The purpose of the current study was to implement and validate joint real-time acquisition of functional and late gadolinium-enhancement (LGE) cardiac magnetic resonance (MR) images during free breathing. Inversion recovery cardiac real-time images with a temporal resolution of 50 ms were acquired using a spiral trajectory (IR-CRISPI) with a pre-emphasis based on the gradient system transfer function during free breathing. Functional and LGE cardiac MR images were reconstructed using a low-rank plus sparse model. Late gadolinium-enhancement appearance, image quality, and functional parameters of IR-CRISPI were compared with clinical standard balanced steady-state free precession breath-hold techniques in 10 patients. The acquisition of IR-CRISPI in free breathing of the entire left ventricle took 97 s on average. Bland–Altman analysis and Wilcoxon tests showed a higher artifact level for the breath-hold technique \( (p = 0.003) \), especially for arrhythmic patients or patients with dyspnea, but an increased noise level for IR-CRISPI of the LGE images \( (p = 0.01) \). The estimated transmural extent of the enhancement differed by not more than 25\% and did not show a significant bias between the techniques \( (p = 0.50) \). The ascertained functional parameters were similar for the breath-hold technique and IR-CRISPI, that is, with a minor, nonsignificant \( (p = 0.16) \) mean difference of the ejection fraction of 2.3\% and a 95\% confidence interval from –4.8\% to 9.4\%. IR-CRISPI enables joint functional and LGE imaging in free breathing with good image quality but distinctly shorter scan times in comparison with breath-hold techniques.

**KEYWORDS**
cine loop, late enhancement, late gadolinium-enhancement, magnetic resonance imaging, real-time imaging, spiral trajectory

**Abbreviations used:** bSSFP, balanced steady-state free precession; CRISPI, cardiac real-time imaging using a spiral k-space trajectory; ECG, electrocardiogram; EDV, end-diastolic volume; EF, ejection fraction; ESV, end-systolic volume; GRAPPA, generalized autocalibrating partial parallel acquisition; GROG, GRAPPA operator gridding; GSTF, gradient system transfer function; IR, inversion recovery; LGE, late gadolinium-enhancement; PSIR, phase-sensitive inversion recovery; SV, stroke volume; TI, inversion time.
1 | INTRODUCTION

Cardiac cine magnetic resonance imaging allows for assessment of myocardial morphology, regional and global kinetics, and cardiac function. Late gadolinium enhancement (LGE) imaging represents the current gold standard in myocardial viability assessment, as it enables an excellent depiction of acute and chronic myocardial infarction and detection of fibrotic and inflamed tissue. Typically, data for cine and LGE imaging are acquired independently, but both sets are sampled in a segmented pattern across several heartbeats for each slice or group of slices. This results in lengthy total acquisition times and requires patients to have the ability to hold their breath intermittently for the duration of these protocols. Conventional LGE imaging requires prospective contrast agent application and acquires one image with one specific contrast at a predefined heart phase. Optimal contrast can be achieved by setting the inversion time (TI) to the value that nulls the signal of healthy myocardium. However, TI must be adjusted by the examiner prior to the acquisition.

Conversely, nonsegmented real-time magnetic resonance (MR) imaging offers the means to acquire cardiac MR images without the need for breath-holds. Technical advances have continuously improved the quality of cardiac real-time imaging over recent years. In particular, non-Cartesian sampling schemes and compressed sensing techniques have aided in the improvement of spatial and temporal resolution. By applying a gradient system transfer function (GSTF)-based gradient pre-emphasis, trajectory errors in non-Cartesian imaging could be eliminated and stable cardiac real-time imaging using spiral read-outs (CRISPI) were enabled at both high spatial and temporal resolution.

In this work, we combine real-time CRISPI imaging with an initial inversion of the magnetization (IR-CRISPI) to allow the reconstruction of cine and LGE images from a single dataset acquired in free breathing. In 10 patients with cardiac disease, IR-CRISPI examinations of the whole human left ventricle acquired in less than 120 s were compared with cine and LGE images obtained in the same setting using conventional segmented breath-hold techniques.

2 | EXPERIMENTAL

2.1 | Patient study

This prospective study was approved by the ethics committee of the Medical Faculty of the University of Würzburg. Written informed consent was obtained from all subjects. The inclusion criteria were clinical indication and a patient’s suitability for contrast-enhanced cardiac MRI. In total, 10 patients (seven men, three women; mean age 52.4 years; age range 20–78 years) were enrolled in this study with the following underlying cardiac disease: acute myocardial infarction (four patients), Fabry disease (four), myocarditis (one), and one patient with left ventricular hypertrophic cardiomyopathy and a history of myocardial ablation. The exclusion criteria were general contraindications to MRI.

The examinations were conducted on a 3-T MR scanner (MAGNETOM Prisma; Siemens Healthcare, Erlangen, Germany). All 10 patients received the contrast agent intravenously (0.4 ml/kg body weight of Dotagraf [Jenapharm, Jena, Germany]). Prior to contrast agent application, a balanced steady-state free precession (bSSFP) cine acquisition was performed, as is typical for clinical routine: (TE: 1.41–1.51 ms, TR: 3.19–3.48 ms, flip angle: 42°–50°, in-plane resolution: 1.44 × 1.44–1.26 × 1.26 mm², slice thickness: 8 mm, temporal resolution 38.3–40.9 ms). The acquisition was performed in breath-holds over 12 heartbeats. Parallel imaging was applied with an acceleration factor of 2. Twenty-five cardiac phases were reconstructed.

Subsequently, the contrast agent was applied intravenously. After a delay of 9 min, a 2D spoiled gradient echo sequence with global inversion preparation was acquired. The read-out used a spiral trajectory with an angle increment of 36° for 10 consecutive measurements. Consecutive blocks of 10 read-outs were twisted by one-fifth of the golden angle (≈ 22.25°) to fill gaps in k-space over time. The time course of the IR-CRISPI sequence and the magnetization are depicted schematically in Figure 1. The sequence starts with an ECG-trigger. An adjustable delay (td) allows shifting the LGE images with optimal contrast (suppression of the signal of healthy myocardium) to the intended cardiac phase. Prior to triggering the subsequent slice, a fixed second delay (tC14,C14) was applied to re-establish an almost completely recovered longitudinal magnetization.

The sequence parameters were set to TE: 0.84 ms, TR: 5.0 ms, flip angle: 12°, tC14,C14: 3 s, and in-plane resolution: 1.54 × 1.54–1.42 × 1.42 mm². td was set to 300 ms for the acquisition of LGE images in diastole for eight of the 10 patients with heart rates of 54 to 74 beats per min. td was adjusted to 100 or 450 ms, respectively, for the patients with heart rates of 93 and 40 beats per min. Twelve to 16 slices with 8-mm slice thickness were acquired without gaps. To avoid artifacts originating from changes in the non-Cartesian read-out trajectory, an automatic pre-emphasis based on the GSTF was used for all three physical gradient axes. To this end, the scanner-specific GSTF was measured and its inverse was used to correct the input waveforms for the gradient amplifiers.

Directly following the IR-CRISPI sequence, a TI scout for the preparation of conventional LGE imaging was acquired. With the individually determined TI a routine breath-hold IR-bSSFP sequence was applied with TE: 1.50–1.54 ms, flip angle: 40°, breath-hold durations of 10–12 s and TI: 300–390 ms, five inversion preparations and resolution: 1.25 × 1.25–1.41 × 1.41 mm².
Reconstruction

The IR-CRISPI images were reconstructed offline using MATLAB (MathWorks, Natick MA). Ten consecutive spiral read-outs each were initially binned for a temporal resolution of 50 ms and a total of 70 undersampled Cartesian k-spaces were created using generalized autocalibrating partial parallel acquisition (GRAPPA) operator gridding (GROG). From these k-spaces, 70 images with a field of view between 725 x 725 and 771 x 771 mm$^2$ were reconstructed using a low-rank plus sparse approach, similar to CRISPI. In addition to the latter, a spatial wavelet constraint was applied for improved denoising performance. The underlying optimization problem can be formulated as

$$
\min_{L, S} \frac{1}{2} \|E(L + S) - d\|_2^2 + \lambda_L \|L\|_1 + \lambda_S \|TS\|_1 + \lambda_W \|W(L + S)\|_1.
$$

The norms denoted with 1, 2, and * represent $l_1$, $l_2$, and the nuclear norm, respectively. $d$ is the measured data, $E$ the multicoil encoding operator, $T$ the temporal Fourier transform, and $W$ the wavelet transform. $S$ is the sparse and $L$ the low-rank part of the time-resolved image series. The regularization parameters $\lambda_L$, $\lambda_S$, and $\lambda_W$ were chosen empirically ($\lambda_L : 0.01$, $\lambda_S : 0.05$, $\lambda_W : 0.003$). The optimization problem was solved using a proximal gradient method. The reconstruction of a single slice consisting of 70 2D frames took 40 min on a workstation with an Intel Xeon W-2195 CPU@ 2.3 GHz and 256 GB main memory.

For evaluation of the cardiac function, the images of the second heartbeat were chosen. To assess late gadolinium-enhancement, the 20 images acquired in the first second after the inversion pulse were selected. Additionally, 19 images were created by linear interpolation from two consecutive images, respectively, to decrease $\Delta TI$ of the reconstructed images to 25 ms. Magnitude and phase-sensitive (PSIR) images were determined.

Evaluation

IR-CRISPI cine was quantitatively compared with the breath-hold cine. Using cvi42 (Circle Cardiovascular Imaging Inc., Calgary, Canada) for each patient the end-diastolic volume (EDV), the end-systolic volume (ESV), ejection fraction (EF), stroke volume (SV), and the myocardial mass in diastole were manually determined by a physician (with 5 years of experience in cardiovascular imaging).

IR-CRISPI LGE images were compared with the breath-hold LGE images by two physicians (with 5 and 10 years of experience in cardiovascular imaging). On a patient by patient basis, both physicians independently determined the existence of late gadolinium-enhancement on the IR-CRISPI LGE images and the LGE images from the breath-hold sequence. The images of both sequences were evaluated on a five-point scale (0–4; 0: low, 1: rather low, 2: medium, 3: rather high, 4: high; or stated otherwise) according to:
Transmurality (0: none, 1: 0%–25%, 2: 25%–50%, 3: 50%–75%, 4: 75%–100%)
confidence in the late gadolinium-enhancement assessment (0: none, 1: unsure, 2: potential, 3: probable, 4: certain)
overall image quality
artifact level
noise level
image contrast between late gadolinium-enhancement and myocardium
image contrast between late gadolinium-enhancement and blood.

The contrast ratings were omitted for patients without any or with uncertain late gadolinium-enhancement. Regarding each patient, the reviewers also stated whether they had used multiple TI contrasts from IR-CRISPI for the interpretation.

2.4 | Statistics

IR-CRISPI images were compared with those of the breath-hold technique by Bland–Altman analysis. To test for significant differences between the results from IR-CRISPI and the breath-hold acquisition, a Wilcoxon signed-rank test was performed. The significance level was set to 0.05 without correction for multiple testing.

3 | RESULTS

IR-CRISPI images, including both LGE and cine depiction of the entire left ventricle in short axis view, could be acquired on average in 97 s in 10 patients.

FIGURE 2  Selection of IR-CRISPI images from a 58-year-old man with acute antero-septal infarction and microvascular obstruction. (A) Four slices at different positions with TI = 285 ms. (B) IR-CRISPI magnitude images of a midventricular slice at TI = 185, 285, and 985 ms (in systole) and TI = 1385 ms (in diastole). The dotted line shows the cross section for the time course in (D). (C) IR-CRISPI PSIR images of a midventricular slice at TI = 185 and 285 ms. (D) Time course of the profile indicated in (B). IR-CRISPI, inversion recovery-cardiac real-time imaging using spiral read-outs; PSIR, phase-sensitive inversion recovery
Figure 2 shows IR-CRISPI images from a 58-year-old man with acute antero-septal infarction. Four out of 15 slices acquired in short axis orientation are shown at $T_1 = 285$ ms in Figure 2A. An area of late gadolinium-enhancement involves large parts of the antero-septal wall with signs of microvascular obstruction and a transmurality greater than 75%. Figure 2B presents IR-CRISPI images from a midventricular slice at four different TIs, including a short TI (185 ms), an optimal contrast for late gadolinium-enhancement (285 ms), and images in systole and diastole in steady-state contrast ($T_1 = 985$ and 1385 ms, respectively). IR-CRISPI PSIR images ($T_1 = 185$ and 285 ms, respectively) are presented in Figure 2C. The time course of the profile (indicated in Figure 2D) illustrates rapidly changing contrasts in the first second. Subsequently, IR-CRISPI images with steady-state contrast show the cardiac and breathing motion.

### 3.1 Functional analysis

Depending on the individual heart rate, 13–29 images with a temporal resolution of 50 ms were reconstructed from the second heartbeat after the inversion for IR-CRISPI. Figure 3 shows a comparison of the breath-hold cine and the IR-CRISPI results for a 49-year-old patient with Fabry disease. Images acquired in systole and diastole and a time course of a horizontal profile are shown in the three rows, respectively. Bland–Altman plots comparing the parameters of cardiac function for IR-CRISPI with the breath-hold cine sequence are presented in Figure 4. Biases and confidence intervals are additionally listed in Table 1 (upper rows). The analysis yields a bias of breath-hold technique versus IR-CRISPI of 6.5 ml (3.8%) in EDV, −1.2 ml (−1.7%) in ESV, 2.3% (4.8%) in EF, 7.7 ml (8.8%) in SV, and 5.0 g (3.2%) in myocardial mass. The Wilcoxon signed-rank test did not show any significant differences between IR-CRISPI and the breath-hold sequence ($p$ values regarding EDV: 0.38, ESV: 0.63, EF: 0.16, SV: 0.23, and mass: 0.28).

### 3.2 LGE imaging

Figure 5 shows the LGE images of a 54-year-old male patient with acute infarction. The image acquired with the breath-hold sequence (Figure 5A) and the IR-CRISPI images reconstructed for different TIs (Figure 5B1: 135 ms; Figure 5B2: 235 ms; and Figure 5B3: 260 ms) show a
FIGURE 4  Bland–Altman plots of end-diastolic volume (EDV), end-systolic volume (ESV), ejection fraction (EF), stroke volume (SV), and myocardial mass of all 10 patients for IR-CRISPI cine and breath-hold cine. IR-CRISPI, inversion recovery-cardiac real-time imaging using spiral read-outs.

TABLE 1  Bias and confidence interval (1.96 × standard deviation) of Bland–Altman analysis of the results for the IR-CRISPI sequence with respect to the breath-hold sequences

|                      | Bias | Confidence interval |
|----------------------|------|--------------------|
| EDV (ml)             | 6.54 | 35.5               |
| ESV (ml)             | -1.19| 9.24               |
| EF (%)               | 2.29 | 7.07               |
| SV (ml)              | 7.72 | 31.5               |
| Mass (g)             | 4.96 | 20.2               |
| Transmurality        | 0.20 | 1.33               |
| Confidence in assessment | 0.05 | 1.31               |
| Overall quality      | 0.05 | 2.01               |
| Artifact level       | 0.75*| 1.74               |
| Noise level          | -0.80*| 2.02               |
| Contrast LGE/myocardium | 0.47  | 1.73               |
| Contrast LE/blood    | 0.20 | 3.14               |

Note: Significant differences are marked with an *.

Abbreviations: EDV, end-diastolic volume; EF, ejection fraction; ESV, end-systolic volume; IR-CRISPI, inversion recovery-cardiac real-time imaging using a spiral k-space trajectory; LGE, late gadolinium-enhancement; SV, stroke volume.

FIGURE 5  LGE images of a 54-year-old man with acute infarction in the infero-lateral midventricular wall with involvement of papillary muscle and a transmurality greater than 75%. Comparison of an image of the breath-hold technique (A) with IR-CRISPI images reconstructed for different times after the inversion (B1–B3). (B1) For an early TI of 135 ms the infarcted tissue appears dark, while remote myocardium is still bright. At and after the zero-crossing of the myocardial signal the infarcted region is bright (B2) at TI = 235 ms, (B3) at TI = 260 ms. IR-CRISPI, inversion recovery-cardiac real-time imaging using spiral read-outs; LGE, late gadolinium-enhancement.
late enhancement in the infero-lateral midventricular wall with a transmurality greater than 75% and involvement of papillary muscle. While the finding is obvious in both techniques in this slice, the noise level on average was rated higher for IR-CRISPI (IR-CRISPI: 2.0; breath-hold 0.0).

Another example shows the LGE images of a 38-year-old man with Fabry cardiomyopathy (Figure 6). A typical patchy area of late gadolinium-enhancement was observed in the lateral wall, corresponding to a focal intramural fibrosis. The artifact level for this patient was clearly higher for the breath-hold sequence (average ratings IR-CRISPI: 0.5; breath-hold: 2.0). This correlates with the patient’s difficulties in holding his breath. Indeed, the acquisition of some slices of the breath-hold late gadolinium-enhancement technique for this patient had to be repeated because of severe motion artifacts (Figure 7). The image shown in Figure 7A1 was not included in the evaluation.

The ratings regarding the presence of late gadolinium-enhancement, transmurality, and confidence in the assessment of the two readers are listed in Table 2. The evaluated LGE transmurals from the IR-CRISPI and the breath-hold technique differed by 25% at maximum. Also, the confidence in the assessment at most differed by only one grade between the different sequences. The detection of late gadolinium-enhancement agreed between IR-CRISPI and the breath-hold technique in nine of the 10 patients.

The results of Bland–Altman analysis of all evaluated parameters for LGE imaging are presented in the lower rows of Table 1. Bland–Altman analysis showed a small bias between the techniques for the transmurality, confidence in assessment, and the overall image quality (a median of 3 [rather high] for both techniques). The contrast of the breath-hold images was rated as superior, but the Wilcoxon test did not show a significant difference. The largest average differences between the IR-CRISPI and the breath-hold method were found for artifact level (+0.75) and noise level (−0.80). These differences were significant according to the Wilcoxon test.

For each patient, both readers stated that they had used multiple TI contrasts for the evaluation of IR-CRISPI LGE images.

Figure 8 shows the LGE images of a 66-year-old woman with Fabry cardiomyopathy. For this patient (#5 in Table 2), the assessment of existence of a late gadolinium-enhancement differed between the methods for one reader. Again, motion artifacts hamper the evaluation of the images acquired with the breath-hold technique. Nevertheless, both readers judged the findings in the lateral wall in Figure 8A1 as late gadolinium-enhancement. Because of its acquisition in free breathing, IR-CRISPI shows slightly different slices of the heart. In these IR-CRISPI images (Figure 8B1–8B3), no late gadolinium-enhancement is detectable. However, reader 1 detected a shallow enhancement in the lateral wall when viewing the images from the first second after the inversion in cine mode.
**TABLE 2** LGE ratings from two radiologists for the breath-hold reference and IR-CRISPI

| Patient # | LGE present? | Transmurality | Confidence in assessment |
|-----------|--------------|---------------|--------------------------|
|           | reference    | IR-CRISPI     | reference | IR-CRISPI | reference | IR-CRISPI | reference | IR-CRISPI |
| 1         | no/no        | 0/0           | 3/3        | 4/3        |
| 2         | yes/yes      | 4/4           | 4/4        | 4/4        |
| 3         | yes/yes      | 3/3           | 3/3        | 4/3        |
| 4         | no/no        | 0/0           | 4/4        | 4/4        |
| 5         | yes/yes      | 2/3           | 3/2        | 2/3        |
| 6         | yes/yes      | 3/3           | 3/4        | 4/3        |
| 7         | yes/yes      | 1/2           | 4/4        | 4/4        |
| 8         | yes/yes      | 2/2           | 3/4        | 2/3        |
| 9         | yes/yes      | 4/4           | 4/4        | 4/4        |
| 10        | yes/yes      | 4/4           | 4/4        | 4/4        |

Note: (reader 1/reader 2) transmurality of the LGE: (0: none, 1: 0%–25%, 2: 25%–50%, 3: 50%–75%, 4: 75%–100%); confidence in assessment: (0: none, 1: unsure, 2: potential, 3: probable, 4: certain). The rating of late gadolinium-enhancement detection is inconsistent for IR-CRISPI images of patient 5 between the two radiologists.

Abbreviations: LGE, late gadolinium-enhancement; IR-CRISPI, inversion recovery cardiac real-time imaging using a spiral k-space trajectory.

**FIGURE 8** Exemplary LGE breath-hold (A) and IR-CRISPI (B) images at different slice positions of a 66-year-old woman with Fabry cardiomyopathy. (A1) shows a late enhancement in the lateral wall (white arrow). Artifacts can be seen in the myocardium in the breath-hold image (red arrows). No late gadolinium-enhancement is visible in the static IR-CRISPI images with optimal myocardial contrast (B) in mid-diastole.

IR-CRISPI, inversion recovery cardiac real-time imaging using a spiral k-space trajectory; LGE, late gadolinium-enhancement

**4 | DISCUSSION**

IR-CRISPI in free breathing allows for acquisition of functional cine and LGE images within a single real-time acquisition per slice and achieves an image quality comparable with conventional breath-hold scans. The total acquisition time of less than 100 s on average for the complete coverage of the left ventricle for IR-CRISPI is significantly shorter compared with the duration of two acquisitions, as conventionally performed in clinical practice breath-hold imaging (cine and LGE images). For the latter, 12–16 slices in total are necessary, corresponding to 24–32 breath-holds for the patient. Thus IR-CRISPI not only reduces motion artifacts, it also clearly improves the comfort, especially for patients with dyspnea. In addition, the reduced scan time also has an overall economic impact.
Recommendations for protocols for cardiovascular imaging already suggest real-time acquisition for cardiac cine and LGE imaging for patients with arrhythmic heartbeats or for those who experience difficulties in holding their breath. In these recommendations, as well as in the current study, the ‘term ‘real-time’ is used for dynamic imaging without the need for repetition’. As slice orientation and slice thickness are recommended to be identical for cine and LGE imaging, a combination of both techniques is straightforward. Compared with first implementations, technical advances allow for higher spatial and temporal resolutions. Additionally, spiral trajectories offer more flexibility in covering the k-space compared with Cartesian and radial acquisitions. The employment of nonselective inversion pulses requires a minimum time interval between two inversions (\( t_{\text{seq}} + t_e \)), even for two different slices, in order to re-establish an almost completely recovered longitudinal magnetization. If the acquisition of the functional information fits into this interval, the combined acquisition of LGE and cine information is less time consuming compared with running independent LGE and cine real-time acquisitions. Additionally, the low-rank plus sparse reconstruction benefits from the combination of LGE and cine information by a potentially superior determination of the low-rank part. To test the highest possible acceleration, the second heartbeat was used for the functional evaluation in our study. This can allow a reduction of the acquisition duration \( t_{\text{seq}} \) and subsequent optimization of \( t_e \) in future studies.

Promising results of real-time cine imaging using undersampled spiral real-time imaging have already been proposed. The cine results for IR-CRISPI are similar to these published results. However, the standard deviation of the difference between both methods for EDV and SV were higher in the current study compared with the results published recently. This could be caused by the selection of patients for this study. We also included patients unable to hold their breath or with irregular heartbeats. Dyspnea and arrhythmia not only cause image artifacts in the breath-hold images, they can also lead to variations of averaged EDVs and SVs compared with the volumes determined from individual heartbeats.

In the current study, the timing after contrast agent application was optimized for the LGE breath-hold sequence. IR-CRISPI was acquired in the dead time between contrast agent application and acquisition of the LGE images with the breath-hold technique, as part of the standard protocol. While the contrast of the IR-CRISPI cine might have profited from the contrast agent, especially in the blood, the contrast in the IR-CRISPI LGE images could have been decreased compared with the breath-hold sequence because of early acquisition after contrast agent delivery. Theoretically, it might be a disadvantage of the IR-CRISPI technique that the timing after contrast agent administration is the same for both cine and LGE images.

The detection of late gadolinium-enhancement was equal for both techniques in all patients except for one patient with Fabry disease. This patient’s images showed a discrete enhancement that could not be identified by both readers in the IR-CRISPI images. Whether differences in the detectability of late gadolinium-enhancement might have been caused by the time point after contrast agent application, by an unfavorable cardiac phase at the best LGE contrast, or because of other reasons, remains to be determined by future studies. In the current study, different slices were acquired in different breathing states. This might have led to slice misalignment and eventually to gaps between neighboring slices. To avoid this, respiratory gating could be used in future studies. On average, the overall image quality of IR-CRISPI and the breath-hold technique are rated as similar. Especially in patients unable to hold their breath or those with irregular heartbeats, artifacts corrupted the image quality in the breath-hold technique. In these patients, the IR-CRISPI LGE image quality was superior to that of the breath-hold technique. Artifacts caused by through-plane motion in the free breathing sequence were not observed. On the other hand, as expected, the distinctly shortened acquisition time as well as the implementation of IR-CRISPI as spoiled gradient echo leads to decreased signal-to-noise ratio compared with bSSFP acquisition in the breath-hold technique. Nevertheless, the determined transmurality as well as the confidence in the assessment were both rated as being similar for IR-CRISPI and the breath-hold method.

An advantage of IR-CRISPI is the possibility of varying the contrast (TI) after acquisition of the data. While in our study the prospectively selected TI was adequate in all patients, IR-CRISPI at least renders the acquisition of a TI scout unnecessary. In the future, IR-CRISPI’s short acquisition time could be exploited to a further extent. For example, the dynamics of the wash in and wash out of the contrast agent, artifacts caused by through-plane motion in the free breathing sequence were not observed. On the other hand, as expected, the distinctly shortened acquisition time as well as the implementation of IR-CRISPI as spoiled gradient echo leads to decreased signal-to-noise ratio compared with bSSFP acquisition in the breath-hold technique. Nevertheless, the determined transmurality as well as the confidence in the assessment were both rated as being similar for IR-CRISPI and the breath-hold method.

In general, IR-CRISPI can be considered a real-time extension of recently proposed techniques combining relaxation time mapping in the myocardium and cine imaging. Fast free breathing imaging is made possible with IR-CRISPI by optimizing the k-space coverage using spiral trajectories instead of radial read-outs. Additionally, the short TE of 0.84 ms realized by the center out spiral helps to reduce \( T_2^* \) effects. Reconstructing the images based on a low-rank plus sparse model furthermore waives the need for image registration, as used in alternative approaches. In-plane motion correction algorithms typically prolong the overall reconstruction time and introduce the risk of additional image distortion or blurring. In this study, we assumed that respiratory through-plane motion could be neglected. In future studies, this assumption has either to be investigated by measuring the breathing motion in a slice perpendicular to the IR-CRISPI slices, or the motion can be frozen by adding an additional respiratory trigger to the sequence.

5 | CONCLUSION

The proposed IR-CRISPI technique allows for joint assessment of cardiac function and myocardial viability in free breathing within a short scan time of less than 100 s for the whole left ventricle. IR-CRISPI reduces artifacts caused by the inability of a patient to hold their breath or because of arrhythmia. Additionally, IR-CRISPI imaging allows retrospective adjustment of the TI, which waives the need for additional TI scout.
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CONFLICT OF INTEREST
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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are openly available in zenodo at DOI: 10.5281/zenodo.5729315. URL: https://zenodo.org/record/5729315#.YaDOR9DMKMq

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