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Motion-Robust Cardiac B_1^+ Mapping at 3T using Interleaved Bloch-Siebert Shifts

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Abstract

Purpose—To develop and evaluate a robust motion-insensitive Bloch-Siebert shift based B_1^+ mapping method in the heart.

Methods—Cardiac Bloch-Siebert B_1^+ mapping was performed with interleaved positive and negative off-resonance shifts and diastolic spoiled gradient echo imaging in twelve heartbeats. Numerical simulations were performed to study the impact of respiratory motion. The method was compared to 3D actual flip angle imaging (AFI) and 2D saturated double angle method (SDAM) in phantom scans. Cardiac B_1^+ maps were acquired in six healthy volunteers, using Bloch-Siebert and SDAM in different views (SHAX, 4CH, 2CH) during breath-hold and free-breathing. In vivo maps were evaluated for inter-view consistency using the correlation coefficients of the B_1^+ profiles along the lines of intersection between the views.

Results—For the Bloch-Siebert sequence numerical simulations indicate high similarity between breath-hold and free-breathing scans and phantom results show low deviation from the 3D AFI reference (normalized-root mean square error, NRMSE=2.0%). Increased deviation is observed with 2D SDAM (NRMSE=5.0%) due to underestimation caused by imperfect excitation slice-profiles. Breath-hold and free-breathing Bloch-Siebert in vivo B_1^+ maps are visually comparable with no significant difference in the inter-view consistency ($p>0.36$). SDAM shows strongly impaired B_1^+ map quality during free-breathing. Inter-view consistency is significantly lower than with the Bloch-Siebert method (breath-hold: $p=0.014$, free-breathing: $p<0.0001$).

Conclusion—The proposed interleaved Bloch-Siebert sequence enables cardiac B_1^+ mapping with improved inter-view consistency and high resilience to respiratory motion.

Keywords

Cardiac imaging; abdominal imaging; B_1^+ mapping; Bloch-Siebert shift; motion robustness

Introduction

The advent of quantitative tissue characterization of the myocardium, with its promise for prognostic and diagnostic value in a plethora of cardiomyopathies, has spiked great research interest (1,2) and triggered a large number of clinical studies (3–7). Available tools for MR-based quantitative tissue characterization in the heart include perfusion (8–10), T_1 (11,12), T_2 (13), T_2^* relaxation mapping techniques (14–16) and a combination thereof (17,18).

However, many of these approaches, including the most widely used method for myocardial T_1 mapping technique MOLLI (19), have previously been reported to be susceptible to the distribution of the radio-frequency (RF) transmit field (B_1^+) and the resulting excitation flip angle (20–23). This problem is particularly severe when moving to high and ultra-high fields, due to the increased heterogeneity of B_1^+ (24–26). It has been demonstrated in several targets (27–31), as well as in the heart (22), that MR-based quantification accuracy greatly improves when correction for B_1^+ is included. Therefore, obtaining reliable absolute B_1^+ magnitude maps ($|B_1^+|$) is critical to achieve accurate quantification in the presence of B_1^+ heterogeneity (32–35).

However, quantification of the transmit B_1 fields in the heart remains challenging due to cardiac and respiratory motion, and has received limited attention. Recent studies explored cardiac B_1^+ mapping using the saturated double angle method (SDAM) (36,37), where $|B_1^+|$ is derived from the ratio of two images acquired at different flip angles (38). In SDAM, an additional saturation preparation allows shortening of the repetition time (TR), as waiting for full magnetization recovery is no longer required. Schar et al. (37) proposed the use of SDAM for combined B_1^+ and B_0 mapping of multiple slices in a single breath-hold. To enable rapid image acquisition, accelerated spiral imaging was employed at low spatial resolutions. Similarly, cardiac B_1^+ mapping with SDAM was utilized for variable flip angle T_1 mapping by Clique et al. (22). In this application, k-space data readout was performed using echo planar imaging (EPI) to enable the data acquisition in a single breath-hold.

Breath-holding is most commonly used in these cardiac B_1^+ mapping methods for respiratory motion compensation. However, the acquisition of two separate images along with the use of segmented k-space readout schemes causes high sensitivity to motion. Hence, B_1^+ map quality may be critically impaired by residual motion, as commonly observed in patients despite breath-holding (39), and remains a major limiting factor for quantitative cardiac imaging.

Among recently proposed B_1^+ mapping techniques, the use of Bloch-Siegert shifts (40) obtained excellent results, enabling the acquisition of B_1^+ maps insensitive to T_1 and B_0 with short repetition times (TR). Here, an off-resonant pulse is used to induce a quadratically $|B_1^+|$ dependent phase shift. Bloch-Siegert shift based B_1^+ mapping emerged to one of the most widely used methods for transmit field mapping (41–44), including applications to non-proton MRI and spectroscopy (30,31,45). In a recent study, Bloch-Siegert phase shift based $|B_1^+|$ quantification was applied to the heart using a spectroscopic PRESS sequence (46). Although this approach cannot provide spatially resolved maps, as required for image

based parameter quantification, the results indicate improved robustness to respiratory motion.

In this study, we sought to develop a cardiac B_1^+ mapping method based on the Bloch-Siegert phase shift technique combined with an electrocardiogram (ECG)-triggered spoiled gradient echo (SPGR) imaging readout. The positive and negative off-resonance preparations were acquired in an interleaved manner to improve robustness to cardiac and respiratory motion. Numerical simulations and phantom imaging were performed to study sensitivity to motion and to validate quantification accuracy. In vivo experiments were conducted in six healthy subjects to compare the Bloch-Siegert method with the previously proposed SDAM with an EPI readout.

Methods

Sequence

In the proposed sequence, cardiac B_1^+ maps are acquired by measuring two $|B_1^+|$ dependent Bloch-Siegert shifts as previously proposed (40). The Bloch-Siegert shift is induced using off-resonant Fermi pulses. Imaging is performed with a two dimensional SPGR imaging readout. The sequence is performed with ECG triggering to allow imaging in diastolic quiescence. During acquisition, k-space is sampled in a segmented fashion with 10 lines of data acquired for each of the two Bloch-Siegert shifts (Figure 1). In order to minimize the impact of motion between images obtained with different Bloch-Siegert shifts, positive and negative off-resonance pulses are interleaved for each k-space line acquisition.

An off-resonant Fermi pulse was played between the slice rewinder and the phase encoding gradient lobes to induce the Bloch-Siegert phase shift: pulse duration $\tau_{BS}=8.0$ ms, off-resonance shift $\omega_{BS}=\pm 4.0$ kHz, bandwidth containing 99% of the pulse energy=2.1 kHz. Unless stated otherwise, the total energy of the Fermi pulse was chosen equivalent to that of a rectangular pulse with a nominal flip angle of 60° .

Cardiac Bloch-Siegert B_1^+ mapping was performed with the following imaging parameters: TR/TE=11.7/9.6 ms, nominal excitation flip angle= 10° , bandwidth=500 Hz/Px, FOV=320×320 mm², in-plane resolution=2.5×2.5 mm², slice-thickness=10 mm, scan-time=12 heartbeats.

Numerical Simulations

Numerical simulations were performed to predict the sensitivity of the proposed cardiac B_1^+ mapping method to respiratory motion. A numerical model of a cardiac short axis slice with compartments for myocardium, blood, epicardial fat, subcutaneous fat and liver was generated (47), with T_1 relaxation times of 1550/2500/380/380/810 ms, respectively (48,49). A static B_1^+ field was modelled with a linearly decreasing trend from foot to head for simulation purpose.

Respiration was simulated with sinusoidal diaphragmatic motion along the foot-head dimension. A respiratory frequency of 0.17 Hz was assumed with motion amplitudes between 0 and 3 cm corresponding to four intensities (i.e. breath-hold, shallow-breathing,

free-breathing, heavy-breathing) (50). The effect of breathing motion on the B_1^+ map quality was studied using Bloch simulations of the acquisition throughout the respiratory cycle. Dynamic changes in B_1^+ and B_0 throughout the respiratory cycle were neglected.

Imaging

All imaging was performed on a 3T scanner (Magnetom Prisma; Siemens Healthcare, Erlangen, Germany) using the standard body transmit RF-coil in dual-drive mode for excitation, with a 30-channel receive array. Standard B_1^+ calibration and shimming were performed, using the default techniques supplied by the vendor (TimTX TrueForm; Siemens Healthcare, Erlangen, Germany).

Phantom

B_1^+ mapping was performed in a cylindrical phantom, containing five spherical compartments with T_1/T_2 times in the range of in vivo muscle tissue (48).

The accuracy and linearity of the proposed technique was compared to the 3D actual flip angle (AFI) method (51), which was reported to show excellent flip angle accuracy in phantom measurements at 3T (41). This method acquires two interleaved images with different TR. The following sequence parameters were utilized: $TR_1/TR_2/TE=25/125/3.8$ ms, nominal excitation flip angle= $40-80^\circ$, bandwidth= 260 Hz/Px , $FOV=320\times320\times160\text{ mm}^3$, in-plane resolution= $2.5\times2.5\times5\text{ mm}^3$, scan time=10 min 20 s.

For further comparison, 2D SDAM, as previously applied for cardiac B_1^+ mapping, was performed with an EPI readout (22). The sequence parameters were: non-refocused EPI imaging train with 8 echoes, $TE=1.7$ ms, $TR=RR\text{-interval}$, nominal flip angle 1/ flip angle 2= $40-80^\circ/80-160^\circ$, bandwidth= 1500 Hz/Px , $FOV=320\times320\text{ mm}^2$, in-plane resolution= $2.5\times2.5\text{ mm}^2$, slice-thickness=10 mm, GRAPPA-factor=2, sequence duration=18 heartbeats.

For quantitative comparison the Bloch-Siegert sequence and SDAM were calibrated with respect to the reference 3D AFI method: The transmit power of the Fermi pulse in the Bloch-Siegert sequence and of the slice-selective excitation pulse of the lower flip angle in SDAM were chosen such that the resulting flip angle measurements were identical to 3D AFI at a nominal flip angle of 40° . Subsequently, the transmit power of the Fermi pulse in the Bloch-Siegert sequence and the excitation pulse in SDAM and 3D AFI, were linearly scaled by factors of 1.0, 1.25, ..., 2.0 corresponding to achieve nominal flip angles of 40° , 50° , ..., 80° , respectively.

Flip angles were measured from the B_1^+ maps obtained with the three methods using an ROI manually drawn in one of the phantom vials with a T_1 of 1270 ms that is similar to the healthy myocardium at 3T. The accuracy of the flip angle measurements using Bloch-Siegert and SDAM was assessed as the normalized root-mean-square-error (NRMSE) with respect to the 3D AFI method. Furthermore, all three sequences were validated by determining the linearity between the transmit power (nominal flip angle) and the measured flip angle, as previously proposed by Lutti et al. (52). The linearity was determined using the correlation coefficient.

In Vivo

The imaging protocol was approved by the local institutional review board, and written informed consent was obtained from all participants prior to each examination for this HIPAA compliant study. B_1^+ mapping was performed in six healthy volunteers (2 men, 33 ± 16 years old). Cardiac B_1^+ maps were obtained with the proposed Bloch-Siegert sequence and SDAM in three cardiac orientations: mid-ventricular short axis (SHAX), two chamber (2CH) and four chamber (4CH) views. SAR was recorded for all scans and compared between the two sequences. No in vivo comparison to the 3D AFI reference method was feasible, as there was no sequence variant for cardiac imaging available.

All scans were performed twice to study the impact of respiratory motion: subjects were instructed to hold their breath during the first acquisition, while the second acquisition was performed during free-breathing.

To quantify consistency between different orientations, the line of intersection within each pair of orientations (e.g. SHAX vs. 2CH) was independently identified for each sequence and each acquisition. Subsequently, this line of intersection was restricted to the region of the heart, by manually drawing ROIs excluding extracardiac tissue in both views. Consistency was defined as the correlation coefficient between the B_1^+ profiles along the cropped line of intersection in the two views. Statistical significance in the difference between the inter-view consistencies of the different methods at a specific breathing mode (breath-hold/free-breathing) across all orientation pairs was assessed using a mixed linear model analysis. Differences in the inter-view consistency of one method between the breathing modes for each pair of orientations were tested for statistical significance using paired Student's t-tests. For all tests p-values < 0.05 were considered to be significant.

Results

Numerical Simulations

Figure 2 shows the B_1^+ maps simulated with the numerical torso model for different breathing amplitudes. In Figure 2a, upper row, typical motion-induced ghosting artifacts of increasing severity at larger breathing amplitude are readily visible in the baseline images, however, good homogeneity and depiction of the linear B_1^+ field is observed in the maps. Although the B_1^+ profiles across the short axis of the heart from the right to the left lateral end clearly show local deviations in the presence of breathing in Figure 2b, high correlation is preserved even during heavy breathing: $R = 1.000/0.9973/0.9943/0.9928$ (breath-hold/shallow/free/heavy breathing).

Phantom

Figure 3 depicts the flip angle (average $\pm$ standard-deviation) for each method at all five flip angles. Flip angles assessed with the Bloch-Siegert sequence yield a NRMSE of 2.0% (range: -3.3% – 2.1%). SDAM showed higher NRMSE (5.0%) with underestimation of high flip angles by up to 7.5%, due to the well-known effect caused by non-rectangular slice-profiles of the slice-selective excitation (37). The linearity analysis showed excellent correlation between nominal and measured flip angle for both 3D AFI and Bloch-Siegert

B_1^+ maps, with regression coefficients of 0.9999 and 0.9996, respectively. The linearity of SDAM was slightly compromised by slice-profile effects, leading to a regression coefficient of 0.9990.

In vivo

Representative in vivo B_1^+ maps of the heart acquired with the proposed interleaved Bloch-Siebert sequence and the EPI SDAM are depicted in Figure 4, for acquisitions during breath-hold and free-breathing. For the breath-hold acquisitions, a visual inspection of the magnitude images and of the B_1^+ maps generated using the proposed method reveals a clear and smooth depiction of the B_1^+ pattern without noticeable artifacts. By contrast, the magnitude images acquired with SDAM are clearly contaminated by ghosting artifacts attributed to the segmented EPI acquisition. These ghosting artifacts persist in the calculated B_1^+ maps although the effect is reduced due to similar artefactual patterns in both baseline images.

For the free-breathing acquisitions, noticeable ghosting artifacts can be seen in the phase-encode direction of the magnitude images acquired using the Bloch-Siebert sequence especially at the level of the anterior chest wall. However, the area of the B_1^+ map covering the cardiac region is well preserved, reproducing closely the pattern measured in the heart under breath-hold conditions. By contrast, the free-breathing SDAM acquisition results not only in ghosting artifacts distributed over the entire field of view of the baseline images, but also in deeply altered B_1^+ maps, including deterioration in the cardiac regions, rendering these maps unusable.

Average in vivo scan times were 11.1 ± 1.9 s for the Bloch-Siebert sequence and 17.3 ± 3.2 s for SDAM. The SAR burden was significantly higher with the proposed method (0.49 ± 0.11 W/kg) compared with SDAM (0.043 ± 0.007 W/kg).

Figure 5a depicts representative B_1^+ maps acquired with Bloch-Siebert and SDAM in all three orientations during breath-holding. Exemplary lines of intersection, as used for the inter-view consistency analysis are indicated. The results of the quantitative inter-view consistency analysis are shown in Figure 5b. Two major observations can be made regarding the consistency analysis. First, for each of the three inter-view pairs, no significant difference was observed between the inter-view consistency of B_1^+ profiles obtained with the Bloch-Siebert sequence in breath-hold compared to that obtained in free-breathing, emphasizing the robustness of the Bloch-Siebert approach against respiration motion ($p > 0.36$). In contrast, SDAM resulted in a markedly reduced consistency between free-breathing and breath-hold B_1^+ profiles in SHAX vs. 4CH ($p < 0.029$). Second, regardless of the breathing status, the inter-view consistency across all orientation pairs obtained with Bloch-Siebert was always significantly greater than with SDAM. The mixed linear model analysis identified a significant effect of the sequence on the inter-view consistency (difference in consistency [95% confidence interval]): breath-hold: -0.26 [-0.47 – -0.06], $p = 0.014$; free-breathing: -0.43 [-0.60 – -0.26], $p < 0.0001$.

Discussion

In this work, we studied a cardiac B_1^+ mapping method based on interleaved Bloch-Siegert shifts induced by a Fermi pulse, followed by SPGR imaging. Despite the use of a segmented acquisition, interleaving the positive and negative off-resonance shifts for each k-space line enabled motion robustness in the cardiac B_1^+ mapping procedure by dramatically reducing the average delay occurring between the two final images. Higher B_1^+ map quality was obtained in comparison with SDAM. This difference was particularly strong during free-breathing.

Quantitative mapping of the transmit field in cardiac MRI is challenging due to the presence of cardiac and respiratory motion. To enable the acquisition in a single breath-hold, previous methods employed segmented acquisitions with rapid imaging techniques such as EPI or spiral readouts (36,37). These methods suffer from artifacts in cardiac applications, including susceptibility to motion, hardware inaccuracies and off-resonance effects (53). This hinders the integration into clinical scan protocols for cardiac applications. The proposed method enables the imaging to be performed with an SPGR Cartesian k-space readout, as commonly used in a multitude of clinical CMR sequences. This confers robustness against acquisition-specific artifacts, while relying on standard reconstruction techniques commercially available on most MRI systems.

The inter-view consistency analysis revealed a systematic trend of decreased consistency in pairs including the 2CH view when compared to the SHAX vs. 4CH pair in all $|B_1^+|$ measurements with both techniques. This is likely because the 2CH views showed flat B_1^+ profiles compared to other views throughout the study. This renders the correlation coefficient used in the consistency analysis more sensitive to small changes in the profiles slope.

Previously published approaches (36,37) employed 2D acquisitions of two separate images with different flip angles. Such approaches are inherently biased by the dependency between the assessed excitation flip angle and the actual slice-profile. Although, these inaccuracies can be mitigated by Bloch-simulation based corrections, residual error or T_1 dependence might remain (37). Furthermore, double-angle methods are most effective within a range where the higher flip angle is typically larger than 90° (54). This range does not include flip angles commonly utilized in SPGR cardiac sequences (typical flip angle is about $10\text{--}15^\circ$ (55)). The use of the Bloch-Siegert shifts, on the other hand, enables B_1^+ mapping that is independent of the excitation pulse. The B_1^+ encoding Fermi pulses are played separately from the excitation pulse, with a single slice excitation flip angle and profile maintained throughout the entire acquisition.

The proposed method derives B_1^+ maps, from GRE images acquired with comparably long echo times. However this renders the signal sensitive to off-resonance and flow effects, substantially compromising the baseline SNR compared with commonly used cardiac GRE sequences. Short T_2^* times ($15\text{--}25$ ms, (56)) especially in the lateral and apical parts, cause rapid signal decay after imaging excitation. Furthermore, “flow-void” effects were observed in previous studies with long TE GRE images ($TE = 12$ ms, (57)) in the presence of

turbulent jet streams of high velocities. However, flow induced signal-loss can be expected to be minimized by data acquisition during diastole, where flow velocities are an order of magnitude lower than jet stream velocities (58,59). Correspondingly, our data indicates that baseline SNR was sufficient for robust extraction of the phase-shift in this healthy cohort. However, chaotic flow patterns, as commonly observed in patients, or substantially shortened T_2^* , as observed in ultra-high fields, may potentially cause further reduction in SNR hindering robust phase extraction. Optimized designs for the off-resonant pulse (60,61) can be employed for these cohorts to substantially shorten the TE and minimizing the signal-loss.

Spatial variations in the flip angle have previously been reported to hinder the identification of regional variations induced by pathologies in cardiac MRI (62). Furthermore, B_1^+ mapping has been identified as one of the major cofounders in various quantitative imaging applications (21,23,28,63). Robust mapping of the transmit field, allows for identification of B_1^+ induced variations and facilitates accurate quantitative measurements (22,29,32,33,35).

Although 1.5T is still dominant in cardiac MRI, high-field systems are increasingly being used for cardiac applications. Due to dielectric effects that depend on the Larmor frequency, the transmit field inhomogeneity is significantly increased in high and ultra-high field applications (24). Cardiac imaging at ultra-high fields, e.g. 7 T, has recently been facilitated by major advances in hardware engineering (25,26,64), including the availability of multi-channel transmit systems. With these systems, B_1^+ shimming can be applied to adaptively combine excitation profiles of multi transmit channels/modes for homogenous excitation profiles (65–67). Additionally, tailored RF-excitation pulses have been proposed to compensate for transmit field variabilities (68–70). As robust B_1^+ mapping is a prerequisite for these B_1^+ shimming and tailored RF-excitation methods, it constitutes a crucial need for overall image quality at ultra-high fields. Additionally, the B_1^+ field around the heart at 7T has previously been shown to be dependent on the breathing-state, affecting the B_1^+ shimming and calibration (71). An extension of the proposed motion-robust cardiac B_1^+ mapping method to ultra-high field applications, potentially allows for robust B_1^+ mapping at various positions in the respiratory cycle. Inaccurate ECG-triggering is another challenge UHF cardiac imaging. Magnetohydrodynamic effects lead to frequent misdetections of the R-wave, potentially causing substantial variation in the cardiac phases of ECG-triggered sequences. Although, the proposed sequence showed good resilience to respiratory motion, no direct evaluation of the resilience to cardiac motion was performed in this study. The evaluation of cardiac motion sensitivity and the potential benefits of the proposed sequence for inaccurate ECG-triggering at 7T will be investigated in future studies.

However, SAR burden has previously been reported to be a major limiting factor for Bloch-Siegert sequences, with particular importance for ultra-high field imaging (72). Accordingly, the proposed Bloch-Siegert sequence shows significantly higher SAR compared with SDAM. This is primarily due to the high SAR contribution of the off-resonance Fermi pulse (61). Recently, improved encoding pulse designs (60) including adiabatic pulses (61) have been proposed to induce the Bloch-Siegert shift with increased SAR efficiency, enabling B_1^+ mapping at ultra-high fields. Reduced imaging flip-angles, and increased scan times might

be necessary to reduce the SAR load further. This will be studied in future research, to enable the use of the proposed B_1^+ mapping technique for cardiac imaging at 7T.

This study and the proposed methods have several limitations. The numerical simulations represented an idealized setting, with several simplifications on in flow effects, cardiac motion, and dynamic changes in the B_1^+ and B_0 fields throughout the respiratory cycle. Although 3D AFI was used as a reference method in phantom scans, no in vivo comparison to this method could be performed. Due to in flow effects, cardiac and respiratory motion, a cardiac implementation of this 3D steady-state sequence was beyond the scope of this study. While SDAM enables the acquisition of a slice stack with up to seven parallel slices in a single breath-hold, the Bloch-Siegert method as proposed here, only allows for the acquisition of a single slice. Accelerated data acquisition using, e.g. parallel imaging or simultaneous multi-slice imaging, can be used to facilitate multi-slice coverage in the proposed breath-hold sequence and will be subject of future studies. Despite the centric view-ordering, the use of the long end-diastolic imaging window warrants further investigation of the applicability in patients with tachycardia or substantial arrhythmias.

Conclusion

In this study, the use of an interleaved Bloch-Siegert SPGR sequence for cardiac B_1^+ mapping was demonstrated in vivo at 3T, with robust B_1^+ map quality in a twelve second breath-hold and high resilience to respiratory motion. Furthermore, a higher consistency between B_1^+ profiles obtained in different views was obtained compared to previously proposed methods. This indicates promise to improve quantitative imaging and RF pulse optimization for various cardiac applications.

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Figure 1.

Sequence diagram depicting the proposed cardiac Bloch-Siebert B_1^+ mapping sequence. A segmented spoiled gradient echo image acquisition is performed with ECG triggering to allow imaging during the diastolic quiescence. Images with negative and positive phase shift, as induced by an off-resonance Fermi pulse, are acquired in an interleaved fashion.

Figure 2.

Numerical simulations studying the sensitivity of the proposed cardiac Bloch-Siebert sequence to respiratory motion. Respiratory induced translational motion was simulated at four intensities (No motion, shallow, free and heavy breathing). Panel a) shows the effect on the simulated magnitude images and quantitative B_1^+ maps. Strong ghosting artifacts are readily visible in the magnitude images, while a clear depiction of the B_1^+ trend is maintained in the B_1^+ maps. Panel b) depicts the B_1^+ profile across the heart, at various breathing modes. High correlation of the B_1^+ profile is obtained even at heavy breathing.

Figure 3.

Phantom evaluation of the proposed Bloch-Siebert sequence and the SDAM EPI method in comparison to a reference 3D AFI method. a) Flip angle measurements (mean $\pm$ standard-deviation within a manually drawn ROI shown, with three B_1^+ mapping methods, at multiple nominal flip angles.

Figure 4.

Representative baseline images and corresponding B_1^+ maps in a cardiac four chamber view, acquired using the proposed interleaved Bloch-Siebert and the saturated double-angle method (SDAM) EPI, during breath-hold and free-breathing. Visually reduced artifact levels, good resilience to respiratory motion and clear depiction of the B_1^+ trend can be observed in the Bloch-Siebert B_1^+ maps.

Figure 5.

In vivo inter-view consistency of Bloch-Siebert and SDAM B_1^+ mapping. a) Representative breath-hold B_1^+ maps, with exemplary inter-view intersection lines, as used in the consistency analysis, indicated in black. b) Inter-view consistency of the B_1^+ profiles along the intersection lines for breath-hold and free-breathing scans. Significantly higher inter-view consistency is observed using Bloch-Siebert B_1^+ mapping with similar performance during breath-hold and free-breathing.