SPGR resulted in more uniform fat suppression over the whole FOV than conventional fat saturation, which further reduced residual breathing artifacts from subcutaneous fat. Both CSE-SPGR and the conventional SPGR protocol with chemical fat saturation performed better than balanced SSFP, which is consistent with previous findings at 3T (35). CSE-SPGR was also found to provide consistent and robust fat suppression near metallic implants, where fat saturation is known to fail due to severe off-resonance. Similar image quality was obtained with and without contrast agent, which suggests a potential application of this technique for imaging children and subjects with a contraindication for contrast administration. In particular, this technique

could be useful for morphological assessment of complex anatomy in children as minimal cooperation for repeated breath-holding is required.

The main disadvantages of CSE-SPGR are the relatively long acquisition times and the increased susceptibility to heart rate variations and eventual drifts in the respiratory pattern. In the comparative study performed in healthy volunteers, CSE-SPGR took approximately twice as long as 3D SPGR and balanced SSFP with conventional fat saturation. However, in these reference sequences, which are part of the clinical protocol routinely used at our institution, the user can only choose over how many RR intervals (two or four) to segment each k_x - k_y plane. For the resolution used in the volunteer study, segmenting the acquisition over 2 RR intervals gave a DAQ duration similar to CSE-SPGR (i.e., approximately half the scan time because only one TR per view is acquired). However, depending on the heart rate, the number of views per segment resulting from increasing the segmentation factor to 4 might be considerably lower than the number of views per segment used in CSE-SPGR, thus resulting in comparable scan times.

Two-point Dixon methods are intrinsically faster and have been shown to provide excellent water-fat separation over the whole heart (5). However, depending on the specific implementation, they might require specific echo times and generally more sophisticated reconstruction techniques to avoid water-fat swaps in areas of large field map variations. Bipolar readout gradients with phase correction could also be used to reduce the repetition time and overall duration of the acquisition at the expense of increased complexity in the reconstruction pipeline (36). In this work, we used an ARC acceleration factor of 2 in both phase encoding directions that reduced scan time to less than 10 min, with 30–40% navigator efficiency. Recent work performed by several groups aimed at combining compressed sensing with parallel imaging and efficient water-fat separation algorithms (37–39) could provide further acceleration while limiting residual artifacts due to irregular cardiac rates and/or breathing patterns.

In our experience, navigator gating and the robust fat suppression provided by CSE-SPGR were found to reduce residual breathing artifacts to acceptable levels. Additional spatial presaturation pulses or placing the phase encoding direction along the R/L direction could further reduce breathing artifacts at the expense of longer scan times (5). To compensate for cardiac motion, data acquisition was limited to a narrow end-diastolic window, however, significant changes in the heart rate, which are more likely to occur during long acquisitions, can severely degrade image quality. Arrhythmia rejection checks could potentially reduce blurring due to variations in the heart rate at the expense of a reduced efficiency, although their applicability is often incompatible with certain pathology. Self-gated techniques, on the other hand, could provide more reliable synchronization of MR image acquisition to the diastolic phase of the cardiac cycle while also providing synchronization to the respiratory cycle (40).

Bornert and colleagues have recently proposed a similar two-point Dixon method for whole-heart CMRA at 1.5T (5). Both this technique and CSE-SPGR use chemical shift encoding to obtain robust fat suppression over the whole FOV while providing whole-heart coverage during free-breathing. However, the two methods are fundamentally different and essentially

target different applications. The method described by Bornert et al (5) is intrinsically faster than the method proposed here because only two echoes are required. While this is a clear advantage, it also entails additional limitations in terms of the maximum resolution achievable with this technique due to the reduced flexibility in the choice of echo times and a reduced SNR performance with respect to multi-echo methods.

An advantage of the proposed method over previous two-point Dixon techniques for whole heart imaging is the possibility to obtain R_2^* maps in addition to the water and fat images. While the diagnostic utility of the fat image in the context of cardiac imaging is still debated (9), T_2^* ($=1/R_2^*$) is a well-known and widely accepted biomarker of cardiac iron overload whose importance has been extensively reported in the literature (41,42). One of the major challenges inherent to cardiac T_2^* mapping is the wide spectrum of T_2^* values to be resolved. Matching the acquisition echo times to the T_2^* values being measured in normal subjects would typically require prohibitively long scan times, unless specialized acquisition strategies are used to restore the reduced efficiency associated with the acquisition of long echo times (43). The shorter T_2^* values found in the presence of iron makes it easier to match the echo times. In this case, CSE-SPGR could produce T_2^* maps with sufficient SNR by simply increasing the number of echoes per TR while further accelerating the acquisition. This would also provide R_2^* -corrected water and fat images with no additional time penalty and allow accurate fat fraction quantification in the mediastinum. It should be noted that the importance of including T_2^* correction for qualitative water-fat separation is still under investigation and that currently available techniques might lack the precision required to differentiate between normal and pathological fat deposition in the myocardium outlined in recent studies (16,44). In our group of patients, none had cardiac iron overload and inclusion of R_2^* in the signal model added noise to the solution without affecting significantly the water-fat separation, even in the presence of metal.

The main limitation of this study is the small sample size and the fact that the comparative study with SPGR and balanced SSFP with fat suppression was performed in healthy volunteers. Another limitation consists in the lack of a direct comparison between the proposed technique and similar 2-point methods that have been recently shown to provide excellent image quality and fat-water separation (5). Finally, most of the potential advantages of CSE-SPGR over 2-point methods were not practically demonstrated due to the prohibitively long scan time that would result from higher-resolution imaging or acquiring more than 4 echoes for R_2^* mapping in the normal myocardium. Unfortunately, cardiac iron overload is extremely uncommon at our institution as the majority of iron overload results from transfusional hemosiderosis rather than thalassemia.

In conclusion, we have developed a CSE technique for whole-heart imaging during free-breathing and evaluated its performance in healthy volunteers and patients undergoing conventional CMR examinations. Good image quality and excellent fat suppression were obtained with and without contrast administration at 3T, which makes the proposed method particularly suitable for the assessment of complex anatomy in uncooperative patients or when the injection of contrast material is contraindicated. Although encouraging, the obtained results should only be regarded as preliminary, due to the small number of healthy volunteers and patients who participated in the study, and further evaluation in a larger

cohort of patients with a wider spectrum of pathologies is warranted. Future technical developments will focus on further reducing scan time while improving robustness to cardiac and breathing motion by using more advanced sampling patterns/reconstruction techniques and more robust synchronization methods.

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Fig. 1.

Multi-echo 3D SPGR pulse sequence with 4 echoes acquired in 2 interleaves using fly-back gradients (a) and acquisition scheme (b). Prospective cardiac gating and navigator echoes were used to synchronize the acquisition to the cardiac cycle and respiratory waveform, respectively. A T_2 preparation period before data acquisition provided improved contrast between the blood pool and the myocardium. N phase encoding lines, with N determined by the ratio between the prescribed data acquisition window duration (70–100 ms) and actual TR, were acquired per R-R interval.

Fig. 2.

Sampling pattern and segmentation strategy used for the proposed CSE SPGR technique. Corner cutting (80%) and 2D ARC with $2 \times$ acceleration in both phase encoding directions were used to speed up the acquisition. A segmented acquisition scheme with center-out view ordering within each segment was used to acquire all k_y views corresponding to a given k_z before moving to the next k_z . In this schematic representation, every color represents a different segment. Acquisition starts at $k_z = 0$ with the central portion of k-space (red) acquired in the first segment. Outer k-space segments are then consecutively sampled with center-out view ordering within each segment (black, magenta, cyan, yellow, etc.). Dummy excitations are performed in the outermost segment when the required number of views is less than that in the corresponding inner segments.

Fig. 3.

Representative axial (**a,c**) and short axis views (**b**) acquired in a healthy volunteer with the proposed chemical shift encoded (CSE) SPGR technique and 3D SPGR and balanced SSFP with fat saturation. Imaging parameters and acquisition duration was similar in all cases. Note the improved fat suppression achieved with CSE-SPGR over the whole FOV when compared with both SPGR and balanced SSFP with fat saturation (white arrows). Close to the heart, CSE-SPGR and SPGR with fat suppression performed similarly both in terms of overall image quality and quality of fat suppression, while balanced SSFP showed worse fat suppression (black arrows) and a higher level of residual artifacts (white broken arrow) due to increased sensitivity to off resonance.

Fig. 4.

Representative water-only (a,c) and fat-only (b) images acquired in a 19-year-old patient with single ventricle and Fontan repair. Note quality of fat suppression in proximity to the sternal wires and spinal hardware (arrows) and visualization of the trabeculae and ventricular anatomy in the different reformats (resolution = $1.3 \times 1.3 \times 1.5 \text{ mm}^3$).

Fig. 5.

Representative water-only images acquired in a 37-year-old patient with hypertrophic cardiomyopathy (resolution = $1.4 \times 1.4 \times 1.5 \text{ mm}^3$) (a) and a 51-year-old patient with a prosthetic mitral valve (resolution = $1.4 \times 1.4 \times 1.5 \text{ mm}^3$) (b). Note anatomical detail in proximity of prosthesis (arrows) and shading artifact in the lateral wall of the left ventricle probably due to residual B_1 shading and/or coil coupling effects. This artifact was typically observed also in other conventional pulse sequences routinely used to evaluate cardiac morphology and function and is most likely unrelated to our implementation of CSE-SPGR.

Fig. 6.

A 38-year-old evaluated for CAD. Oblique (**a,b**) and curved (**c,d**) reformats of the right coronary artery (arrow) performed on water-only (**c**) and fat-only images (**d**). Note that in this specific case, the information provided by the fat-only image (**d**) improves vessel delineation and characterization when used in conjunction with the water-only image.

Fig. 7.

Evaluation of overall image quality and level of residual artifacts in 20 patients undergoing conventional CMR examinations (0: worst; 3: best). Overall image quality was graded as either good or excellent in all but one case characterized by severe motion artifacts due to a very irregular heart rate. This was the only case with less than diagnostic image quality. In 5/20 cases, residual motion artifacts and B₁ shading, typically observed in the lateral wall of the left ventricle, were such as to partly interfere with the diagnostic content of the images. In the remaining 15 cases, there were few or minimal artifacts.

Table 1
Comparative Study in Healthy Volunteers between CSE-SPGR, SPGR and Balanced SSFP (bSSFP) in Terms of Image Quality, Level of Residual Artifacts, and Quality of Fat Suppression

	Image quality	P-value	Level of residual artifacts	P-value	Fat suppression	P-value
CSE-SPGR	2.8 (±0.41)	–	2.5 (±0.55)	–	3.0 (±0.00)	–
SPGR	2.7 (±0.52)	0.6109	2.0 (±0.63)	0.2031	2.5 (±0.84)	0.2031
bSSFP	2.0 (±0.63)	0.0422 ^a	1.5 (±0.55)	0.0117 ^a	1.8 (±0.75)	0.0127 ^a

^a $P < 0.05$ was considered statistically significant.