B₀ shimming of the human heart at 7T

Michael Hock¹ | Maxim Terekhov² | Maria Roxana Stefanescu¹ | David Lohr¹ | Stefan Herz¹,² | Theresa Reiter¹,³ | Markus Ankenbrand¹ | Aleksander Kosmala¹,² | Tobias Gassenmaier¹,² | Christoph Juchem⁴,⁵ | Laura Maria Schreiber¹

¹Chair of Cellular and Molecular Imaging, Comprehensive Heart Failure Center (CHFC), University Hospital Wuerzburg, Wuerzburg, Germany
²Department of Diagnostic and Interventional Radiology, University Hospital Wuerzburg, Wuerzburg, Germany
³Department of Internal Medicine I, University Hospital Wuerzburg, Wuerzburg, Germany
⁴Department of Biomedical Engineering, Columbia University, New York, New York, USA
⁵Department of Radiology, Columbia University, New York, New York, USA

Purpose: Inhomogeneities of the static magnetic B₀ field are a major limiting factor in cardiac MRI at ultrahigh field (≥ 7T), as they result in signal loss and image distortions. Different magnetic susceptibilities of the myocardium and surrounding tissue in combination with cardiac motion lead to strong spatio-temporal B₀-field inhomogeneities, and their homogenization (B₀ shimming) is a prerequisite. Limitations of state-of-the-art shimming are described, regional B₀ variations are measured, and a methodology for spherical harmonics shimming of the B₀ field within the human myocardium is proposed.

Methods: The spatial B₀-field distribution in the heart was analyzed as well as temporal B₀-field variations in the myocardium over the cardiac cycle. Different shim region-of-interest selections were compared, and hardware limitations of spherical harmonics B₀ shimming were evaluated by calibration-based B₀-field modeling. The role of third-order spherical harmonics terms was analyzed as well as potential benefits from cardiac phase–specific shimming.

Results: The strongest B₀-field inhomogeneities were observed in localized spots within the left-ventricular and right-ventricular myocardium and varied between systolic and diastolic cardiac phases. An anatomy-driven shim region-of-interest selection allowed for improved B₀-field homogeneity compared with a standard shim region-of-interest cuboid. Third-order spherical harmonics terms were demonstrated to be beneficial for shimming of these myocardial B₀-field inhomogeneities. Initial results from the in vivo implementation of a potential shim strategy were obtained. Simulated cardiac phase–specific shimming was performed, and a shim term-by-term analysis revealed periodic variations of required currents.

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1 INTRODUCTION

Ultrahigh-field MRI promises improved image quality as well as new image contrast for the assessment of the pathophysiology of the heart. However, inhomogeneities of the static magnetic field (B₀ field) are a challenge in cardiac magnetic resonance (CMR) imaging at 7 T. Different magnetic susceptibilities of the myocardium, surrounding tissue, and blood in combination with the particular geometrical shape of the heart lead to a complex spatial B₀-field distribution. The resulting macroscopic field gradients induce image distortions and lead to significant signal loss in measurements of myocardial microstructure due to a shortened effective transverse relaxation time T²*. In addition, cardiac and respiratory motion generate temporal B₀-field variations inside the heart between different cardiac phases and breathing positions. Standard CMR techniques used to assess cardiac function, such as balanced SSFP cine imaging, suffer from these B₀ inhomogeneities, as they create dark band artifacts, but SSFP-based techniques are not widely used at 7 T because of specific absorption rate constraints. Other fast imaging techniques, such as spiral readout trajectories and EPI, also require a homogeneous B₀ field. In particular at 7 T, the peak amplitudes of parallel-transmit RF pulse waveforms and amplitudes are optimized for a certain target range of the B₀-field offset to limit the required RF power and, thus, the specific absorption rate. Therefore, the spatial and temporal correction of the B₀ inhomogeneities is of high importance in CMR imaging at 7 T.

The homogenization of B₀ magnetic field distributions is usually referred to as B₀ shimming. Inhomogeneities of the static magnetic field increase linearly with the field strength, making B₀ shimming particularly important for ultrahigh-field MRI. The correcting shim field is typically generated by room-temperature shim coils, which are integrated into the MR system. The coils are located around the bore of the scanner and generate magnetic fields with spatial profiles based on the spherical harmonics (SH) functions. Shim systems in clinical 1.5T or 3T MR scanners are usually capable of creating magnetic fields up to the second order of the SH profiles (second-order shims). Based on the measured magnetic field distribution (B₀ map), a driving current is calculated for each shim coil and applied before subsequent measurements to homogenize the B₀ field. Particularly at 7 T, CMR may benefit from higher-order shim coils to compensate for the increased B₀ inhomogeneities compared with lower field strengths. The role of higher order and degree B₀ shimming was described for the human brain at 7 T. First-order to third-order shimming resulted in a substantial gain in B₀-field homogeneity over the entire region of interest compared with first-order to second-order shimming. However, such work is missing so far for B₀ shimming of the heart at 7 T, and it needs to be investigated whether higher-order (≥3) shims are beneficial for magnetic field homogenization.

There are several methods to map the magnetic field distribution. One-dimensional projection-based techniques measure the B₀ field along specific directions and offer the advantage of short measurement time. Projection B₀ mapping is most suitable to compute the SH components of local B₀ fields, which can easily be compensated by first-order and second-order shims. For complex spatial distributions of B₀ inhomogeneities over a large FOV, such as the entire heart, 3D volumetric techniques are another option. One example is the voxel-wise calculation of the B₀ map from the complex phase maps acquired at different TEs of a multi-gradient-echo pulse sequence. Both an appropriate spacing of the TE to obtain a sufficiently large dynamic range of the MR signal, and a sufficiently large SNR at the longest TE are important for this phase method. The approach is used in common shim tools such as customized BODETOX software.

So far, the B₀-field inhomogeneities inside the heart have been analyzed at 1.5 T, 3 T, and 4 T. At 7 T, B₀ inhomogeneities were considered both for an optimized saturation pulse train for human first-pass myocardial perfusion imaging, and for the design of parallel-transmit RF pulses robust against respiration in cardiac MRI. However, considerations for cardiac-specific B₀ shimming have only been addressed for 1.5 T and 3 T, and an analysis at 7 T is demanded. B₀-map calculation from phase maps acquired at two TE times, as used in clinical routine at lower field strengths, may be problematic at ultrahigh field due to an increased likelihood of multiple phase wraps, which are problematic to correct unambiguously. In addition, the temporal B₀-field variations between different cardiac phases are not addressed in the standard vendor-supplied B₀-shim protocols. The vendor-supplied shimming is performed for a cuboid-shaped volume, which is typically adjusted to the whole heart. However, B₀ shimming targeted to an
anatomy-driven shim region of interest (SROI) improved the field homogeneity in the heart at 3 T.\textsuperscript{8,29} The implementation of this approach at 7 T would be a first step toward dynamic shim updating (DSU)\textsuperscript{30,31} on subvolumes of the heart, which successfully reduced $B_0$ inhomogeneities in the brain at 7 T.\textsuperscript{16}

This work aimed to assess the spatial and temporal $B_0$-field variations in the myocardium of the human heart at 7 T. The following challenges for state-of-the-art cardiac $B_0$ shimming are demonstrated and discussed: (1) the SROI selection, (2) hardware limitations of the SH shim system, (3) the usefulness of third-order SH terms, and (4) potential benefits of cardiac phase–specific shimming (CPSS) (ie, DSU on cardiac phases). A potential shimming strategy is proposed, and its benefits and limitations for successful CMR imaging are discussed.

2 | METHODS

2.1 | Magnetic resonance imaging setup

All measurements were performed on a 7T whole-body MR system (MAGNETOM Terra; Siemens Healthineers, Erlangen, Germany). The scanner was equipped with 80 mT/m gradients and a partial third-order SH shim system; the coils corresponding to the third-order terms $Z_3$, $Z_2X$, $Z_2Y$, and $Z(X^2-Y^2)$ were available for $B_0$ shimming, whereas the coils for correcting terms $X_3$, $Y_3$, and $XYZ$ were not implemented. Imaging data were acquired with a 1TX/16RX thorax coil array (MRI Tools, Berlin, Germany). A vendor-supplied multi-gradient-echo pulse sequence in different modifications was then used to measure the field map data.

2.2 | Cardiac triggering

During all in vivo measurements, both the scanner-integrated electrocardiogram and an acoustic cardiac triggering (ACT) system (EasyACT; MRI Tools, Berlin, Germany) were permanently used to monitor cardiac activity.\textsuperscript{32} In contrast to the electrocardiogram, the ACT is not affected by magnetohydrodynamic effects and shows no interferences with electromagnetic fields produced by the gradient system. It detects the first heart tone of the phonocardiogram, which corresponds to the closure of the atroventricular valves at the beginning of systole. For this reason, the ACT was preferred for cardiac triggering according to a previous study,\textsuperscript{33} in which ACT was compared with vector electrocardiogram and pulse oximetry triggering in cardiac 2D cine imaging at ultrahigh field. The quality of the ACT signal depends on proper positioning of the stethoscope and could be degraded by potential additional noise interferences and patient breathing.

2.3 | Subject cohort

Eleven healthy volunteers were scanned after the approval of this study by the Ethics Committee of the University of Wuerzburg under application number 7/17-sc. Written, informed consent was obtained from each subject. The first 4 subjects, forming the training group (all female), were 25.0 ± 3.7 years old and had a body weight and height of 57.5 ± 3.7 kg and 165.8 ± 2.6 cm. Subjects 5 to 10, forming the study group (3 female, 3 male), were 23.7 ± 2.7 years old, had a weight of 73.5 ± 15.4 kg, and a height of 176.5 ± 9.4 cm. The eleventh subject scanned to validate the shim strategy was a male with a weight of 78 kg.

2.4 | Scan protocols for in vivo measurements

The training group measurements were performed to set up a scan protocol for the study group, which allowed us to assess the spatial $B_0$-field distribution across the heart, its temporal variation between systolic and diastolic cardiac phases, and different SROI selections. To assess functions of the heart chambers, CMR images are typically acquired in double-oblique slice orientations. However, arbitrary slice orientations are not supported yet by the software version used for the $B_0$-field simulation and shim computation. Thus, all data for the $B_0$-field mapping was acquired with transversal slice orientation.

2.4.1 | Spatial $B_0$-inhomogeneities

Middiastolic field-map data were acquired at an average trigger delay of 490 ± 66 ms with the following sequence parameters: $TE_1/TE_2/TE_3/TE_4/TE_5 = 1.7/2.8/4.0/6.0/9.7$ ms, $TR = 401$ ms, matrix = $128 \times 128$, $FOV = 300 \times 300$ mm$^2$, number of slices = 3, slice thickness = 6.0 mm, slice separation = 1.2 mm, flip angle = $25^\circ$, GRAPPA = 3, and number of segments = 29. The scan time, which was predetermined by a single breath-hold duration of 15 seconds, limited the data acquisition to a set of three parallel midventricular slices.

2.4.2 | Temporal $B_0$-field variations between different cardiac phases

The measurement of the $B_0$ field at various cardiac phases required an adjustment of the sequence parameters such as TR and number of TEs. Field-map data were acquired at eight cardiac phases equally spaced over an average RR interval of 970 ± 127 ms with the following parameters: $TE_1/TE_2/TE_3 = 1.7/2.8/4.0$ ms, $TR = 90$ ms, matrix = $128 \times 128$,
BO maps were therefore acquired after three adjustments of individually, and the shim system calibration is a necessity to-shim interactions, each SH component cannot be treated formed in MATLAB R2015b (MathWorks, Natick, MA) after the field-map data were exported from the shim software. GRAPPA = 2, and number of segments = 1.

2.4.3 Selection of shim-region-of-interest

An accurate SROI selection was demonstrated to be advantageous to obtain a homogeneous B0 field within the heart.8,29 B0 maps were therefore acquired after three adjustments of a transversal SROI cuboid using the vendor-supplied shimming platform: (1) volume-selective shimming covering the entire heart, (2) slab-selective shimming of the three measured slices, and (3) slice-selective shimming of only the central slice. No further anatomy-driven SROI selection was possible here. The vendor-supplied B0 mapping, which was performed in exhaled breath-hold position and without cardiac triggering at the shortest available first TE and interecho spacing,34 had the following default sequence parameters: TE1/TE2 = 1.02/3.06 ms, TR = 4.3 ms, matrix = 64 × 64, FOV = 282 × 282 mm2, number of slices = 52, slice thickness = 4.4 mm, slice separation = 0.9 mm, flip angle = 4°, GRAPPA = 2, and number of segments = 1.

2.5 B0-mapping

The B0 maps were reconstructed offline by voxel-wise linear regression of the signal phase evolution over TE in customized BODETOX shim software. Spatial phase unwrapping was performed using an algorithm of the FMRIB Software Library from the Oxford Center for Functional MRI of the Brain.35 Further analysis, such as calculation of SDs and interquartile ranges (IQRs) of the B0 distributions, was performed in MATLAB R2015b (MathWorks, Natick, MA) after the field-map data were exported from the shim software.

Temporal B0-field variations in the left-ventricular and right-ventricular myocardium were quantified as the differences in SDs (ΔSD) and IQRs (ΔIQR) between B0 maps acquired at systolic and diastolic cardiac phases. Here, the IQR represents the difference between the 25th and 75th percentiles of the frequency distribution within a B0 map.

2.6 Calibration of SH shim system

The B0-field distributions can be decomposed into SH components, and each term in inverse polarity is then required to correct the measured B0-field inhomogeneities. Due to shinto-shim interactions, each SH component cannot be treated individually, and the shim system calibration is a necessity for the computation of shim fields and corresponding currents.16 In addition, the total dynamic ranges (ie, the shim capabilities of each SH-term coil) are derived from the calibration process. The final calibration matrix, which yields all information on the particular SH terms and cross-terms, connects the calculated shim settings with the SH components of the B0 field before shimming and allows noniterative single-step adjustments.

The calibration measurements were performed on a spherical oil phantom using a 1TX/2RX birdcage coil (Siemens Healthineers, Erlangen, Germany). The value of each shim term was varied in seven steps relative to a reference B0 map using 10% of the dynamic range for the linear gradients, and 30% for the higher orders. For each shim setting, the field map data were acquired with the following sequence parameters36: TE1/TE2/TE3/TE4 = 1.0/1.3/2.0/4.0 ms, TR = 30 ms, matrix = 108 × 128, FOV = 186 × 220 mm3, number of slices = 64, slice thickness = 2.7 mm, flip angle = 25°, no parallel imaging acceleration was used, and phase maps for each TE were acquired in a single-echo experiment. The total dynamic ranges were: X = 2124 Hz/cm, Y = 2120 Hz/cm, Z = 2129 Hz/cm, X2-Y2 = 6.1 Hz/cm2, ZY = 12.6 Hz/cm2, Z = 40.2 Hz/cm2, ZY = 12.3 Hz/cm2, XY = 6.2 Hz/cm2, Z(X2-Y2) = 0.10 Hz/cm3, Z2X = 0.35 Hz/cm3, Z3 = 0.68 Hz/cm3, and Z2Y = 0.34 Hz/cm3.

2.7 Calibration-based shim-field analysis

The field map data were loaded into the shim software to reconstruct the B0 maps (“measured field map”) from the phase maps as described in section 2.5. The anatomy-driven SROI was selected manually on the magnitude images by the user. Afterward, the measured field maps were decomposed into SH components. The computation of the required shim fields was achieved by constrained least-squares fitting using the Levenberg-Marquardt algorithm,37,38 which was demonstrated to be most robust against changes in the starting-point values in comparison to other generic constrained nonlinear optimization methods.39 In the least-squares optimization, the resulting shim field could be limited to the dynamic ranges of the shim coils (ie, could be regularized to the hardware capabilities). Based on the determined SH components in the measured field map, a shim field (“simulated shim”), which is necessary to generate the individual field shapes in opposite polarity, and corresponding shim currents were computed.

2.7.1 Simulation of static shimming

The spatial B0-field distribution in the heart was assessed on middiastolic field-map data to avoid the effect of cardiac
motion resulting from ventricle contraction during the systolic phase.\textsuperscript{1,1} It was evaluated whether the dynamic range of each shim coil was sufficient to compensate for the corresponding SH component by not limiting the currents for the least-squares fitting during magnetic-field modeling. Moreover, the role of the third-order terms was evaluated by simulating three different shims: second order only, second order plus third order taking hardware limitations into account, and second order plus third order not considering those limitations. All three types of shims were simulated based on the unshimmed $B_0$ field, which was acquired under the system’s default shim settings using less than 5% current of the total dynamic range in each coil.

### 2.7.2 Simulation of cardiac phase-specific shimming

Time-resolved $B_0$ maps were acquired at eight equally spaced cardiac phases to evaluate the potential of CPSS. After adjusting the SROI and computing the shim settings for a SROI to be updated on each phase, the temporal variation of the individual shim terms was analyzed. Because the current MR system is not equipped with the hardware required for DSU, such as dedicated shim amplifiers, an averaged shim may be useful for cine imaging. This scenario was evaluated by simulating an averaged static shim, which applied the mean of all eight CPSS fields.

### 2.8 Implementation of potential shim strategy

A potential shim strategy was developed based on the study group measurements and implemented for in vivo shimming. The strategy consists of the following steps\textsuperscript{40,41}:

1. The triggered acquisition of middiastolic $B_0$ maps for three midventricular slices using ACT;
2. Manual, anatomy-driven SROI selection on the magnitude images in each slice in combination with a voxel-specific field-gradient threshold to exclude outliers;
3. The calibration-based SH $B_0$-field modeling in dedicated shim software and transformation of the field amplitudes in Hz/cm$^n$, where $n$ describes the order of the SH shim terms, to shim settings in hardware units; and
4. The application of the computed shim on the MR system and a repetition of step 1 as a control measurement of the $B_0$ field.

The measured magnitude images and phase maps were transferred from the scanner console to a dedicated workstation and loaded into the shim software. The $B_0$ maps were reconstructed as described in section 2.5, and an anatomy-driven SROI was selected on the magnitude images by the operator. The computation of the required shim fields and currents was performed as described in section 2.7. The resulting full set of shim settings could be exported from the shim software and be applied at the scanner console. The whole process takes about 6-8 minutes, in which most of the time is required for the manual anatomy-driven SROI selection and application of the shim settings on the scanner console.

### 3 RESULTS

The spatial $B_0$-field distribution inside the heart of a volunteer is shown in long-axis (LA) and short-axis (SA) views in Figure 1. In the LA view, high negative $B_0$-field distortions occur near the apex (1). In the SA view, high $B_0$-field inhomogeneities are present at the anterior (2) and posterior (3) part of the left-ventricular myocardium. The windowing of the long-axis and short-axis images was adjusted for visualization using the “adapthisteq” MATLAB function, which performs contrast-limited adaptive histogram equalization

![Figure 1](image)

**FIGURE 1** Anatomical views of the $B_0$ distribution inside the heart of a healthy volunteer. In the long-axis view, high negative $B_0$-field distortions occur near the apex (1). In the short-axis view, high $B_0$-field inhomogeneities are present at the anterior (2) and posterior (3) part of the left-ventricular myocardium. The windowing of the long-axis and short-axis images was adjusted for visualization using the “adapthisteq” MATLAB function, which performs contrast-limited adaptive histogram equalization.

A detailed histogram analysis of the spatial $B_0$ distribution within the heart showed that most data points were located within $\sim$100 Hz to 100 Hz. However, the extreme values were located in localized spots within the left-ventricular and right-ventricular myocardium (Figure 2). The $B_0$ field in the myocardium showed a temporal variation between systolic and diastolic cardiac phases (Figure 3). In the septum, smaller $\Delta SD$ and $\Delta IQR$ were observed compared with the rest of the...
myocardium. The ΔSD in the left-ventricular myocardium also varied from slice to slice (Figure 3A). Averaged over all slices and subjects of the study group, ΔSD accounted for $10 \pm 5$ Hz and ΔIQR for $19 \pm 12$ Hz between the same systolic and diastolic cardiac phases, as shown for subject 3. In the right ventricle, ΔSD accounted for $17 \pm 9$ Hz and ΔIQR for $17 \pm 10$ Hz averaged over all slices and subjects of the study group (Figure 3B). Within the septum, which was segmented for all subjects as visualized in Figure 2C (segment 4), a temporal B0-field variation of ΔSD Sep = $3 \pm 2$ Hz was observed. Zeroth-order B0-field (ie, center frequency) changes (∆F0) accounted for ∆F0,LV = $8 \pm 6$ Hz in the left-ventricular myocardium and ∆F0,RV = $16 \pm 11$ Hz in the right-ventricular myocardium across all subjects and slices.

The SROI selection was evaluated from a comparison of B0 maps measured after applying the volume-selective, slab-selective, and slice-selective vendor-supplied shimming protocol (Figure 4). The slab-selective shimming resulted in a reduced SD and IQR in all three acquired slices, indicating a more homogeneous B0-field distribution. Throughout the 6 subjects of the study group, the slab-selective shimming reduced the SD of the middiastolic B0-field distributions by $13 \pm 6$ Hz and 26% ± 11% compared with the volume-selective shimming (Table 1). However, Table 1 reveals that slice-selective shimming reduced this value further for only 2 subjects.

The field maps measured after the slab-selective shimming revealed the spatial B0-field distribution within the anatomy-driven SROI (Figure 5A,B). Calibration-based shim field simulations using the proposed shim strategy resulted in predicted B0-field distributions (Figure 5D), which showed reduced SD and IQR for all subjects compared with the measured field maps. The shim settings for the slab-selective shimming and the simulated shim (Figure 5C) are plotted in Figure 6. The X-gradient, Y-gradient, and Z-gradient offsets showed similar medians for both shims (Figure 6, top row). A comparison of the third-order SH components revealed that the zonal term Z3 showed the largest variation: The median for the slab-selective shimming accounted for 0.06 Hz/cm3, whereas the median for the simulated shim accounted for $-0.58$ Hz/cm3. In 4 of the 6 subjects, simulated shim settings exceeded the maximum of the hardware dynamic range (Figure 6, bottom plot), namely, Z2Y for subject 5, Z3 for subject 7, Z3 and Z2Y for subject 8, and Z3, Z2X, and Z(X2-Y2) for subject 9. A comparison between second order only and second plus third-order shims demonstrated that the
third-order terms were particularly beneficial to correct the myocardial B₀ inhomogeneities in the anterolateral segment of the left ventricle (Figure 7). However, residuals of the third-order terms remained due to the hardware limitations of the shim system. The second-order terms did not exceed the hardware limitations for any shim.

The B₀-field distributions measured after volume-selective shimming showed a temporal variation over eight cardiac phases equally spaced by 90 ms (Figure 8A). Reduced B₀-field inhomogeneity was observed after simulation of the averaged static shim (Figure 8B). The B₀-field homogeneity was improved further after simulated CPSS for SROIs updated on each cardiac phase (Figure 8C), which was beneficial for the correction of myocardial B₀ inhomogeneities (Figure 8, cardiac phase 3, white arrows). A detailed analysis of the required CPSS currents revealed a temporal variation of individual shim terms over the cardiac cycle (Figure 8D, red arrows). Across all subjects, CPSS yielded an improvement of ΔSD = 1 ± 1 Hz in B₀-field homogeneity over the entire heart compared with the averaged static shim. Again, it has to be noted that CPSS was beneficial to reduce myocardial B₀ inhomogeneities, as exemplary shown in Figure 8 for subject 3.

Pilot results of the experimental implementation of the developed shim strategy are shown in Figure 9. Large B₀-field inhomogeneities were observed within the left-ventricular and right-ventricular myocardium before the shim (Figure 9B). The simulated shim is expected to reduce these inhomogeneities significantly (Figure 9D). The experimental shim outcome (Figure 9E) matched the simulated shim outcome and reduced the SD within the SROI from 45-52 Hz slice-to-slice down to 26-33 Hz. However, smaller B₀-field inhomogeneities remain within the myocardium.

**DISCUSSION**

In this work, the spatio-temporal B₀-field inhomogeneities in the human heart at 7 T were characterized. The extreme values of the B₀-field distribution were located in the myocardium and showed a temporal variation between systole and diastole. Various SROI selections were compared, with the anatomy-driven approach demonstrating improved B₀-field homogeneity in contrast to the standard SROI cuboid. The scanner-integrated third-order SH terms reduced the SD of...
the $B_0$ field compared with second order only; however, individual subject-specific third-order terms could not be removed completely due to hardware limitations. Simulated CPSS revealed varying required shim currents on the basis of a shim term-by-term analysis.

4.1 Spatial $B_0$-field inhomogeneities

The high $B_0$-field inhomogeneities in the myocardium were in agreement with earlier studies.$^4,12$ Their origin was evaluated in previous work by high-resolution simulations.

**FIGURE 4** Selection of the shim region of interest. A, Schematic views illustrate the selection of the shim region-of-interest cuboid for the vendor-supplied volume-selective, slab-selective, and slice-selective shimming. All three approaches covered all cardiac tissue, but as less surrounding tissue as possible in plane. The measured $B_0$ fields (B) are shown for subject 7 together with the corresponding histograms (C) obtained after the volume-selective (red bins), slab-selective (blue bins), and slice-selective (green bins) shimming.

**TABLE 1** $B_0$-field homogeneity after different vendor-supplied shimming approaches.

| Subject | Volume-selective shimming SD (Hz) | Slab-selective shimming SD (Hz) | Slice-selective shimming SD (Hz) |
|---------|----------------------------------|---------------------------------|----------------------------------|
| 5       | 42                               | 32                              | 39                               |
| 6       | 49                               | 28                              | 54                               |
| 7       | 44                               | 31                              | 28                               |
| 8       | 66                               | 46                              | 42                               |
| 9       | 49                               | 45                              | 49                               |
| 10      | 51                               | 39                              | 45                               |

*Note: Schematic illustrations of the volume-selective, slab-selective, and slice-selective shimming are shown in Figure 4A. All three shims only differed in the selection of the shim region of interest. The SDs within middiastolic $B_0$ maps of the heart, as visualized for subject 7 in Figure 4, are given for the central slices.*
of the $B_0$-field conditions in the human heart, which furthermore showed that typical locations of $B_0$-field inhomogeneities and dark band artifacts overlap. However, $B_0$-shimming of the anatomy-driven SA and LA slice orientations was not feasible with the current implementation of B0DETOX. In the future, this problem could be resolved by adapting the geometric formalism demonstrated for shimming of single-oblique slices in the brain in the rotations described by the two Euler angles. Another option would be to cover the heart region assessed in the SA and LA orientation by a stack of transversal slices. The anatomy-driven SROI selection could then be performed again in each slice, and a sufficient number of slices would allow us to shim based on transversal field-map data. However, the slice orientation might result in partial volume effects. To avoid this, an increased slice resolution, and therefore measurement time for the shimming procedure, will be required.

### 4.2 Temporal $B_0$-field variations over the cardiac cycle

The $B_0$-field distribution within the myocardium changed over the cardiac cycle except for the septum. This is in agreement with earlier studies, in which the correlation

![Image of Calibration-based shim-field simulations for the $B_0$ field within the heart. The $B_0$ fields measured after the vendor-supplied slab-selective shimming as visualized in Figure 4A are shown for the central slices with zeroth-order center frequency (“measured field map”) (A) and without (“after offset removal”) (B), as well as with the shim fields computed based on the developed third-order shim strategy (“simulated shim”) (C) and the expected $B_0$-field distribution after applying this shim (“predicted $B_0$ distribution”) (D). Note that (C) and (D) refer to an anatomy-driven shim region of interest.](image-url)
between the myocardial effective transverse relaxation time $T_2^*$ and the left-ventricular wall thickness was examined. The temporal $B_0$-field variations between systolic and diastolic cardiac phases supported the use of a triggered field-map acquisition. However, no trend was observed for the systolic SD of $B_0$ to always being larger than the diastolic SD across all analyzed data sets. This might result from the fact that the $B_0$-field data were acquired in transversal orientation, which leads to strongly subject-specific views. It might be the case that, for example, for SA orientations, either systolic or diastolic SD would always be higher and has to be evaluated when the shim strategy will be tailored to SA and LA views. To overcome the temporal $B_0$-field variations between different cardiac phases, an earlier study at 3 T demonstrated CPSS for SSFP cine imaging.\textsuperscript{47} In the future, the shim settings may therefore be adjusted during systolic and diastolic heart phases for cine imaging.

### 4.3 Selection of shim-region-of-interest

Compared with the volume-selective shimming, the slab-selective shimming reduced the cardiac $B_0$ inhomogeneities significantly. In the latter case, the SROI cuboid had the same height of 18 mm as the stack of measured slices, and in-plane covered the entire heart but as little surrounding tissue as possible. The slice-selective shimming, with the SROI covering the central of the three slices in height but the same in-plane region, resulted in no further reduction of the SD in 4 of the 6 subjects. However, purely transversal slice orientations might result in partial volume effects.\textsuperscript{44} Moreover, physiological changes between the acquisition of the initial $B_0$ map, which forms the basis for the calculation of the shim currents, and the measurement for the evaluation of the shim may have influenced the slice-selective shim results. In this regard, respiration-induced $B_0$-field variations between different breath-holds are discussed in detail in section 4.4.3.
This means that the 3D field map should cover an SROI at least one slice thickness (in this case 6 mm) larger in both directions for a reliable shim within it. In-plane shim field simulations showed that an anatomy-driven SROI selection could reduce B0-field inhomogeneities compared with slab-selective shimming in the shape of a cuboid. In this work, static B0 shimming was performed. Slab-wise DSU is expected to improve the B0-field homogeneity inside the heart further.5

4.4 Tailoring the shim strategy

4.4.1 Hardware limitations of SH shim system

After the partial third-order SH B0-field modeling, however, localized spots of smaller B0-field inhomogeneities would remain within the myocardium. The remaining inhomogeneities might result from the hardware limitations of the SH shim system, as the subject-specific shim exceeded the dynamic range of one or more shim coils in some cases. It has to be noted here that for different slice geometries the third-order SH terms might be more or less effective than for the transversal orientation, and hardware requirements might change consequently. Another reason could be the presence of higher-order SH residuals such as the third-order terms X3, Y3, and XYZ, which are not implemented in the scanner’s shim system. The more complex field modeling needed to shim these B0-field inhomogeneities may be addressed by a dedicated multichannel shim coil approach like DYNAMITE,21,48 AC/DC,49 or iPRES.50 Arranging the shim coils in the same localized setup for all measurements, however, would be more complicated for the heart due to different body shapes, and remains the subject for future studies.

4.4.2 Dynamic shimming

The developed shim strategy is capable of applying a static shim tailored for a certain cardiac phase. However, the MR system used for this study did not support dynamic shimming (ie, slice-by-slice DSU or CPSS) in its current state. Dynamic shimming requires a dynamic shim interface for pre-emphasis and B0 compensation, as well as dedicated shim amplifiers, to rapidly switch shim currents.16 To keep updating times for the electronics short, slice-specific or CPSS sets could be stored at the local hardware memory of the dynamic shim interface. Without the possibility of dynamic shimming, a static shim averaged over the cardiac cycle may be an appropriate solution. This may be achieved by monitoring the B0-field dynamics in terms of optimal CPSS settings and performing an averaged static shim, which applies the mean of all CPSS shim fields. The effect of CPSS on cine imaging could be evaluated by repeating the measurement with a specific trigger delay for each cardiac phase using the corresponding CPSS setting, and therefore without the need for DSU. Note that CPSS might be more or less effective for different slice geometries, making it necessary to repeat the analysis when shim strategies will be tailored for SA and LA orientations.

4.4.3 Respiration-induced B0-field variations

The SH terms like X2-Y2 or XY strongly depend on the B0-field distribution in plane, where the resolution of the measured data was relatively high. The SH components with a significant contribution in z-direction, such as the zonal term Z3, were modeled based on the data in through-slice direction due to the transversal field-map orientation. Here, the number of slices was limited to three within a single breath-hold of 10-15-second duration. An extension of the measurement over multiple breath-holds could result in local respiration-induced B0 inhomogeneities, which could be investigated by repeating a scan several times over subsequent breath-holds.
A recent study showed that local $B_0$ variations approached 100 Hz and more, although the mean value of the $B_0$ field changed only moderately between exhaled, half-inhaled, and inhaled breath-hold positions. When more slices distributed over several breath-holds have to be acquired, the $B_0$ maps may in the future be acquired together with diaphragm navigator images, to identify the respiratory position during a calibration scan and apply an appropriate correction. Direct $B_0$-field monitoring with a field probe and real-time $B_0$-field updating using a dynamic shim module might be another option and has been demonstrated to reduce respiration-induced field inhomogeneities in the human chest at 7 T.
5  |  CONCLUSIONS

This work assessed the spatial $B_0$-field distribution in the human heart at 7 T and its temporal variation in the myocardium between systolic and diastolic cardiac phases. Several challenges for state-of-the-art vendor-supplied shimming methodology, including cardiac triggering and an adequate SROI selection, were demonstrated and discussed. Third-order SH terms were shown to be useful for $B_0$ shimming of the human heart at 7 T, while subject-specific required shim currents even exceeded the hardware capabilities of the SH shim system. Simulations of CPSS and proof-of-principle in vivo shimming demonstrated a considerable gain in $B_0$-field homogeneity in comparison to standard static shimming. A potential workflow for CPSS shimming was proposed, and its benefits and limitations were discussed. The presented findings contribute to the development of dedicated shim strategies to correct the $B_0$ field within the human myocardium. In combination with future technical advances, including shimming of double-oblique SA and LA slice orientations and calibration scans to overcome respiration-induced $B_0$-field variations, improved CMR imaging at 7 T could be achieved.

ORCID

Michael Hock  https://orcid.org/0000-0003-2450-6738

Maxim Terekhov  https://orcid.org/0000-0001-5617-7751
David Lohr  https://orcid.org/0000-0002-6509-3776
Stefan Herz  https://orcid.org/0000-0002-6360-0578
Markus Ankenbrand  https://orcid.org/0000-0002-6620-807X
Aleksander Kosmala  https://orcid.org/0000-0002-9313-9356
Tobias Gassenmaier  https://orcid.org/0000-0002-1089-2036
Christoph Juchem  https://orcid.org/0000-0002-1505-201X
Laura Maria Schreiber  https://orcid.org/0000-0002-8827-1838

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