Localized $B_0$ shimming based on $^{23}$Na MRI at 7 T

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Purpose: To validate the feasibility of localized $B_0$ shimming based on $B_0$ maps acquired with sodium ($^{23}$Na) MRI.

Methods: A localized $B_0$ shimming routine based on a constrained regularized algorithm in combination with $^{23}$Na MRI data acquired with a 3D density-adapted radial readout scheme was implemented on a 7T MR system. Measurements were performed using a dual-tuned $^{23}$Na/$^1$H head coil. The quality of $B_0$ maps reconstructed from $^{23}$Na images and the resulting shim values was examined depending on the acquisition duration between 10 minutes and 15 seconds to examine clinical applicability. The $B_0$ shimming based on $^{23}$Na $B_0$ maps was performed both for phantom and human head of 6 healthy volunteers, and the resulting $B_0$ homogeneity was compared with the vendor-provided $^1$H MRI–based gradient-echo brain shimming routine.

Results: The proposed $^{23}$Na MRI–based shimming routine showed a reduction in $B_0$ variation comparable to the vendor-provided shim both in phantom and in vivo measurements. Within the examined multicompartment phantom, the $B_0$ variations could be reduced by up to 77% using the $^{23}$Na MRI–based shimming. In human head, $B_0$ variations were reduced by approximately 50% using an acquisition time of 15 seconds for the $^{23}$Na $B_0$ maps and only 1 iteration of $B_0$ shimming.

Conclusion: The $^{23}$Na MRI–based localized $B_0$ shimming is possible at 7 T within clinically acceptable acquisition durations (<1 minute). It was shown that using the proposed $^{23}$Na MRI–based shimming approach, the $^{23}$Na image quality at ultrahigh field strength can be strongly improved.

Keywords
7 Tesla, $B_0$ shimming, sodium MRI, ultrahigh field strengths
INTRODUCTION

Ions such as sodium (Na⁺), potassium (K⁺), and chlorine (Cl⁻) play a vital role in many cellular processes, such as the excitability of neurons and muscle cells. Magnetic resonance imaging of these nuclei—often denoted as X-nuclei MRI—is a promising approach to examine cell viability noninvasively. Especially ²³Na MRI has evolved into a valuable tool in biomedical research during the past 2 decades.⁰⁻³ Due to low in vivo concentrations as well as low gyromagnetic ratios, the use of ultrahigh magnetic field strengths (B₀ ≥ 7 T) is desirable for X-nuclei imaging to achieve a sufficient SNR.⁴ As B₀ inhomogeneities increase with increasing field strength, they are a major challenge in ultrahigh field applications. Especially for quantitative measurements⁵ as well as for advanced acquisition techniques such as multiple quantum filtration,⁶⁻⁸ a homogeneous B₀ field is indispensable. In X-nuclei imaging, localized B₀ shimming is usually performed using ¹H MRI–based shimming routines provided by the manufacturers of the MRI system. However, in various applications, X-nuclei RF coils without ¹H channel are used. Both single-tuned X-nuclei coils (e.g., ²³Na head or body coils)⁹ and dual-tuned X-nuclei-only coils (e.g., ²³Na/²⁵Cl¹⁰ or ²³Na/³⁹K¹¹) are available.¹² If the MR system is not equipped with a ¹H body coil, which is usually the case for ultrahigh-field MRI systems, B₀ shimming cannot be performed using vendor-provided localized B₀ shimming routines.

In general, localized B₀ shimming techniques can be divided into projection mapping techniques such as FASTMAP, FASTERMAP, and FASTESTMAP,¹³⁻ⁱ⁵ which acquire only a few linear projections, and volumetric mapping techniques. The latter measure a full 3D data set and are therefore more time-consuming; however, they can better account for local B₀ variations. Volumetric mapping techniques can be further differentiated by the algorithm used for the solution of the shim value optimization. A detailed description of the most commonly used algorithms and a comparison of their performance at 7 T and 9.4 T can be found in Nassirpour et al.¹⁶

The aim of this work was to implement a B₀ shimming routine that is based on ²³Na MRI data acquired in clinically acceptable acquisition times (< 1 minute), and to evaluate its performance by comparing it with the vendor-provided ¹H MRI–based gradient-echo (GRE) brain-shimming routine both in phantom and in vivo measurements.

METHODS

Measurements were performed at a 7T whole-body MR system (Magnetom Terra; Siemens Healthcare, Erlangen, Germany) using a double-resonant ²³Na/¹H head coil (Rapid Biomedical, Rimpar, Germany). The ²³Na data sets for shim-value calculation were acquired using a double-echo 3D density-adapted radial readout scheme¹⁷ (parameters: TR = 50 ms, TE₁/₂ = 0.3/5.8 ms, flip angle [FA] = 50°, and nominal spatial resolution Δx = 5 mm³). Reconstruction and postprocessing of the radial data sets were performed offline using MATLAB (The MathWorks, Natick, MA). To account for the reduced SNR of radially undersampled data sets, ²³Na images were reconstructed using a Gaussian filter with increasing SD (5 mm to 9.3 mm) for decreasing number of radial projections.

First, the 2 echoes of the ²³Na acquisitions were reconstructed as complex images and phase-unwrapped,¹⁸ resulting in phase images Φ₁,unwrapped and Φ₂,unwrapped. Next, the ΔB₀ map, which describes the local deviations of the effective B₀ field from the nominal B₀ field, was calculated according to

\[
\Delta B_0 = \frac{\Phi_{2,\text{unwrapped}} - \Phi_{1,\text{unwrapped}}}{\gamma (TE_2 - TE_1)},
\]

with the TEs of the double-echo acquisition (TE₁ and TE₂) and the gyromagnetic ratio of ²³Na (γ₂³Na = 11.269 MHz/T).

In the following, these maps will be denoted as B₀ maps. The volume of interest to be shimmed was determined by calculating a 3D mask based on the magnitude image reconstructed from the first echo using a thresholding approach. The corresponding threshold was chosen subject-specific to include the whole head.

In general, localized B₀ shimming requires the solution of the optimization problem

\[
\min_x \left\| (A \cdot x - \Delta B_0) \right\|^2,
\]

where A is the matrix of the shim fields produced by the shim coils, ΔB₀ denotes the B₀ map calculated as described previously (Equation 1), and x is the vector of the shim currents to be determined. In general, the shim fields are described by spherical harmonics. However, the real shim fields often deviate from the theoretical description, so it is advisable to include a decomposition coefficient matrix C modeling the real shim fields¹⁹ as follows:

\[
\min_x \left\| ((A \cdot C) \cdot x - \Delta B_0) \right\|^2 = \min_x \left\| (A' \cdot x - \Delta B_0) \right\|^2.
\]

The decomposition matrix for the third-order shim coils of the MR system was determined using a 32-channel ¹H head coil (Nova Medical, Wilmington, MA) and a spherical oil phantom (diameter = 17 cm). Field maps of the 12 different shim coils were acquired using a 2D-GRE B₀ mapping sequence (TR = 304 ms, TE₁/₂ = 2.99/4.60 ms, FA = 17°, Δx = 4 mm³, 50 slices, FOV = 240 × 240 × 200 mm³, acquisition time [TA] = 38 seconds) at 5 different input current...
amplitudes (+100 mA, 200 mA, 500 mA, and 1000 mA) and fitted by a linear model using a fifth-order spherical harmonic approximation as described by Chang et al. This resulting coefficient matrix can be found in Supporting Information Table S1.

The $^{23}$Na $B_0$ maps were acquired using the default shim currents of the system (denoted as “Tune Up” shim settings). Shim values were then calculated based on these $B_0$ maps using the constrained regularized pseudo-inversion approach (ConsTru) proposed by Nassirpour et al. This algorithm using the constrained regularized pseudo-inversion approach solves Equation 3 by directly pseudo-inverting the matrix $A'$. If this violates hardware restrictions, the smallest singular value of the matrix $A'$ is truncated and the resulting new matrix is re-inverted. This step is repeated until no hardware restrictions are violated. Due to the truncation of the smallest singular values of the $A'$ matrix, the ConsTru algorithm was shown to be robust against noisy input data. All shim value calculations based on $^{23}$Na $B_0$ maps were performed directly on the host computer of the scanner using a MATLAB script, and the resulting shim values were automatically transferred to the shim settings.

As a reference, shim values were calculated using the vendor-provided $^1$H MRI–based GRE brain shimming routine (parameters: $TR = 4.3$ ms, $TE_{1/2} = 1.02/3.06$ ms, $FA = 3°$, $Δx = 4.4$ mm$^3$, 52 slices, FOV = $282 × 282 × 274$ mm$^3$, $TA = 14$ seconds). For better comparability, only 1 iteration of shimming was performed each for the ConsTru and the GRE brain-shimming routine in all measurements. Additionally, the acquisition duration of the $^{23}$Na images used for the shim-value calculation was chosen to match the acquisition duration of the GRE brain shimming $B_0$ map acquisition ($N_{proj} = 300$).

The $B_0$ shimming performance of the different shimming routines was evaluated by calculating the $B_0$ variation represented by the SD $σ$ of $ΔB_0$ over the entire volume of interest. In addition, the range of $ΔB_0$ values in which 95% of the voxels within the volume of interest can be found (95th percentile P) was calculated.

### 2.1 Phantom measurements

In a first step, measurements of a 5-compartment phantom were performed to evaluate the performance of the implemented $^{23}$Na MRI–based $B_0$ shimming routine. The 4 cylindrical compartments (diameter 6 cm, height 13 cm) were filled with 2% and 3% xanthan gel as well as 4% and 8% agarose gel (Carl Roth, Karlsruhe, Germany). All gels were produced using a solution containing 50 mM NaCl. The space between the cylindrical compartments was filled with the same solution (compare with Gast et al).

The $^{23}$Na $B_0$ maps were acquired with a varying number of radial projections (12 000, 6000, 1200, 300) to examine the effect of the acquisition duration on the $B_0$ map. Shim values were calculated using the ConsTru algorithm for all $^{23}$Na acquisitions. Moreover, shimming was performed using the GRE brain shim. To compare the $B_0$ homogeneity before and after shimming, $^{23}$Na $B_0$ maps were acquired for each set of calculated shim values (1200 radial projections/TA = 1 minute).

To examine the effect of an unshimmed and shimmed $B_0$ field on the $^{23}$Na image quality, spin-density weighted (SDW), triple-quantum filtered (TQF), and double-quantum filtered with magic angle excitation (DQF-MA) $^{23}$Na data sets of the phantom were acquired before and after shimming using the $^{23}$Na-based ConsTru shim (300 projections, TA = 15 seconds). Multiple quantum-filtered acquisition techniques without 180°-refocusing pulse are highly prone to $B_0$ inhomogeneities and can therefore serve as an indicator of the shim quality. In TQF acquisitions, signal loss due to $B_0$ inhomogeneities can be expected. In contrast, $B_0$ deviations result in signal breakthrough of compartments that are supposed to be suppressed in DQF-MA measurements (parameters: $TR = 86$ ms, $TE = 0.3$ ms, $FA = 90°$, $Δx = 3 × 3 × 6$ mm$^3$, and TA = 10:23 minutes for SDW; $TR = 258$ ms, $TE = τ = 5$ ms, $Δx = 8 × 8 × 16$ mm$^3$, and TA = 18:10 minutes for TQF; and TR = 150 ms, $TE = τ = 4$ ms, $Δx = 8 × 8 × 16$ mm$^3$, and TA = 10:34 minutes for DQF-MA).

### 2.2 In vivo measurements

The $B_0$ shimming was performed in vivo on the heads of 6 healthy volunteers (3 males, 3 females, 26.2 ± 1.6 years old). The study was approved by the local ethical review board and all volunteers provided informed consent before the scan. Again, the $B_0$ map quality depending on the acquisition duration of the underlying $^{23}$Na images was examined by varying the number of radial projections between 12 000 and 300. Shim values were calculated using the ConsTru algorithm from $B_0$ maps acquired with the $^{23}$Na 3D density-adapted radial readout sequences ($N_{proj} = 300$) and were compared with the vendor-provided GRE brain shim as described for the spherical phantom. For all calculated shim values, a $^{23}$Na $B_0$ map was acquired (1200 radial projections/TA = 1 minute). Moreover, SDW and TQF-$^{23}$Na images were acquired for 1 volunteer (male, 27 years old) using Tune Up shim currents as well as shim values calculated using the $^{23}$Na-based ConsTru shim (300 projections, TA = 15 seconds) (parameters: $TR = 86$ ms, $TE = 0.3$ ms, $FA = 90°$, $Δx = 3$ mm$^3$, and TA = 10:02 minutes for SDW; $TR = 200$ ms, $TE = τ = 5$ ms, $Δx = 8$ mm$^3$, and TA = 14:34 minutes for TQF).

### 3 Results

#### 3.1 Phantom measurements

The $B_0$ maps of the multicompartment phantom reconstructed from fully sampled and undersampled $^{23}$Na data sets,
as well as corresponding histograms of the $\Delta B_0$ distribution within the phantom, are in good accordance for all acquisition durations (Figure 1A). The corresponding magnitude images depending on the acquisition duration can be found in Supporting Information Figure S1. A slight decrease in the strength of the measured $B_0$ variation $\sigma$ with decreasing acquisition duration can be observed. The ConsTru shimming algorithm markedly improved the $B_0$ homogeneity (Figure 1B). Similar results were achieved for the different acquisition durations of the $^{23}$Na $B_0$ maps.

A comparison of the $B_0$ homogeneity within the phantom before and after shimming using the $^{23}$Na-based...
ConsTru and the $^1$H-based GRE brain shim is shown in Figure 2. Both approaches result in a clear reduction of the $B_0$ inhomogeneities within the phantom. Using the same acquisition duration of 15 seconds for the acquisition of the underlying data sets, the $^{23}$Na MRI-based ConsTru shimming routine leads to a similar reduction of the $B_0$ variation $\sigma$ (reduction by 77%) as the GRE brain shim (reduction by 79%).

In addition, the SDW, TQF, and DQF-MA $^{23}$Na images of the multicompartment phantom were acquired before and after shimming with the $^{23}$Na ConsTru shimming routine (Figure 3). In the SDW $^{23}$Na image (Figure 3A) acquired with Tune Up shim currents (upper row), slight artifacts due to the $B_0$ inhomogeneities can be observed in the center of the phantom that are eliminated after shimming with the $^{23}$Na ConsTru shim (lower row). In the $^{23}$Na TQF image (Figure 3B), strong signal loss can be observed in the unshimmed measurement compared with the acquisition after shimming. The $^{23}$Na DQF-MA image (Figure 3C) shows unwanted signal of the agarose compartments when using the Tune Up shim currents that is suppressed in the acquisition performed after shimming.

### 3.2 In vivo measurements

As for the phantom, $^{23}$Na data sets of the human head acquired in less than 1 minute yield $B_0$ maps comparable to the fully sampled $^{23}$Na data set (see Supporting Information Figure S1 for $^{23}$Na images depending on the acquisition duration) and can therefore be used for shim value calculation. The $B_0$ homogeneity after $^{23}$Na-based ConsTru shimming compared with the vendor-implemented GRE brain shimming routine of the same volunteer can be found in Figure 4. Again, both shimming routines significantly reduced the $B_0$ deviations compared with the Tune Up shim currents. Over the 6 examined volunteers, a very similar performance of both shimming routines with a mean reduction of the $B_0$ variations $\sigma$ by 53% ± 7% ($^1$H GRE brain) and 52% ± 7% ($^{23}$Na ConsTru) over the entire head volume was observed. Moreover, the mean 95th percentiles $P$ were reduced by 43% ± 10% ($^1$H GRE brain) and 44% ± 12% ($^{23}$Na ConsTru). The results for all volunteer measurements can be found in Supporting Information Table S2.

The impact of $B_0$ inhomogeneities on in vivo $^{23}$Na acquisitions of the human head was examined by acquiring SDW and
Figure 3  Spin-density weighted (SDW) (A), triple-quantum filtered (TQF) (B), and double-quantum filtered with magic angle excitation (DQF-MA) (C) $^{23}$Na images of a multicompartment phantom containing compartments of agarose gel (1 and 3), xanthan gel (2 and 4) and NaCl solution (5). Images were acquired before (upper row) and after shimming with the $^{23}$Na image-based ConsTru shimming routine (lower row). D. Corresponding $B_0$ maps. Using Tune Up shim currents, the SDW image depicts artifacts in the center of the phantom due to $B_0$ inhomogeneities that are eliminated after shimming (see red arrow). Stronger effects can be observed in the multiple quantum-filtered acquisitions: $B_0$ inhomogeneities lead to strong signal reduction in the TQF acquisition, which is intended to show only signal of motionally restricted areas (agarose/xanthan gel), whereas they lead to the breakthrough of unwanted signal in the DQF-MA acquisition, which is intended to show only signal of regions exhibiting anisotropic orientation (xanthan gel).

Figure 4  In vivo $B_0$ maps of a healthy subject acquired using Tune Up shim currents (A) compared with $B_0$ maps using shim values calculated with the vendor-provided $^1$H GRE brain shimming routine (B), as well as the ConsTru shimming routine based on $^{23}$Na image data (C), together with corresponding $\Delta B_0$ distributions (lower row). To ensure comparability, all shown $B_0$ maps were acquired using the same $^{23}$Na MRI protocol (isotropic nominal resolution = 5 mm, TA = 1 minute). In this example, the $B_0$ variations were reduced by about 49% by applying shim values calculated using the GRE brain shim and by about 46% using shim values calculated by the $^{23}$Na image-based ConsTru shim, each using 1 iteration of $B_0$ shimming.
TQF $^{23}$Na images before and after shimming (Figure 5A,B, respectively). The corresponding $^{23}$Na $B_0$ maps can be found in Figure 5C. In the SDW image acquired with Tune Up shim currents (Figure 5A, left column), $B_0$ inhomogeneities lead to a blurring that is especially noticeable in small structures (compare red arrows). These artifacts can be clearly reduced using shim values calculated by the $^{23}$Na image–based ConsTru algorithm (Figure 5A, right column). An even stronger effect can be observed in the TQF acquisition, as the images provide different information in the case of an unshimmed and shimmed $B_0$ field (Figure 5B). Although the TQF signal intensity can be observed primarily in the frontal lobe using Tune Up shim currents, a more homogeneous signal distribution over the entire brain is found using ConsTru shim values.

**FIGURE 5** The SDW (A) and TQF (B) $^{23}$Na images of human head before (left column) and after shimming with the ConsTru shimming routine based on a $^{23}$Na $B_0$ map acquired in 15 seconds (right column). C, Corresponding $B_0$ maps. Using Tune Up shim currents, small structures are blurred in the SDW image due to $B_0$ inhomogeneities (red arrows). In the TQF image, $B_0$ inhomogeneities lead to strong signal reduction and therefore significant loss of information.

4 | DISCUSSION

In this work, a localized $B_0$ shimming routine based on 3D $^{23}$Na $B_0$ maps was implemented on a 7T MR system equipped with a third-order shim system. The $B_0$ maps reconstructed from $^{23}$Na data sets acquired with the 3D density-adapted radial readout scheme were found to provide sufficient SNR for shim value calculation using the ConsTru algorithm, even when using strong radial undersampling. Shim values calculated from $^{23}$Na $B_0$ maps acquired in 15 seconds resulted in a reduction in $B_0$ variation comparable to the vendor-provided $^1$H MRI–based GRE brain shimming routine both for phantom and in vivo measurements.

As shown in both phantom and in vivo measurements of the human brain, the $B_0$ homogeneity has a strong impact on the $^{23}$Na image quality. This is in agreement with previous work that examined the effect of $B_0$ correction on quantitative $^{23}$Na MRI measurements. Moreover, it was shown that a homogeneous $B_0$ field is of special importance when performing advanced imaging techniques as multiple quantum filtration. In contrast to quantitative measurements, for these techniques no $B_0$ correction can be performed, and deviations from the nominal $B_0$ field result in strong image artifacts.

In a clinical context, the acquisition duration of 10 minutes for a fully sampled $^{23}$Na image is not applicable. Therefore, a certain degree of radial undersampling and consequent loss of information has to be accepted. Due to the increasing filter strength used for the image reconstruction to maintain the SNR of the fully sampled data set, $B_0$ maps calculated from $^{23}$Na images with shorter acquisition durations are smoothed and the variation of $\Delta B_0$ is slightly underestimated compared with the fully sampled $^{23}$Na acquisitions. However, the resulting shim values lead to a comparable $B_0$ homogeneity as the fully sampled data set. Moreover, in the measurements performed in this work, similar $B_0$ variation was found using shim values calculated by the $^{23}$Na MRI–based ConsTru as using the vendor-provided $^1$H MRI–based GRE brain shim, despite the significantly lower SNR and slightly lower resolution of the $^{23}$Na $B_0$ maps. One possible reason might be
that $^{23}$Na acquisitions are influenced less by $B_1$ inhomogeneities than $^1$H acquisitions at 7 T, leading to fewer areas with very low signal intensity and therefore a better overall $B_0$ map quality. Acquiring $^{23}$Na $B_0$ maps with higher resolution than the chosen value of 5 mm would again lead to longer measurement times and was not found to provide better shimming results. In addition, in the presented $B_0$ shimming approach, the ConsTru algorithm is used in combination with the modeled shim fields, while the vendor-provided shim routine is based on the assumption of ideal shim fields described by spherical harmonics. Therefore, the ConsTru algorithm can provide better $B_0$ homogeneity when using only 1 iteration of $B_0$ shimming. 10

In general, $B_0$ shimming in X-nuclei imaging is performed by using the $^1$H channel of a dual-tuned coil. 12 However, for some applications, the use of an X-nuclei coil without $^1$H channel is desirable, such as to facilitate coil design or in exchange for a second X-nuclei channel. In this case, usually no $B_0$ shimming is performed. 11 Another approach is exchanging the X-nuclei RF coil by an $^1$H RF coil without moving the head to perform shimming on the $^1$H frequency. 5

The presented $^{23}$Na MRI-based approach allows localized $B_0$ shimming even when no $^1$H channel is available. Therefore, the $B_0$ homogeneity and the resulting image quality of X-nuclei acquisitions can be improved significantly.

So far, the calibration of the shim system used in this work was performed only for the FOV of a head coil, and the workflow was optimized for $^{23}$Na measurements of the human head. Therefore, the applicability of the presented shimming routine to other parts of the body, such as in measurements of skeletal muscle, and using other nuclei than $^{23}$Na for $B_0$ shimming still has to be evaluated.

5 | CONCLUSIONS

In this work, the feasibility of localized $B_0$ shimming based on 3D $^{23}$Na $B_0$ maps acquired in clinically acceptable acquisition times (< 1 minute) at 7 T was demonstrated. These results are promising for future ultrahigh-field X-nuclei MRI applications, in which no $^1$H MRI data can be acquired, such as when using single-tuned $^{23}$Na RF coils.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

FIGURE S1 Magnitude $^{23}$Na images of the multicompart-ment phantom (A) and a healthy subject (B) depending on the acquisition duration. Images were reconstructed using a Gaussian filter with increasing filter strength to maintain the SNR of the fully sampled data set (TA = 10 minutes)

TABLE S1 Decomposition coefficient matrix for the shim system. Note: The columns represent the 9 nonlinear shim coils of the shim system as denoted by the manufacturer. The corresponding theoretical shim fields are described by second-order (A20-B22) and third-order (A30-A32) spherical harmonics. The decomposition coefficients describing the contribution of spherical harmonics of zeroth to fifth order to the real shim fields can be found in the lines

TABLE S2 $B_0$ variations $\sigma$ and 95th percentiles $P$ describing the range in which 95% of the $\Delta B_0$ values within the volume of interest can be found. Note: Values for $\sigma$ and $P$ are shown for all individual volunteers. Tune Up shim currents, as well as shim values calculated by the vendor-provided $^1$H GRE brain shim and the $^{23}$Na ConsTru, were used. No significant differences for $\sigma$ and $P$ were observed between the $^1$H GRE brain and $^{23}$Na ConsTru shim

How to cite this article: Gast LV, Henning A, Hensel B, Uder M, Nagel AM. Localized $B_0$ shimming based on $^{23}$Na MRI at 7 T. Magn Reson Med. 2020;83:1339–1347. https://doi.org/10.1002/mrm.28011