Respiration induced $B_1^+$ changes and their impact on universal and tailored 3D kT-point parallel transmission pulses for 7T cardiac imaging

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Purpose: Human heart imaging at ultra-high fields is highly challenging because of respiratory motion-induced artefacts and spatially heterogeneous $B_1^+$ profiles. This work demonstrates that respiration resolved 3D $B_1^+$-maps can be used with a dedicated tailored and universal parallel transmission (pTx) pulse design to compensate respiration related $B_1^+$ changes in subjects performing shallow and deep breathing (SB/DB).

Methods: Three-dimensional (3D) $B_1^+$-maps of the thorax were acquired in 31 subjects under SB and in 15 subjects under SB and DB. Different universal and tailored non-selective pTx pulses were designed from non-respiration resolved (NRR) and respiration resolved (RR) reconstructions of the SB/DB $B_1^+$-maps. The performance of all pulses was tested with RR-SB/DB $B_1^+$-maps. Respiration-robust tailored and universal pulses were applied in vivo in 5 subjects at 7T in 3D gradient-echo free-breathing scans.

Results: All optimized pTx pulses performed well for SB. For DB, however, only the universal and the tailored respiration-robust pulses achieved homogeneous flip angles (FAs) in all subjects and across all respiration states, whereas the tailored respiration-specific pulses resulted in a higher FA variation. The respiration-robust universal pulse resulted in an average coefficient of variation in the FA maps of 12.6% compared to 8.2% achieved by tailored respiration-robust pulses. In vivo measurements at 7T demonstrate the benefits of using respiration-robust pulses for DB.

Conclusion: Universal and tailored respiration-robust pTx pulses based on RR $B_1^+$-maps are highly preferred to achieve 3D heart FA homogenization at 7T when subjects perform DB, whereas universal and tailored pulses based on NRR $B_1^+$-maps are sufficient when subjects perform SB.
1 INTRODUCTION

Ultra-high field (UHF) MRI is often challenged by spatial inhomogeneities of the transmit (Tx) magnetic radiofrequency field \(B_1^+\) generated by the Tx coil elements. As a result, spatially variable flip angles (FA) with potential FA voids yield a spatially varying image and contrast. Such spatial FA variations can be successfully reduced, among other techniques, by applying parallel transmission (pTx) techniques.1–11

In the human body, varying body shapes and dimensions typically cause strong inter-subject variations of the spatial FA pattern.9 Therefore, pTx in the human body is typically tailored for each subject individually based on subject-specific \(B_1^+\)-maps.9,12–15 In contrast, the concept of pre-computed calibration-free universal pulses (UPs), originally developed and tested for various applications in the human brain16–21 has been successfully applied to the human body to save precious scan time by using non-respiration-resolved (NRR) \(B_1^+\)-maps of subjects performing shallow breathing (SB).22

Preliminary data, however, suggest that three-dimensional (3D) kT-point pulses calculated based on NRR \(B_1^+\)-maps acquired during SB perform inferiorly for larger respiratory amplitudes such as deep breathing (DB).9 This preliminary observation is in line with other works performed for 2D cardiac breath-hold imaging with tailored slice-selective pTx spoke pulses.14 Therein, the impact of \(B_1^+\) changes between deep inhale and exhale was successfully compensated by generating respiration-robust spokes pulses using breath-hold acquired 2D \(B_1^+\)-maps from multiple respiration-states.14 A similar idea was recently also used to design motion-robust spoke pulses for multiple head positions.23,24

For 3D free-breathing cardiac imaging, similar respiration-related problems are expected for DB patterns as well. In addition to the aforementioned observations in 2D acquisitions,14 FA variations across the respiratory cycle may further limit the flexibility and data efficiency of retrospectively binned and motion corrected 3D reconstructions. Therefore, homogeneous FAs across all respiration states in the 3D target region are essential to use the full potential of 3D free-breathing cardiac imaging methods.25,26

Three-dimensional respiration-resolved (RR) \(B_1^+\) mapping was recently proposed in subjects performing SB and DB.12 Such 3D RR \(B_1^+\)-maps enable analyzing and potentially correcting for the impact of respiration-related \(B_1^+\) changes with a dedicated pTx pulse design. However, it is yet unclear if the respiration-robust pulse design principle, proposed for a single (central) 2D slice of the heart,14 also works for larger region-of-interests (ROIs) covering multiple slices and orientations in 3D as well.

This paper aims to investigate the aforementioned issues and to correct the impact of respiration-related motion on the pTx pulse’s 3D FA distributions within the human heart in subjects performing SB and DB. Different 3D kT-point pulse types were designed and investigated, including universal and tailored pulses for NRR-SB \(B_1^+\)-maps,9,22 respiration-specific pulses tailored for each respiration state of the RR-SB/DB \(B_1^+\)-maps and respiration-robust universal and tailored pulses for multiple respiration states of RR-SB/DB \(B_1^+\)-maps. Five tailored and universal pulses were experimentally applied in 5 subjects for shallow and deep breathing 3D gradient echo sequences (GRE) scans at 7T.

2 METHODS

A summary and short explanation of the \(B_1^+\) library/test-case acronyms and the used pulse type acronyms, which will be explained subsequently, can be found in Supporting Information Tables S1 and S2.

2.1 Subjects and MR scanner hardware

MRI was performed according to an approved institutional review board (IRB) protocol and after written informed consent in a total of 46 healthy subjects to build up 2 \(B_1^+\) dataset libraries for offline UP design and 2 \(B_1^+\) test-case groups to evaluate the UP’s performance for shallow and deep breathing: (1) library-SB: 14 male (M)/8 female (F), 21–66 years, body mass index (BMI) = 20–28 kg/m², (2) test-cases-SB: 4 M/5 F, 25–56 years, BMI = 19–35 kg/m², (3) library-DB: 4 M/6 F, 24–56 years, BMI = 21–28 kg/m², and (4) test-cases-DB: 4 M/1 F, 22–40 years, BMI = 20–25 kg/m². Acquisitions were performed on a 7T scanner (Magnetom 7T, Siemens Healthineers, Erlangen, Germany) using an 8-channel pTx system and a whole-body gradient system. The scans were performed with a 32-element body array (MRI.TOOLS, Berlin, Germany) driven in 8Tx/32Rx mode. Safety limits and coil placements were set identically as described in the previous publications.9,12,22
2.2 | Adjustments and calibration scans

RR and NRR relative 3D $B_1^+$-maps\textsuperscript{12} of the human thorax were acquired during free-breathing (no breath-hold) for 2 breathing patterns: (1) under SB (library-SB and test-cases-SB), and (2) under DB (library-DB and test-cases-DB) conditions. Common parameters were: nominal FA = 20°, TE/TR = 2.02/40 ms, FOV = $(250 \times 312 \times 312)$ mm$^3$, resolution $(4 \times 4 \times 4)$ mm$^3$. The radial-phase encoded (RPE) sequence trajectory enabled self-navigation, which was used to separate the free-breathing data into 3 RR datasets for SB and 5 RR datasets for DB. Because of the larger number of respiratory bins that were needed for DB,\textsuperscript{12} 512 RPE lines for each Tx were acquired in 6 min 50 s for DB and 256 lines for each Tx were acquired in 3 min 25 s for SB. All scans were performed using the default tune-up $B_0$ shim.

The reconstruction of the NRR and RR 3D $B_1^+$-data sets\textsuperscript{12} was performed on a remote workstation in ~1 min (NRR) and 5 min (RR) while the subject was in the scanner. Three motion states (RR states: 1,2,3 for SB; 1,3,5 for DB) termed exhale, intermediate, and inhale, are used throughout the manuscript. The sum of magnitudes of the channel-wise SB and DB $B_1^+$-maps, shown in Figure 1B, was used to manually define an ROI covering the 3D heart volume on a slice-by-slice basis for inhale, intermediate, and exhale. The ROI was then used as a binary mask for pTx pulse design and evaluation.

2.3 | Pulse design and evaluation

This work is focused on the design and the evaluation of different non-selective kT-point pTx pulses to generate homogeneous FAs in the 3D heart volume of subjects performing SB and DB: (1) UP: pre-computed for a library of $B_1^+$-maps; (2) tailored-NRR: tailored for subject-specific NRR-SB $B_1^+$-maps; (3–5) tailored-RSpec: tailored for 1 out of 3 subject-specific respiratory states (inhale, intermediate, or exhale); (6) tailored-RRob: tailored for all 3 subject-specific respiration states (inhale, intermediate, and exhale) simultaneously.

Tailored-NRR and UP-SB\textsuperscript{9,22} pulses were designed from NRR-SB $B_1^+$-maps. The source code and the $B_1^+$-maps are provided at https://github.com/chaiger/UP_body.

Tailored-RSpec, tailored-RRob, and UP-DB pulses were designed from RR-SB/DB $B_1^+$-maps and the respiration-robust UP-SBDB was designed from both, NRR-SB and RR-DB $B_1^+$-maps.

Respiration robustness was achieved extending the tailored-NRR approach\textsuperscript{9} to using multiple RR $B_1^+$-maps of different respiration states. Code for the design of tailored-RSpec and tailored-RRob pulses and the used RR-DB $B_1^+$-maps can be downloaded from https://github.com/chaiger/tailored-RRob.

The kT-point pulse design problem to excite a 10° target FA within the heart volume was solved using the small-tip-angle approximation with an interleaved greedy and local optimization.\textsuperscript{27,28}

All pulses were implemented for the MR scan with the same timing structure using 4.015 ms long square RF pulses and 4.09 ms long 3D gradient blips, leading to a total duration of 0.96 ms. The short pulse durations of 0.96 ms allows off-resonance effects to be neglected.\textsuperscript{9,22} Bloch simulations and subsequent quality checks were performed after optimization and before writing the RF pulse file and exporting them to the MR scanner for qualitative comparison to the prediction in the pulse design.

2.4 | Experimental validation of optimized pulses

Isotropic, 3D image datasets were acquired in 5 subjects during SB (UP-SBDB and tailored-NRR) and during DB (UP-SBDB, tailored-Spec and tailored-RRob) using RPE trajectory-based\textsuperscript{29} 3D GRE scans (nominal FA = 10°, TE/TR = 1.58/2.75 ms, TA = 1.05 min, resolution $(4 \times 4 \times 4)$ mm$^3$). The acquired 3D RPE datasets were binned into 5 respiratory motion states to resolve the large deep breathing amplitudes using self-navigation obtained from the 1D projection in the head–feet direction ($k_y = k_z = 0$) to reconstruct 5 different respiratory motion states using an iterative SENSE algorithm.\textsuperscript{30}

3 | RESULTS

3.1 | SB and DB induced changes on NRR and RR reconstructions

Figure 1 illustrates the breathing amplitude of SB (Figure 1A) and DB (Figure 1B) and the impact of respiratory motion from NRR and 3 RR reconstructions (inhale, intermediate, and exhale) in 1 representative subject (subject 8 of library-DB). Depicted are the time-resolved GRE localizer (left) and the 3D sum of magnitudes (SOM) of 8 channel-wise GRE images (acquired for each transmit channel) to suppress $B_1^+$ related artefacts and to analyze the impact of respiration on the NRR and RR reconstructions. SB (Figure 1A) yields similar qualitative results for NRR as compared to RR for respiratory motion amplitudes of HF ~ 12 mm, AP ~ 1.5 mm. For DB (Figure 1B), however, differences between NRR and RR reconstructions because of strong respiratory motion (HF ~ 65 mm, AP ~ 12 mm) such as blurring and motion-induced artefacts (indicated
by an arrow) can be observed in the NRR images. The impact of SB and DB on the FA predictions is shown in Supporting Information Figure S1.

### 3.2 Performance of universal and tailored pulses

Figure 2 shows the resulting coefficient of variations (CVs) of the predicted FA patterns in the heart volume generated by 6 different pTx pulses during SB (Figure 2A) and DB (Figure 2B) in 1 representative subject (subject 8 of library-DB; similar results are obtained in the other subjects). Depicted are the evaluations of UP-SBDB, tailored-NRR, tailored-RSpec, and tailored-RRob for exhale, intermediate and inhale motion states. The tailored-NRR pulse yielded low CVs for SB (mean, 8.3%, range, 7.6%–8.7%), but resulted in a larger mean and variation for DB (mean, 15.1%, range, 11.7%–19.8%). The UP-SBDB yielded higher mean CV values (i.e., less FA homogeneity) for SB (mean, 10.81%, range, 10.18%–10.66%), but lower mean CV values for DB (mean, 13.0%, range, 12.3%–14.1%). For tailored-RSpec and tailored-RRob pulses, only minor CV differences were observed.
AIGNER et al. for SB with comparable FA distributions. For DB, however, the CV differences were more pronounced. For instance, the tailored-RSpec pulse designed for inhale resulted in a CV of 7% for inhale, but in 14% for exhale. As expected, the tailored-RRob pulse decreased the FA spread across all respiration states. Even more remarkably, the CVs of the tailored-RRob pulse (8%–9%) remained in the same range as the CVs of the tailored-RSpec results (7%–8%). The FA predictions for DB are shown in Supporting Information Figure S2.

3.2.1 Performance of different pTx pulses across multiple subjects

Figure 3A shows the CV in the heart volume for all 76 datasets (library-SB, test-cases-SB, library-DB and test-cases-DB) using 3 different UPs. UP-SB and UP-SBDB achieve more homogeneous FAs than UP-DB for the unseen test-cases with median CVs of 12.9% and 12.8% versus 14.4%. Moreover, UP-DB resulted up to 22.1%, which might reflect an insufficient database size of only

![FIGURE 2](https://example.com/figure2.jpg)
In summary, UP-SBDB performed best, however, UP-SB performed surprisingly well despite not using any RR DB B₁⁺-maps in the pulse design.

Figure 3B summarizes the quantitative evaluation for 45 RR-DB datasets (library-DB and test-cases-DB) for 6 different pTx pulse types. Depicted are boxplots containing the CVs combined across all respiration states. The boxplots for each respiration state are shown in Supporting Information Figure S3. Tailored-RRob perform best across all datasets and respiration states.
FA CVs across all respiration states. Individual boxplots for each of the 3 respiration states are shown in Supporting Information Figure S3. The pre-computed UP-SBDB pulse resulted in remarkably low CVs across all DB respiration states (median, 12.6%, range, 7.5%–18.2%), whereas tailored-NRR is more prone to the different respiration states and resulted in higher CVs in some of the cases (median, 12.1%, range, 7.4%–36%). Tailored-RSpec-exhale resulted in remarkably low CVs (median, 7.3%, range, 3.9%–9.5%) for the exhale state, but also resulted in elevated CVs in the intermediate state (median, 10.6%, range, 6.1%–15.9%) and exhale state (median, 13.6%, range, 6.5%–21.6%). A similar trend can be observed for tailored-RSpec-intermediate and tailored-RSpec-inhale. As expected, tailored-RRob achieved slightly larger minimal CVs compared to tailored-RSpec for the respiration state that was used in the optimization of the tailored-RSpec. However, tailored-RRob performed best across all subjects and respiration states with the lowest median CV of 8.2% and the lowest CV range of 5.1%–13.6%.

3.3 Validation of respiration specific and respiration robust pulses

Figure 4 shows a coronal slice of the 3D FA predictions for DB and RR 3D GRE images acquired with UP-SBDB, tailored-RSpec and tailored-RRob in 1 subject of test-cases-DB. Qualitatively, a close match between FA predictions and the 3D GRE images were observed. The tailored-RSpec-inhale pulse results in severe signal dropouts for different respiration states. No substantial differences (e.g., signal dropouts) between tailored-RRob and UP-SBDB were found. Supporting Information Figure S4 shows a comparison of FA prediction and GRE reconstructions during SB and DB for another subject of test-cases-DB.

Figure 5 and Supporting Information Figure S5 show a coronal view of the acquired 3D GRE datasets for SB (Figure 5A) and DB (Figure 5B) of 5 subjects using UP-SBDB, tailored-NRR, tailored-RSpec and tailored-RRob pTx pulses. Tailored-RSpec-inhale resulted in severe signal dropouts for different respiration states in 1 of the 5 subjects (arrow in Figure 5B). Qualitatively, the 3D GRE images reflect a similar image quality for tailored-RRob and UP-SBDB across all subjects indicating the feasibility of calibration-free pTx in the human heart in the case of SB, but also in the case of DB.

4 Discussion

This work investigated the impact of SB and DB on NRR and RR B^+-maps and compared the performance of different UPS and tailored k-T-point RF pulses calculated on such maps in a total of 46 subjects of different sex, age, and BMI. The results of this work demonstrate that the impact of respiration induced B^+ field changes can be successfully compensated by tailored-RRob pulses and, with slightly lower FA accuracy, but without the need for lengthy calibration times, also by respiration-robust UP-SBDB.

Qualitatively, no degraded image quality was observed when 3D GRE images acquired with UP-SBDB were compared to acquisitions using tailored-RRob pulses although numeric simulations had suggested stronger FA variations. Moreover, good image quality was observed during shallow and deep breathing with tailored-NRR (SB) or tailored-RRob (DB) and UP-SBDB (SB and DB). Therefore, tailored-NRR or UP-SBDB should be used for subjects performing SB and tailored-RRob or UP-SBDB should be used for subjects performing DB. Although UP-SBDB results in a comparable image quality as tailored pulses, UP-SBDB does not require lengthy calibration times.

We investigated 2 different reconstruction approaches for the B^+1 mapping (NRR and RR). Although NRR B^+1-maps are suitable to resolve B^+1 variations for SB, DB requires performing RR reconstructions to generate B^+1-maps free of breathing artefacts. This work also showed that such RR-DB B^+1-maps can be used to compute tailored-RSpec and tailored-RRob pulses. Whereas tailored-RSpec pulses resulted in increased FA variations, tailored-RRob pulses achieved homogeneous FA patterns across all respiration states. This observation is in line with a previous study that focused on the design of 2D spokes pulses and used B^+1 breath-hold acquired 2D B^+-maps from multiple respiration states. In that work, certain k-space trajectories yielded particularly high respiration-induced FA variations, whereas others showed a higher robustness toward respiration. The observed FA variations of tailored-RSpec pulses in this work are lower as compared to the maximum variations in Schmitter et al, which is likely a result of optimizing both, the RF weights and the excitation k-space locations in this work.

Tailored pTx in the human body can be very challenging and it is typically also very time-consuming. For instance, tailored pTx for NRR B^+1-maps in the case of SB takes ~10–15 min and tailored pTx for RR B^+1-maps in the case of DB takes more than 20 min (B^+1 mapping: 6.25 min, raw data export and RR reconstruction 7 min, manual ROI selection: 5 min, 4KT-points pulse design: 1 min and a variable time for quality checks). Moreover, subject motion between calibration and pTx application is another potential pitfall for the application of tailored pTx. Alternatively, the entire calibration time can be avoided for SB by applying pre-computed UP in the heart. In this work, we additionally tested the performance of different
For RR-DB B1+-maps. The proposed respiration-robust UP (UP-SBDB) was designed from NRR-SB and RR-DB B1+-maps and performs well across all subjects for all DB respiration states with a median CV of 12.6% compared to the median CV of 8.2% with tailored-RRob. Respiration-robust UP pulses are expected to be a good alternative to tailored-RRob pulses particularly for clinical studies, because they do not require time for pulse calibration and provide robustness to respiration. Another useful extension would be the design of pulses with large tip angles (e.g., for preparation, saturation, and refocusing), which seem to be essential for cardiac imaging to achieve relevant tissue contrast. The computationally intensive pulse optimization for larger FAs would further benefit from an offline pre-calculation or the application of fast deep-learning based approaches.31 In this work, however, this was not feasible because of power limitations of the used coil and MR system.

Overall, the results of tailored-RRob and UP-SBDB are convincing concerning the achieved FA homogenization...
and robustness across the different respiration states. A potential extension of this work would be the inclusion of $B_0$ variations in the pulse design. Nevertheless, further investigation is required to implement and validate the impact of respiration resolved 3D $B_0$-maps in the human body.26

5 | CONCLUSION

Although tailored-NRR and UP pulses are suitable for 7T 3D cardiac MR imaging under SB, this in vivo study demonstrates that UP-SBDB and tailored-RRob pulses are highly preferred to achieve 3D heart FA homogenization at 7T when subjects perform DB. Compared to tailored-RSpec pulses, tailored-RRob pulses resulted in a negligible overall decrease of the FA homogeneity with clear benefits of achieving homogeneous 3D FA across all respiration states.

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DATA AVAILABILITY STATEMENT

All design code is available at https://github.com/chaigner/UP_body and https://github.com/chaigner/tailored-RRob. The channel-wise shallow and deep breathing in vivo $B_0$ datasets are available at: https://doi.org/10.6084/m9.figsh.14778345.v2 and https://doi.org/10.6084/m9.figsh.15172899.v1.

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**SUPPORTING INFORMATION**

Additional supporting information may be found in the online version of the article at the publisher’s website.

**FIGURE S1** FA predictions for SB and DB in 1 representative subject (subject 8) when using a non-selective RF pulse with the default RF phase setting set by the coil manufacturer to provide sufficient $B_1^+$ throughout the heart and the aorta based on an electromagnetic simulation of the RF coil. Depicted is 1 sagittal slice of the 3D FA predictions for NRR and 3 RR reconstructions (inhale, intermediate, and exhale). The blue line was added as a reference line to judge the impact of the respiratory motion. Although for SB the FA predictions for RR appear to be sharper as compared to NRR, the overall FA pattern shows a similar shape, which is supported by similar CV values of 47.3%–50.0% and similar minimum FA values of 0.3°–0.6°. For DB, the spatial FA distribution and the position of the FA dropouts differ between the respiration states, but resulted also in similar CV values of 43.2%–45.0% and similar minimum FA values of 0.4°–1.2°. In general, the default RF pulse failed to generate homogeneous FA patterns for SB and DB, expressed by high CV values (mean, 46.6%, range, 43.2%–50.0%).

**FIGURE S2** Predicted FA of 6 different pTx pulse types for RR-DB in 1 sagittal slice of subject 8 of library-DB. The UP-SB and tailored-NRR were tailored on NRR-SB whereas the other pulses were tailored for the RR-DB heart ROIs. UP-SB and tailored-RRob perform best across all respiration states.

**FIGURE S3** Evaluation of 6 different pTx pulse types for RR-DB of all 15 subjects. The boxplots contain the CVs for exhale, intermediate, and inhale. The boxplots across all respiration state are shown in Figure 3B.

**FIGURE S4** Side-by-side comparison of FA predictions and reconstructed, 3D GRE images for 1 subject of test-cases-DB. SB is shown in (A) and deep breathing is shown in (B). The 3D images are free of breathing artifacts and demonstrate the feasibility to achieve a homogeneous calibration-free FA of the whole heart for SB and DB.

**FIGURE S5** Sagittal slices of 3D GRE images across the human heart acquired in 2 subjects (test-cases-DB) with tailored-NRR and UP-SBDB during SB (a), and UP-SBDB, tailored-RSpec-exhale and tailored-RRob during DB (b). The other 3 subjects are shown in Figure 5. The frames indicate if the same respiration state was used in the tailored pulse design and the measurement. White frames indicate that the same respiration state was used for optimization and measurement and orange frames indicate different respiration states. Signal dropouts are marked with an arrow. The 3D images are free of breathing artefacts and both, tailored and universal pulse result in a comparable signal of the 3D heart volume.

**TABLE S1** Explanation of the different $B_1^+$ datasets that are used throughout this work.

**TABLE S2** Explanation of the different acronyms for the different pulse types that are used throughout this work.

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