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TECHNICAL REPORT

Off-Frequency Tuning Error Artifact in Steady-State Free Precession Cine Imaging Due to Adjacent Air-Filled Bowel

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ABSTRACT

Identification of common cardiovascular magnetic resonance (CMR) artifacts is important to optimal image acquisition quality and the avoidance of mistaken clinical diagnosis. We describe an off-frequency tuning error artifact observed during rapid steady-state free precession acquisitions in three patients and resulting in a dramatic appearance within the right and left ventricles. These artifacts were associated with large, adjacent air pockets within a loop of bowel or stomach and were eradicated by retuning of the magnetic resonance scanner's frequency. Awareness of this artifact, its cause and correction, should improve diagnostic image quality and avoid clinical diagnostic confusion. This report also heightens the need for a more robust shimming sequence for cardiac studies.

Key Words: Air–heart interface; Cardiovascular magnetic resonance; Off-frequency artifact; Megacolon; Shim; Steady-state free precession.

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INTRODUCTION

Interest in and clinical applications of cardiac magnetic resonance (CMR) have grown dramatically in recent years as a result of major improvements in hardware and the development of rapid image acquisition sequences. Cine imaging, in particular steady-state free precession (SSFP), has assumed an important role in imaging of the heart and is becoming increasingly used (Carr et al., 2001; Mohiaddin, 2002). In spoiled gradient-echo cine imaging using low flip angles, the MR signal is discarded (spoiled) after each radio frequency (RF) excitation to avoid cross-contamination of signals from different RF excitations. However, this sequence suffers from diminished signal amplitude and hence a low signal-to-noise ratio. With SSFP sequences, rapid, repetitive excitation pulses induce a state of equilibrium for both longitudinal and transverse magnetization. True FISP (true fast imaging in steady-state precession) is a widely used steady-state sequence that uses fully balanced gradients.

True FISP imaging results in high signal intensity, white-blood images with excellent blood-myocardial contrast and favorable spatial and temporal resolution. Fast imaging in SSFP is especially useful for functional cardiac imaging. However, it demands very rapid gradient switching to reduce the time between RF pulses and minimize off-resonance artifact. Thus, sophisticated, automated tuning algorithms for optimization of magnetic field homogeneity (shimming) and for adjusting scanner frequencies have been incorporated into contemporary scanners.

Despite the high technical standards for current CMR scanner construction and the elaborate programs for achieving magnetic field homogeneity and tuning the scanner's operating frequency to the water resonance, artifacts still may arise and can complicate diagnostic imaging. In some cases, the artifact might prevent the visualization of important anatomic structures or be misinterpreted as a pathological finding, causing clinical confusion. Even if recognized as an artifact, the cause may be unknown and the approach to correction uncertain. Furthermore, these artifacts often are subject-related, suggesting subject-specific etiological factors.

Recognition of the artifactual basis of an image feature, understanding its cause, and discovering corrective strategies are important aspects of clinical CMR (Felmlee and Ehman, 1987; Hildebrand and Buonocore, 2002; Jaffer et al., 1996; Markl et al., 2003; Patton, 1994; Perman et al., 1986; Storey et al., 2004). We describe a not uncommon, and sometimes dramatic, CMR artifact presenting on true FISP sequences caused by a prominent gas-filled subdiaphragmatic structure in close proximity to the ventricles. We also provide a straightforward approach to correction.

METHODS

Case and Control Subjects

Three recent examples of this artifact were collected by the authors from subjects undergoing diagnostic CMR for various reasons at the Royal Brompton Hospital. These cases were highlighted because they represented such dramatic examples in which the diagnostic interpretation was hindered until

Table 1. Characteristics of patients and control subjects.

	Age	Sex	Diagnosis	Artifact site	Air pocket?
Case no.					
1.	54	M	ARVC	RV, LV	Yes (transverse colon)
2.	69	M	CAD, CHF	RV, LV	Yes (stomach, bowel)
3.	41	M	CP, Syn X	RV, LV	Yes (transverse colon)
Control no.					
1.	49	M	DCM	None	None
2.	50	M	TR, ?ARVC	LV (minor)	Stomach (max., 3.7 cm)
3.	67	M	AVR: AS/AI	None	None
4.	70	M	Angina	None	None
5.	46	M	Anemia	None	None
6.	43	M	HCM, MR	None	Stomach (3 cm; 4 cm from heart)

Abbreviations: ARVC = arrhythmogenic right ventricular cardiomyopathy; CAD = coronary artery disease; CHF = congestive heart failure; CP = chest pain; DCM = dilated cardiomyopathy; HCM = hypertrophic cardiomyopathy; LV = left ventricle; M = male; MR = mitral regurgitation; RV = right ventricle; Syn X = syndrome X; TR = tricuspid regurgitation.

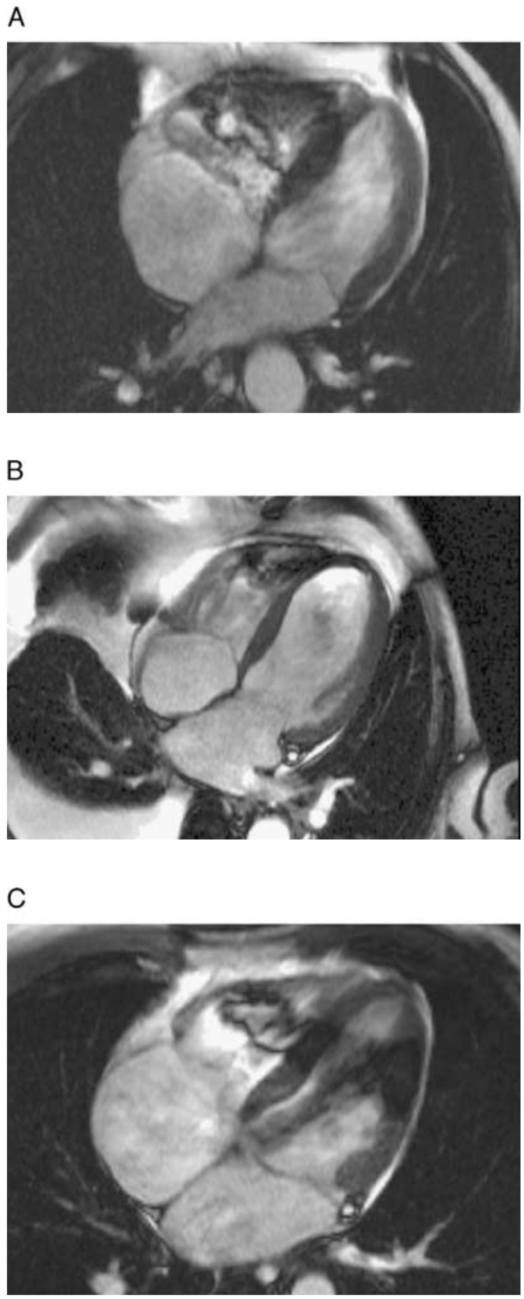

Figure 1. Severe off-frequency tuning error artifact (OFF-TEA) in midsystolic frames on horizontal long-axis (four-chamber view) steady-state free precession (SSFP) cine images for cases 1–3 (A–C).

the appropriate steps were taken to correct it. For each case, two controls were selected who were matched for the date of scan, gender, and age (within 5 years). The image effects of manually changing the scanner's operating frequency for blood was explored on true FISP sequences in two additional subjects undergoing scanning. Ten normal volunteers, who had received CMR studies for educational purposes, served as an additional control group.

CMR Equipment

All studies were performed between April 2002 and May 2003 on a 1.5-T clinical MRI system designed for CMR studies (Sonata, Siemens Medical, Erlangen, Germany). The end-expiratory breath-hold cine SSFP sequence used 3.3 ms between RF pulse, 7 mm slice thickness (SLT), 1.2 mm by 1.9 mm (phase-encode) uninterpolated pixel size, field of view (FOV) approximately 370 mm by 250–300 mm (phase-encode), 25 ms cine frames. A four-element phased-array (2 anterior, 2 posterior) receiver coil was

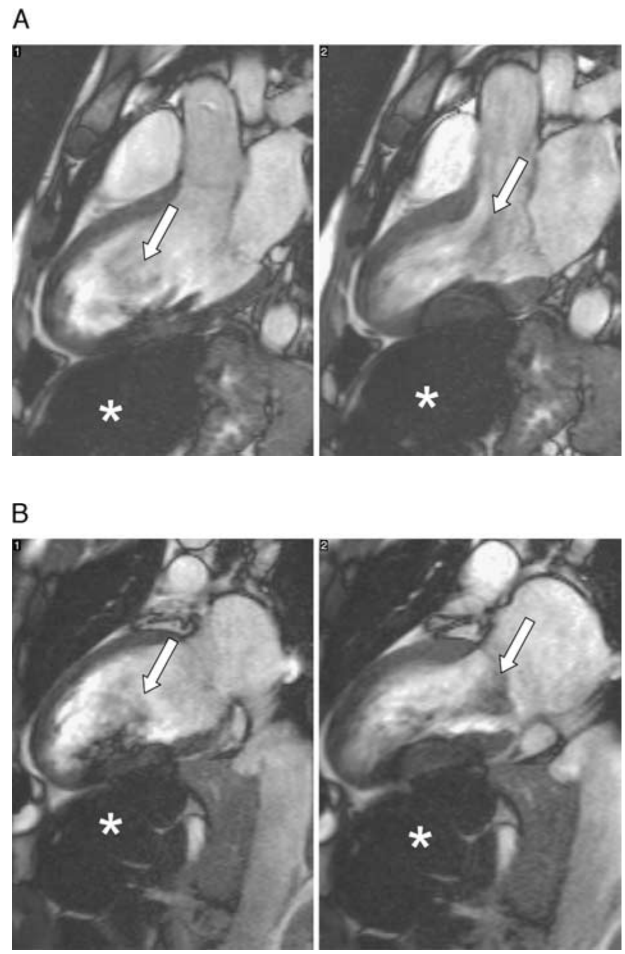

Figure 2. SSFP sequence, oriented in the apical (A) and vertical (B) long-axis (three-chamber and two-chamber views, respectively) of case 2 highlighting the relationship of the subdiaphragmatic air-filled bowel (*) and the adjacent OFF-TEA (arrow). Diastole: left. Systole: right.

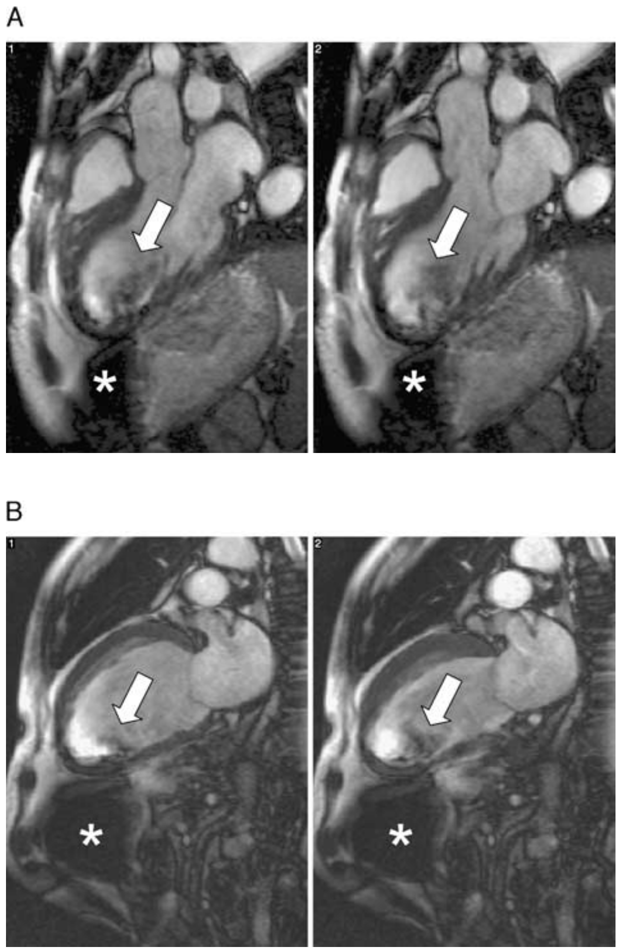

Figure 3. Case 3. Same description as in the legend for Fig. 2.

used. The SSFP sequence ran continuously for maintenance of the steady-state precession, with cardiac-gating control of the phase-encoding and data sampling.

Study Hypothesis and Image Analysis

All FISP images, obtained as part of the clinical studies, were carefully reviewed for the presence, location, and characteristics of imaging artifact. Assessment was made qualitatively and descriptively. The off-resonance tuning-error artifact (OFF-TEA) in FISP is well known to cause dark bands. In addition to the dark bands within the myocardium, their equivalent appearance was obvious in blood where these dark regions varied according to inherent dynamic flow patterns, cardiac cycle, and slice orientation. Due to the degree of the OFF-TEA, which extended through the blood-myocardial borders and was readily recognized as artifactual, the diagnostic information was significantly reduced. In the most recent example in our series, the patient had a massively dilated transverse colon (megacolon) that was potentially responsible for this artifact. On the basis of this observation and our clinical experience, we postulated that this artifact may indeed be created by large air–heart interfaces. Specifically, the subdiaphragmatic region was carefully inspected in transverse black blood spin echo sequence and vertical long-axis single slice and cine true FISP sequences in our clinical subjects and in prospectively selected, matched controls.

Approach to Artifact Correction

Two approaches to correction were examined: 1) reducing the volume for the calculation of shim adjustments, which has been suggested to correct ‘‘shimming artifacts’’ in other static, immobile organs, and 2) manual adjustment of the magnetic resonance scanner’s radiofrequency.

Verification of Off-Frequency Tuning Effects

To further verify the basis for the artifacts observed, manual adjustment of the scanner’s RF was made in a subject without an OFF-TEA in an effort to reproduce the artifact experimentally.

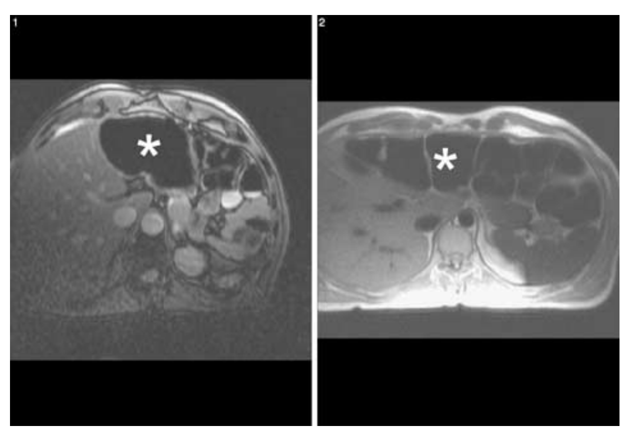

Figure 4. Transverse black blood spin echo multislice sequence at the subdiaphragmatic level for case 1 (left) and 2 (right) showing the extent of the air-filled bowel (*).

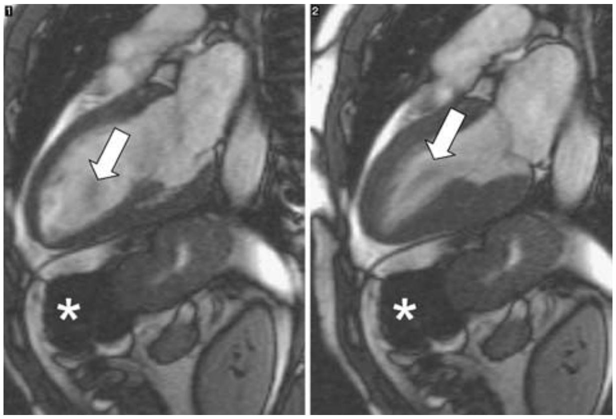

Figure 5. SSFP vertical long-axis image in case control 2. A small pocket of air (*) was noted in the stomach >4 cm below the heart border and created a mild OFF-TEA (arrow).

RESULTS

Artifact Characteristics

Characteristics of the three subjects are presented in Table 1. Cardiac diagnoses were diverse. Each artifact was readily apparent and predominantly located in the apical portion of the ventricular chambers of SSFP gradient echo sequences (true FISP). Figure 1 shows midsystolic frames for the three cases (Fig. 1A–C). Seen are moderate to large, black, off-resonance artifacts in blood and myocardium spanning approximately 40%–80% of the right ventricle (RV) and 5%–60% of the left ventricle (LV). These are in distinct contrast to the surrounding white blood. These undulating, swirling artifacts in cine displays are reminiscent of dense, black smoke and create variable degrees of clinical obstruction. They were most prominent in the systolic phases (Fig. 1), but they could be readily demonstrated throughout the cardiac cycle (Figs. 2 and 3). Although these artifacts are seen in different imaging planes, they vary in appearance depending on the direction of flow relative to the imaging plane.

The two-chamber (vertical long-axis) and three-chamber (apical long-axis) views of the left ventricle are extremely valuable in clarifying the relationship of the inferior and inferolateral borders of the myocardium and adjacent bowel (Figs. 2 and 3). These views provided the necessary insight into the marked adjacent bowel gas which was not visible on the most profoundly affected four chamber (horizontal long-axis) views. Other causes for the 'black smoke' initially considered during the routine clinical review of two of these cases included an apical thrombus with surrounding flow disturbance and a neighboring ferromagnetic object not identified in prescanning screening.

Adjacent Air-Filled Structures

In each of the three cases, a large air-filled, subdiaphragmatic loop of colon or stomach was present (Figs. 2 and 3). The diameter of the air sac was 6 cm or more. These were in close proximity (within 2 cm) to the heart. The full extent of air-filled bowel was readily noted on the initial transverse black blood spin echo sequence (Fig. 4).

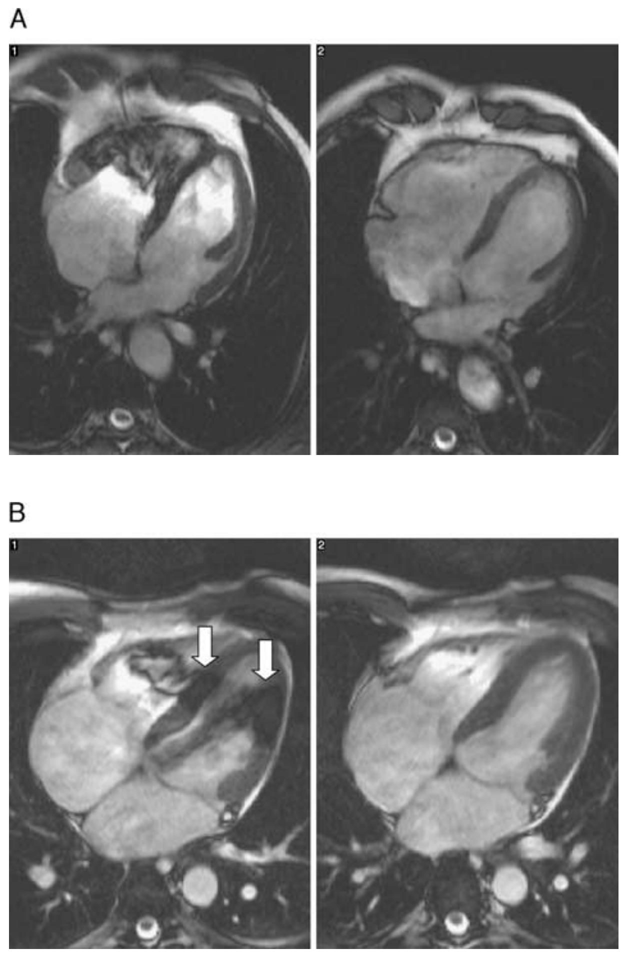

Figure 6. Elimination of the OFF-TEA was not achieved by reducing adjustment region for shim and automated RF correction (left) but was achieved by manually correcting the error in automated selection of tuning frequency (right). (A) Case 1. (B) Case 2. Note the involvement of the myocardium as well as the cavity (arrows).

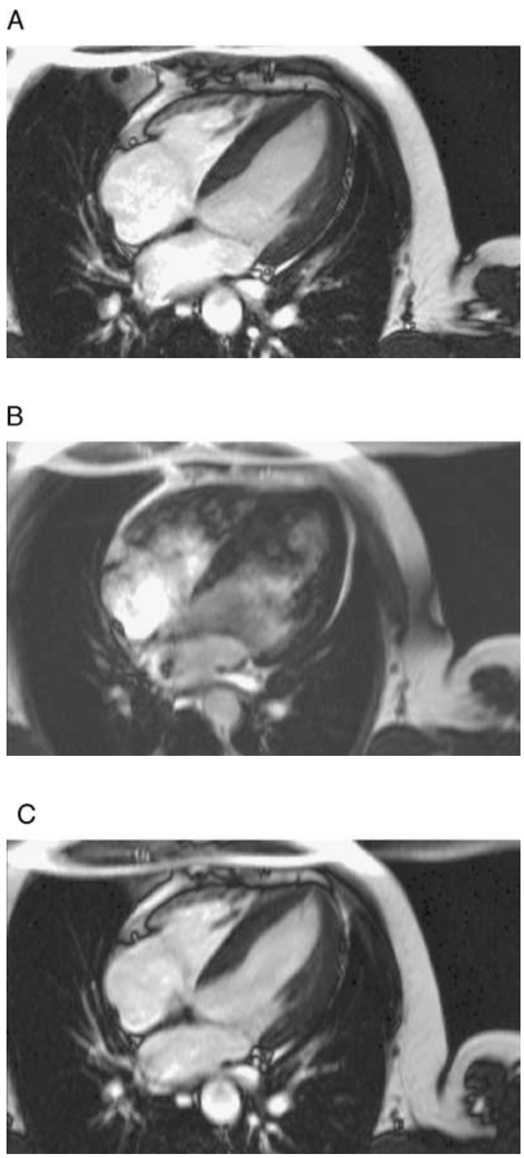

Figure 7. Creation of OFF-TEA by imposing a frequency-tuning offset in a randomly chosen subject. (A) Baseline. (B) After introducing off-frequency scanner RF tuning error (200 Hz above water resonance). (C) After correcting OFF-TEA (retuned to the water resonance frequency). (Also see Fig. 8.)

Findings in Patient Controls

Five of six matched patient controls had neither OFF-TEA nor air pockets adjacent (within 2–4 cm) to the heart (Table 1). Control subject 2 had a small, faint, midcavity LV artifact that did not affect the clinical interpretation of the examination. This was associated with a 3.7-cm air bubble in the stomach that was more than 4 cm below the LV apex (Fig. 5). This patient had normal LV systolic function.

Corrective Maneuvers

Reducing the size of the region used by the scanner software for calculating the shimming adjustments was not successful in eliminating this cardiac artifact (Figs. 6A and B, left panel). However, adjusting the scanner's RF tuning proved successful (Figs. 6A and B, right panel).

Experimental Generation and Correction of Artifact

A readily apparent OFF-TEA was artificially generated in a normal individual by raising the system's RF arbitrarily by 200 Hz. Setting the RF back to the 'water-peak' baseline value corrected the artifact (Fig. 7A–C).

Study of Normal Volunteers

Among the 10 normal volunteers, 9 had neither a OFF-TEA nor an adjacent air pocket. One had a small-to-moderate artifact, primarily in the right ventricle. This was associated with an error in automated RF tuning which, with manual correction, eliminated the artifact. Figure 8 graphically displays the frequency

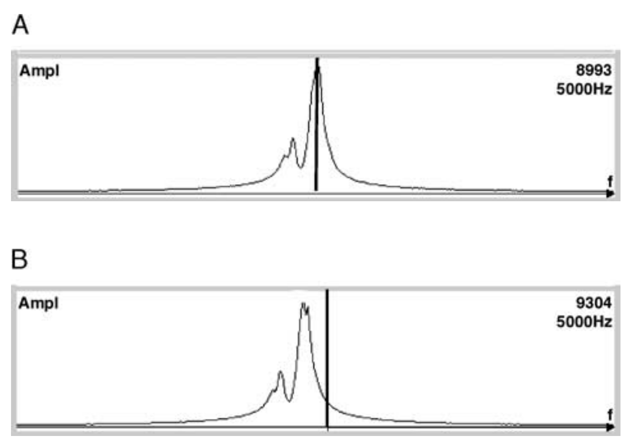

Figure 8. Representative display of fat (left peak) and water (right peak) frequency spectrums. The baseline automatic frequency option was 63.661808 MHz (A). The vertical black line, at 63.662009 MHz, shows representative position manually chosen to create the off-frequency tuning error artifact shown in Fig. 7B (B).

spectrum obtained from the scanner's clinical user interface illustrating fat and water resonant frequencies for this subject (Fig. 8). Manually adjusting the resonant frequency to tune into the water peak eliminated the artifact.

Frequency Difference in Air-Filled Pockets in Cases vs. Controls

Comparing the three cases with the large air-filled bowel cavities with the 16 patient and volunteer controls (with 2 smaller air-filled bowel cavities) yielded a statistically significant difference (3/3 vs. 2/16; p value=0.01; Fisher's exact test).

DISCUSSION

In the present report, we identified and described a prominent artifact seen throughout the cardiac cycle (with systolic accentuation) in the right and to a lesser degree the left ventricular chambers. The artifact was specific to rapidly acquired SSFP sequences as used routinely for cardiac cine images (i.e., true FISP). Three obvious examples from a busy CMR laboratory are provided. These were compared with small groups of matched controls as well as normal volunteers. Strikingly, the artifact was always associated with a large, air-filled cavity in close proximity to the ventricular chambers. In these cases, a subdiaphragmatic, dilated, air-filled loop of bowel or stomach was the offending structure. The general absence of air-filled cavities in controls and normal volunteers without artifact supported the association.

The finding of a minor artifact of the same type in 1 of 6 control patients and 1 of 10 normal volunteers suggests that the artifact is sufficiently common to warrant recognition. Furthermore, the severity of the artifacts used in these illustrations highlight the clinical impact of these which at times may render a CMR examination nondiagnostic.

The mechanism of artifact generation was only partially explored in this study. Rapid steady-state gradient echo sequences, such as true FISP, have been highly successful in producing cine images of moving structures such as the heart, with favorable temporal and spatial resolution, but they are known to be susceptible to off-resonance and other artifacts. We have shown that this OFF-TEA may also be created by nearby and large air-heart interfaces. We postulate that this interface hampered with the automated detection of resonance frequency for water, leading to cancellation rather than enhancement of rephased transverse magnetization in the area of artifact.

Other investigators have supported the concept that prominent air-heart interfaces can create susceptibility artifacts. In a study designed to evaluate the cause of these artifacts, Atalay and coworkers performed CMR with a 3-T system in a porcine model (Atalay et al., 2001). They showed that the primary cause of susceptibility artifacts along the inferoapical myocardial margins was the heart-lung interface. Importantly, they were able to completely eliminate the artifact after performing a lung resection as their sole corrective measure.

Beyond the association with an adjacent air-heart interface, the study clearly identified the mechanism of the artifact to be an off-frequency tuning error. This was shown in three ways: 1) correction of the artifact prospectively by manually adjusting the tuning frequency in case 3, 2) correction of the artifact in a normal volunteer in the same fashion, and 3) creating the artifact by introducing a tuning error and then eliminating it by returning to baseline values in a randomly selected subject without baseline artifact undergoing routine clinical imaging. Notably, reducing the size of the volume used for shimming adjustment, suggested as an approach to correct ''shimming'' artifacts in stationary organs, was ineffective in the highly mobile heart. The sequences for automated shim and RF adjustment require special properties for cardiac applications, such as motion insensitivity. The ungated, nonbreath-hold shimming sequence available for this work was also motion sensitive and, therefore, did not function well on the heart without gating.

Frequency shifting has been successfully used by others to reduce OFF-TEA, which occurs with three-dimensional true-FISP coronary artery-imaging sequences (Deshpande et al., 2003). Modifying the central frequency in steps of approximately 100 Hz and rescanning until the artifacts are reduced or eliminated is one such method. Furthermore, these investigators performed a similar frequency adjustment method to determine the optimal frequency offset for the fat saturation pulse and were then able to improve fat suppression.

Study Limitations

The study is descriptive and limited by small numbers. Also, although the artifact described appears to be common, an exact prevalence was not established. The association with a neighboring air pocket within the gastrointestinal tract was consistent in our series, but we cannot exclude other potential subject-specific causes.

Summary and Implications

Identification of common CMR artifacts is important for improving image quality and avoidance of false diagnosis (e.g., apical thrombus, flow disturbances, and presence of hepatic or other ferromagnetic sources). We describe here an off-frequency tuning error artifact observed during rapid steady-state precession acquisition that resulted in dramatic visual alterations within the cardiac chambers and myocardium. The artifacts in our cases were associated with unusually large and adjacent air pockets within the gastrointestinal tract and were corrected by manual adjustment of the scanner's radiofrequency. Awareness of this artifact, its cause, and correction should improve diagnostic image quality and avoid clinical diagnostic confusion.

CONCLUSIONS

Cardiovascular magnetic resonance imaging using steady-state free precession technique is now widely available and widely applied. It has greatly enhanced image quality, especially in functional cardiac studies due to the excellent contrast between the blood pool and myocardium. However, this method is sensitive to off-frequency tuning artifact as shown in this report. Awareness and understanding of its cause and correction is important. This report also heightens the need for a more robust automated shimming sequence for cardiac studies. The essential ingredients for a robust automatic cardiac shimming sequence should include ECG gating and breath-hold or other respiratory correction methods for the same respiratory phase as used in imaging.

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