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Retrospective self-gating for single-petal rosette trajectory in 2D lung imaging

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Purpose: To investigate the performance of retrospective self-gating techniques in combination with the single-petal rosette (SPR) trajectory for 2D imaging of the lung.

Methods: Eight healthy volunteers underwent free-breathing and breath-hold MRI using the single-petal rosette trajectory (SPR), as well as radial UTE acquisition combined with the tiny golden angle acquisition scheme. Retrospective self-gating techniques (k-space based, image based and nuSG) were used for reconstruction with temporal resolutions of 50, 75 and 100 ms. The SPR trajectory was compared with the conventional radial UTE technique regarding image sharpness and signal-to-noise ratio (SNR) for all investigated resolutions.

Results: Low-spatial high-temporal resolution images used for image-based self-gating techniques benefit from more the efficient k-space sampling pattern of SPR. Image sharpness values are lower for SPR compared with radial UTE for all temporal resolutions but especially prominent for 75 ms temporal resolution. The same was found for SNR, where the highest increase was found for a temporal resolution of 75 ms.

Conclusion: Exploiting the higher efficiency in k-space sampling of the full-petal SPR for image based self-gating can be a means of decreasing temporal resolution.

KEYWORDS

lung MRI, UTE imaging, retrospective self-gating, image based self-gating, breath-hold

1 Introduction

Evaluation of pulmonary function and structure can be done non-invasively using lung magnetic resonance imaging (MRI). The development of reliable and innovative imaging techniques is in increasing demand to address the challenges of lung magnetic resonance imaging, such as respiratory and cardiac motion and low signal intensity of the lung parenchyma due to low proton density. Magnetic resonance imaging of the lung has the advantage of analysis of lung function, including fractional ventilation [1] (FV) and perfusion [2], which probably provides valuable information on lung physiology.

Radial (center-out) k-space sampling schemes, such as radial ultra-short echo time (UTE) [3] and zero echo time (ZTE) [4] have developed to be suitable sequences to counteract the intrinsically short T_2^* relaxation times of lung tissue [3, 5–7] by starting data acquisition immediately after excitation.

However, respiratory and cardiac motion still severely limit scan duration, even when exploiting the sub-Nyquist imaging capabilities of UTE sequences, especially by employing specific angular increments [8–11]. More efficient k-space coverage can be achieved by, e.g., the single-petal rosette trajectory (SPR), which has been proven feasible for imaging of the lung [12, 13] and the brain [14, 15], as well as quantification of the sodium content in articular cartilage [16], which all present with low T_2^* related challenges. Nevertheless, breath-hold imaging limits scan durations to some seconds and relies on patient cooperation. To reliably eliminate respiratory motion, retrospective self-gating techniques can be implemented without the need for additional hardware or measurements, since the gating signal is derived from the imaging data. The self-gating signal can be obtained either from the spatial frequency domain (k-space) [17–19] or from a navigator signal obtained from low-spatial high-temporal resolution images [7, 20].

It has been proposed that the increased k-space coverage of the SPR trajectory could be exploited to decrease temporal resolution of retrospective self-gated images, while keeping the radial UTE-like contrast by only using the center-out half of the petal for final reconstruction. In this work we combine the SPR trajectory with k-space based, as well as image-based retrospective self-gating techniques, including non-uniform self-gating (nuSG) [21] and comparing the performance with radial UTE.

2 Methods

2.1 MR imaging

This work compares two center-out UTE trajectories providing similar contrast. The classic radial UTE [1] that is realized by a straight radial center-out read-out (RO), followed by a rephasing gradient along the same trajectory before spoiling. The second trajectory takes advantage of the rephasing time and replaces the reversed gradients in radial UTE by a rosette petal parametrized by

$$\begin{aligned} \mathbf{k}(t) &= k_x(t) + ik_y(t) \\ &= k_{\max} \sin(\omega t) e^{it}, \end{aligned} \quad (1)$$

where ω accounts for the general shape of the rosette and is chosen from the interval $\omega \in \mathbb{R}$. For $t \in [0, \pi/\omega]$ the rosette reduces to a single petal, starting and ending in k_0 . By doing so, the k-space coverage by read-out can be highly increased with almost negligible increase in repetition time. The trajectory design is described in further detail in [12]. During playing out the entire petal, data is acquired, however, if solely the first half of the petal is used for image reconstruction, radial UTE-like contrast can be achieved. The full petal is used for the reconstruction of preliminary images applied for gating as further described in section 2.2.

A parametrization of the SPR trajectory of $\omega = 5/3$ in Equation 1 was chosen for this publication. The trajectory was calculated in MATLAB (MathWorks, Natick, Massachusetts, United States) and respective gradient waveforms derived by minimizing read-out time considering a maximum gradient strength of 20 mT/m, as well as maximum slew rate of 150 T/m/s. Total read-out duration for SPR was $t_{\text{acq,SPR}} = 1.01$ ms, leading to an effective acquisition time of $t_{\text{acq,SPR,eff}} = 0.51$ ms for the center-out part used for final image reconstruction.

TABLE 1 Scan parameters for the 2D breath-hold SPR acquisitions and radial UTE acquisitions.

2D Acq.	SPR	Radial UTE
FOV/mm	450 × 450	450 × 450
slice thickness/mm	20	20
Matrix	224 × 224	224 × 224
Res./mm	2 × 2 (in-plane)	2 × 2 (in-plane)
TR/ms	3.1	2.6
TE/ms	0.45	0.45
Flip Angle/°	6	6
Scan Duration/s (BH/FB)	2.39/113	1.99/93

Images were acquired on a Philips 3 T whole body MRI (Ingenia 3.0 T CX, Philips Healthcare, Best, Netherlands) using a 16ch DStream torso coil (Philips Healthcare, Best, Netherlands) in combination with an integrated 16ch posterior coil.

In-vivo imaging was performed in eight healthy volunteers with no reported respiratory disorders, with written informed consent obtained prior to examination. A single coronal slice, centered at the bifurcation of the trachea was acquired in each volunteer. Said slice was measured three times for each of the two trajectories (SPR and radial UTE): once in the inhaled state (breath-hold), once in the exhaled state (breath-hold) - each for a duration of 2.4 s for SPR and 1.99 s for radial UTE - and once continuously during free breathing for a total scan duration of 113 s for SPR and 93 s for radial UTE. TE was kept the same for SPR and radial UTE, whereas TR was kept minimal at 3.1 s for SPR and 2.6 m for radial UTE. The number of interleaves for the breath-hold images was chosen equal to the number of interleaves required to Nyquist sample k-space based on the radial UTE sampling scheme (703 interleaves). All relevant scan parameters are shown in Table 1.

2.2 Reconstruction

After data acquisition, raw data were exported and processed with MATLAB (MathWorks, Natick, Massachusetts, United States). Images were obtained using gridding [22] with an oversampling factor of 1.25, a Kaiser Bessel kernel for interpolation and in combination with a 2D Voronoi tessellation for density compensation. During trajectory calculation gradient delays were carefully considered [23] and remaining eddy current induced distortions modeled by a mono-exponential decay function [24] with time constant of $\tau = 43 \mu\text{s}$. No post-processing was applied to any of the presented images.

For evaluation of the trajectory performance for different temporal resolutions when using self-gating, 4 different retrospective self-gating techniques were compared: k_0 -based self-gating (SG_{k_0}), two image-based approaches (SG_{img}), as well as the non-uniform self-gating approach (nuSG).

The k-space based approach [17–19] uses the during each read-out intrinsically measured DC-signal from manually selected coil elements. The DC-amplitudes are bandpass filtered using cut-off frequencies that are individually determined for each volunteer based on a power spectrum analysis. Principal component analysis yields the final respiratory navigator signal that is subsequently sectioned equidistantly along the time axis to obtain the respiratory stages.

The images-based approaches [7, 20], as well as the nuSG approach [21] rely on low-spatial high-temporal resolution images. The required dynamic data is reconstructed applying a sliding window technique with temporal resolution per image of 100, 75 and 50 ms, resulting to 32/39 read-outs for a resolution of 100 ms, 24/29 read-outs for a resolution of 75 ms and 16/19 read-outs for a resolution of 50 ms for SPR/radial UTE, respectively, for the sliding-window reconstruction.

In case of the image-based gating reconstruction, a line was manually placed over the lung-liver interface (LLI). Its line profile automatically underwent gradient analysis to obtain the self-gating signal. The identification of the respiratory stages followed a histogram-based binning approach for the first image-based self-gating technique ($SG_{img,hist}$) and an absolute value based approach for the second image-based self-gating technique ($SG_{img,abs}$).

The nuSG reconstruction is based on the reconstruction process that is described in detail in [21]. The low-spatial high-temporal resolution images obtained by the sliding-window reconstruction were used to identify a region of interest (ROI) covering the LLI and, by pairwise correlation of all frames, a correlation matrix M_c was calculated. Paths of high correlation coefficients were identified using a contour fit approach. Certain motion states are reconstructed from the intersections of the motion state and all grown contour fits combined.

All self-gating reconstruction techniques are described in further detail in [25].

2.3 Image analysis

For further assessment of all images, the parenchyma was segmented semi-automatically by manually drawing approximate contours around the left and right lung and by subsequently applying intensity thresholds to exclude large vessels.

The signal-to-noise ratio (SNR) of the lung parenchyma was calculated according to [26] by

$$SNR = \sqrt{2 - \frac{\pi}{2} \frac{SI_{ROI}}{\sigma_{BG}}}, \quad (2)$$

where SI_{ROI} is the mean intensity within a selected ROI and σ_{BG} is the noise standard deviation of the pixel intensities within a selected background ROI. The square-root pre-factor in Equation 2 corrects for the Rician distribution of noise in the evaluated magnitude images.

To check for statistically significant differences in SNR, a Wilcoxon signed-rank test for paired samples was performed, with p -values smaller than 0.05 considered significant.

Image sharpness assessment was done across an intensity line profile over the LLI. The position of the pixels corresponding to 25 and 75% of the maximum signal intensity was identified by

a standard metric [21, 27] and the resulting distance used as a sharpness measure.

3 Results

3.1 Image quality and overall gating performance

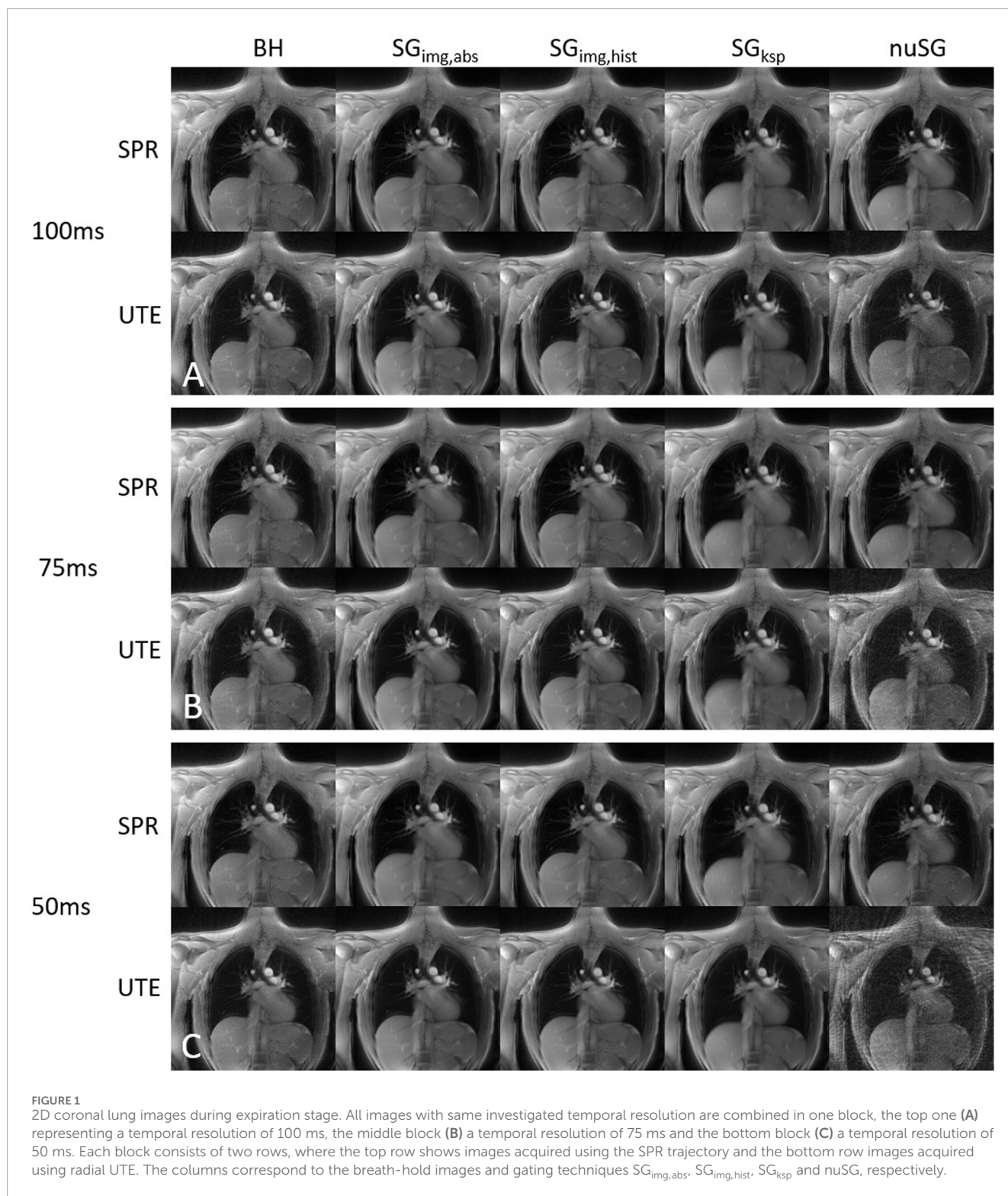
Data acquisition was completed successfully for six volunteers, the data of two volunteers needed to be excluded due to insufficient image quality of the radial UTE images. Images of one volunteer are exemplarily shown in Figure 1 for breath-hold, as well as all self-gating reconstruction techniques at all investigated temporal resolutions for radial UTE and SPR trajectory. Additionally, Figure 2 shows the images reconstructed using $SG_{img,hist}$ at a temporal resolution of 50 ms for SPR and radial UTE at different windowing, to allow better appreciation of the lung structure. The overall image quality is comparable for all reconstructed images reconstructed at 100 ms temporal resolution. At lower temporal resolutions, especially radial UTE combined with nuSG reconstruction leads to more apparent artifacts.

As they form the core for image-based self-gating reconstruction techniques, as well as nuSG, the low-spatial high-temporal resolution images were further analyzed. A single frame of the sliding window reconstruction for SPR and radial UTE at all reconstructed temporal resolutions is shown in Figure 3. The aliasing artifacts resulting from the undersampling during sliding window reconstruction visibly increases for lower temporal resolutions, but, while radial UTE produces distinct spoke-like artifacts, the noise in the SPR images appears more evenly distributed. Additionally, since with SPR, the entire petal is used for the sliding window reconstruction, the signal intensity is visibly higher in the liver compared to radial UTE. The full sliding window reconstructions can be found in the Supplementary Material S1–S6.

Figure 4 shows the time course of the profile identified over the LLI that is used for image based gating and nuSG for all temporal resolutions for SPR and radial UTE. The self gating signal that was obtained using gradient analysis is shown in red. The algorithm reliably tracks the LLI for 100 and 75 ms for the SPR trajectory with few outliers even at 50 ms temporal resolution. For radial UTE, the algorithm produces several outliers already at 100 ms temporal resolution. The number of outliers increases as temporal resolution decreases, leading to only a low level of correlation between the automatically tracked LLI and the actual breathing pattern. The fitted correlation matrices used for nuSG reconstruction for SPR and radial UTE for all temporal resolutions can be found in the Supplementary Material S7.

3.2 Sharpness

The line profiles across the LLI for both trajectories at all temporal resolutions that were used for sharpness analysis of one volunteer are shown in Figure 5 for SPR and radial UTE during breath-hold, as well as for all analyzed self-gating techniques at temporal resolutions of 100, 75 and 50 ms. Especially for radial UTE



combined with nuSG, a clear decay in image sharpness for decreased temporal resolution is visible in the line profile over the LLI.

Mean image sharpness is listed in Table 2. The percentage decrease when comparing the sharpness value measured for SPR acquired images with the sharpness obtained from radial UTE acquired images is shown in Figure 6. The data is

presented in green for end-inspiration stage and in blue for end-expiration stage. Especially the image-based self-gating techniques yield best results for a temporal resolution of 75 ms. Also noticeable is the approximation of the performance comparing SPR to radial UTE during end-expiration stage when using nuSG.

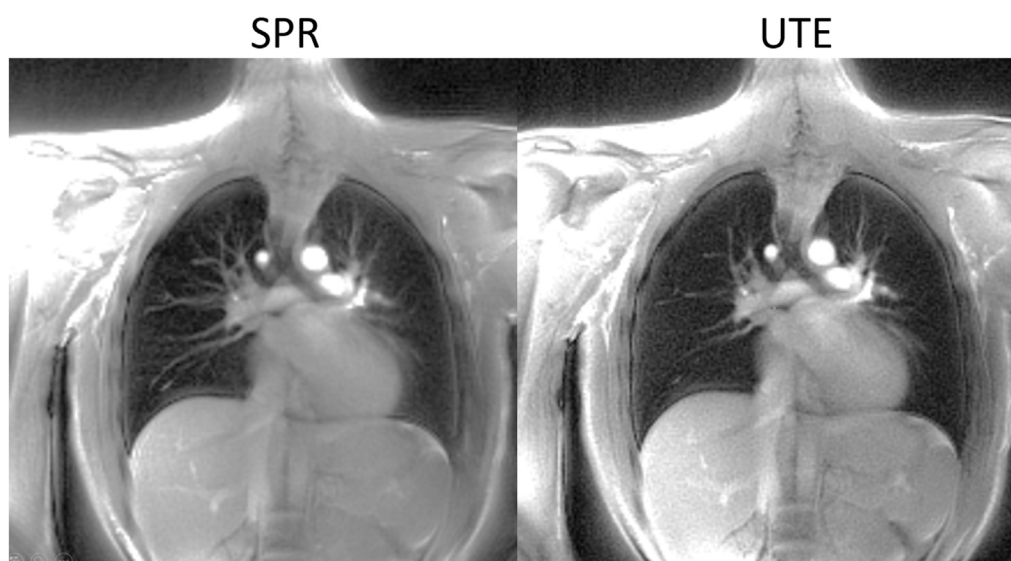


FIGURE 2
2D coronal lung images during expiration stage. Both images were reconstructed using the $SG_{img,hist}$ at a temporal resolution of 50 ms. The left hand image shows the image acquired using SPR, the right hand image was acquired using the radial UTE trajectory.

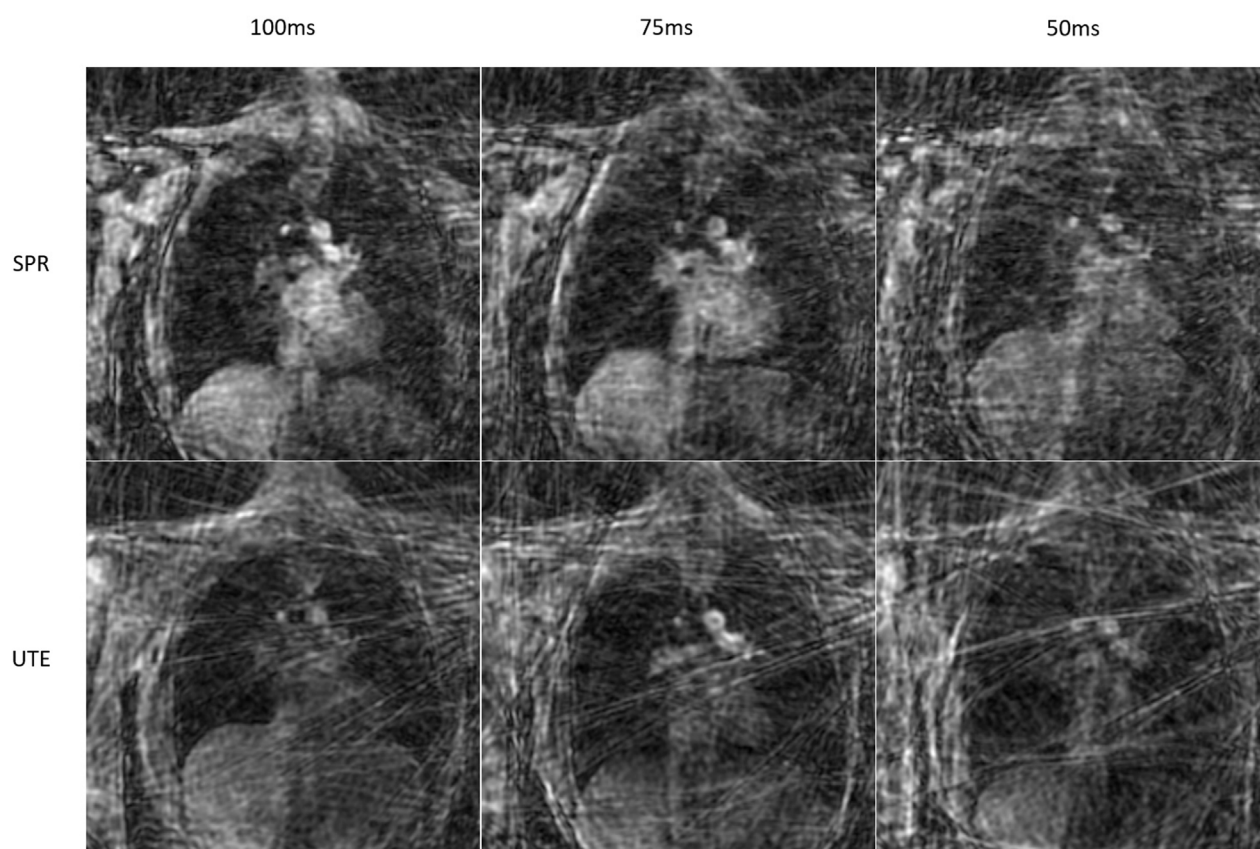


FIGURE 3
Single frame of the low-spatial high-temporal resolution images used for image-based self-gating techniques, as well as nuSG. The top row shows the SPR images, the bottom row the radial UTE images. From left to right, the columns correspond to a temporal resolution of 100, 75 and 50 ms. Clear spoke-artifacts can be seen in the radial UTE images, whereas the noise in the SPR images is more homogeneous.

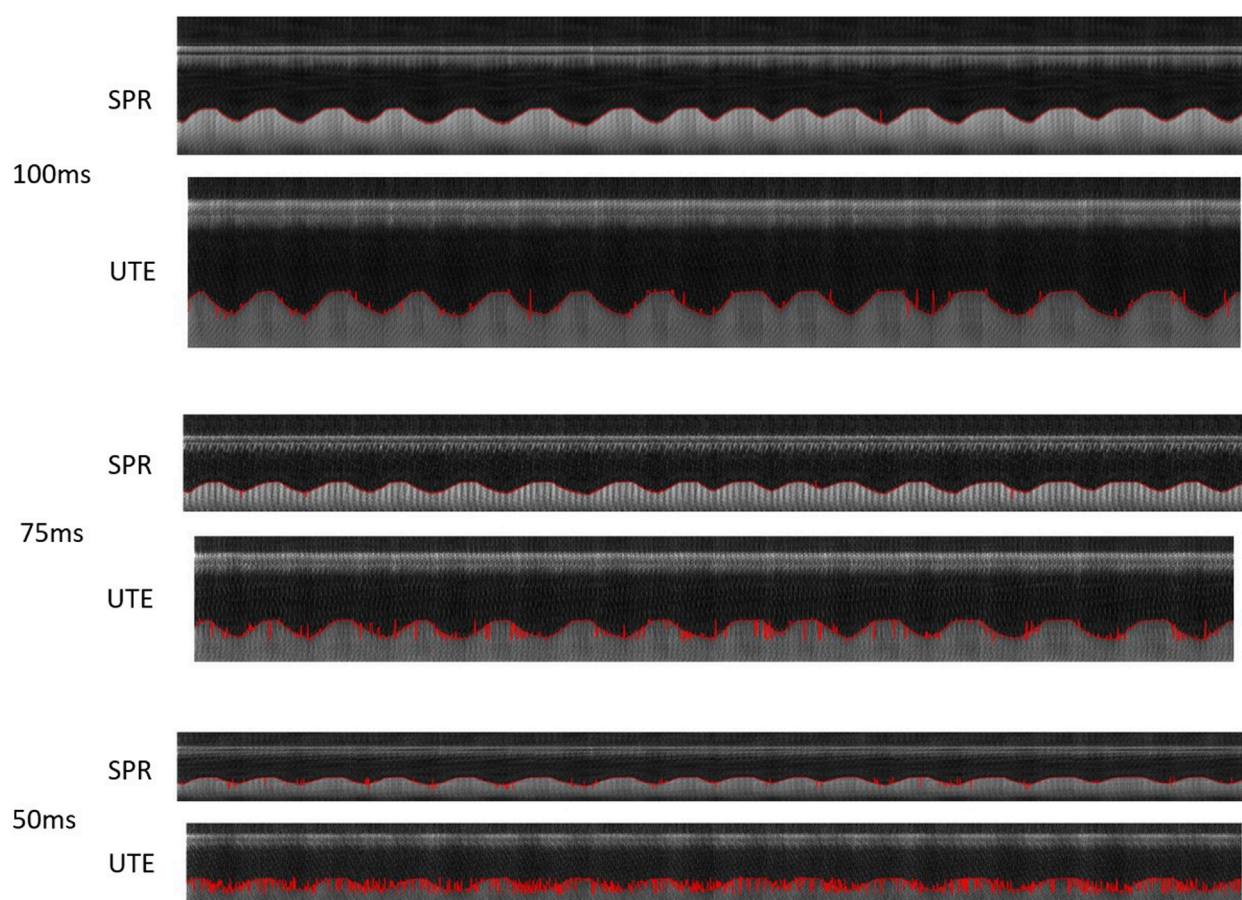


FIGURE 4

By identifying a line profile over the LLI in high-temporal low-spatial resolution images, a time course corresponding to the breathing cycle can be constructed. These time courses are shown for temporal resolutions of 100, 75 and 50 ms for SPR and radial UTE. The self-gating signal, obtained by gradient analysis is shown in red.

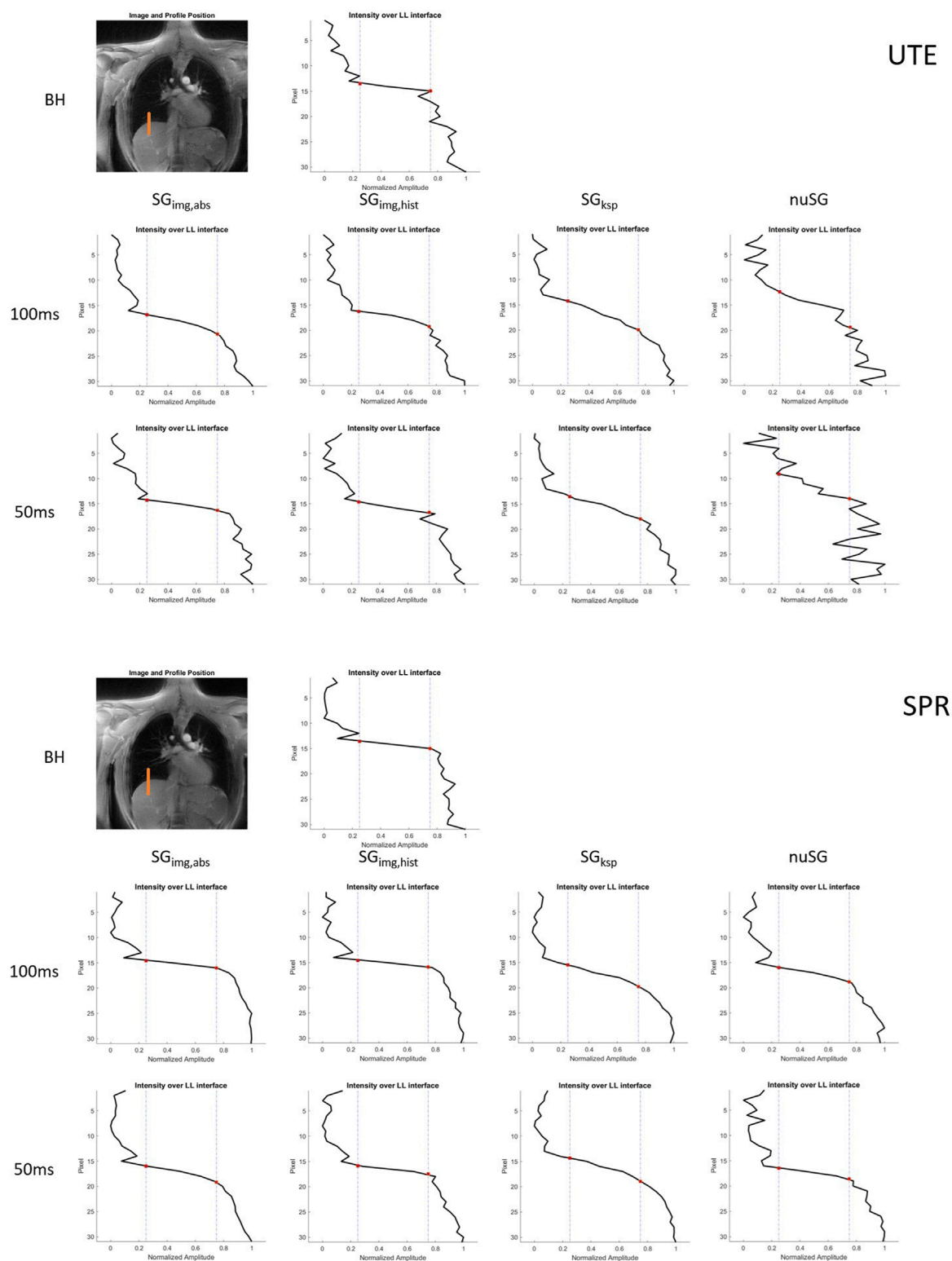
3.3 SNR

Mean SNR values in the lung parenchyma including *p*-values indicating the significance of increase in SNR when comparing SPR to radial UTE can be found in Table 3. When comparing the data acquired using SPR to data acquired using radial UTE, the BH images show no significant increase in SNR, for a temporal resolution of 100 and 75 ms, all gating techniques except for nuSG yield a significant increase in SNR, while for a temporal resolution of 50 ms all gating techniques except for nuSG show significant increase in SNR only for the end-inspiratory stage. The percentage increase in SNR between SPR and radial UTE acquired images is shown in Figure 7. The data is presented in green for end-inspiratory stage and in blue for end-expiratory stage. SNR is higher for SPR compared to radial UTE for all temporal resolutions of all self-gating techniques, as well as for breath-hold images. The highest increase is found at a temporal resolution of 75 ms.

4 Discussion

The intrinsic advantage of more efficient sampling of *k*-space of the SPR trajectory is exploited in the low-spatial high-temporal resolution images used for image-based retrospective self-gating techniques. As discussed in [12], undersampling artifacts are more evenly distributed and lack the distinct spoke-like structure found in radial UTE. This is also clearly visible in Figure 3, leading to a more robust performance of the gradient analysis, used to determine the position of the LLI. Additionally, the longer read-out duration increases signal in the liver due to higher T_2^* , yielding a higher contrast between lung and liver, which also improves the performance of the gradient analysis algorithm that is used for the determination of the LLI position in the image-based self-gating techniques.

Although overall image quality is good for radial UTE and SPR, especially for the nuSG self-gating technique, limits in temporal resolution can be seen in radial UTE images, already at temporal

**FIGURE 5**

Sharpness analysis of a line profile over the LLI, depicted in orange. Images in top show data acquired using radial UTE for breath-hold (BH), as well as all self-gating techniques (SG_{img,abs}, SG_{img,hist}, SG_{ksp} and nuSG) at temporal resolution of 100 and 50 ms. The results for SPR are shown in the bottom box.

TABLE 2 Mean sharpness values calculated for a line profile over the lung-liver interface for breath-hold and self-gated images of both trajectories at all investigated temporal resolutions.

		BH	SG _{img,abs}	SG _{img,hist}	SG _{ksp}	nuSG
100 ms						
SPR	inspiration	2.5 ± 1.6	1.6 ± 0.8	2.8 ± 1.3	1.8 ± 0.9	2.5 ± 0.5
	expiration	1.3 ± 1.0	1.5 ± 1.1	1.7 ± 0.7	2.2 ± 1.1	2.1 ± 1.2
radial UTE	inspiration	4.1 ± 2.3	2.7 ± 1.0	3.8 ± 1.9	2.6 ± 0.7	4.1 ± 2.3
	expiration	2.4 ± 1.8	2.7 ± 1.6	2.9 ± 2.1	3.6 ± 2.4	4.0 ± 2.5
75 ms						
SPR	inspiration	2.5 ± 1.6	1.5 ± 0.6	2.9 ± 1.1	2.1 ± 1.0	2.9 ± 1.5
	expiration	1.3 ± 1.0	1.4 ± 0.8	2.4 ± 1.3	2.2 ± 1.1	3.2 ± 1.5
radial UTE	inspiration	4.1 ± 2.3	2.7 ± 1.1	5.3 ± 1.5	2.6 ± 0.6	3.7 ± 2.1
	expiration	2.4 ± 1.8	2.2 ± 1.1	3.1 ± 2.2	3.4 ± 2.3	4.6 ± 3.8
50 ms						
SPR	inspiration	2.5 ± 1.6	2.2 ± 1.0	3.1 ± 1.3	2.3 ± 0.8	2.5 ± 1.0
	expiration	1.3 ± 1.0	1.8 ± 1.3	4.8 ± 4.1	2.6 ± 1.0	4.4 ± 2.6
radial UTE	inspiration	4.1 ± 2.3	4.0 ± 2.3	4.5 ± 1.8	4.4 ± 2.1	3.9 ± 1.3
	expiration	2.4 ± 1.8	4.1 ± 2.7	3.4 ± 1.5	3.0 ± 0.6	5.5 ± 4.2

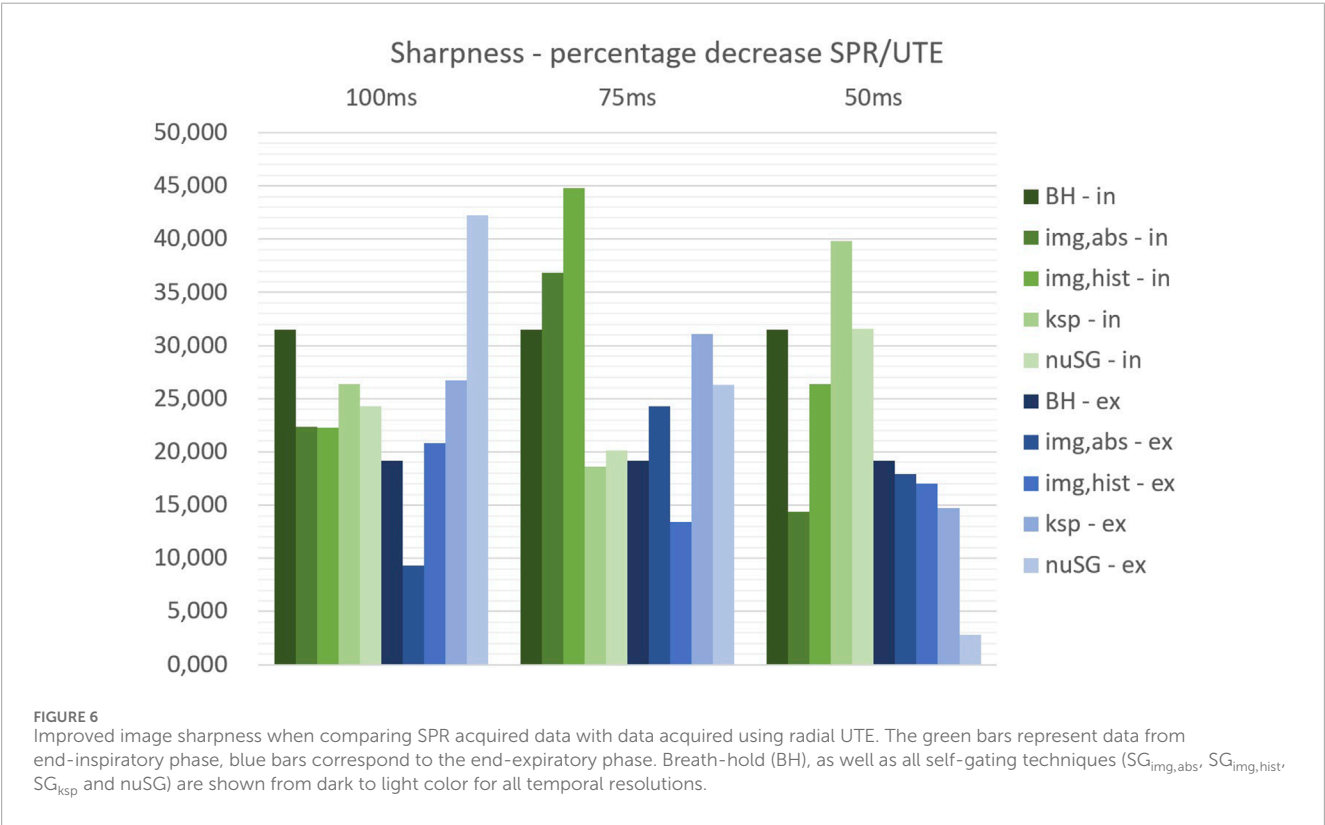


TABLE 3 Mean SNR values in the lung parenchyma for breath-hold and self-gated images of both trajectories at all investigated temporal resolutions, as well as *p*-values indicating the significance of increase when comparing SNR values measured using SPR data to SNR values measured using radial UTE data.

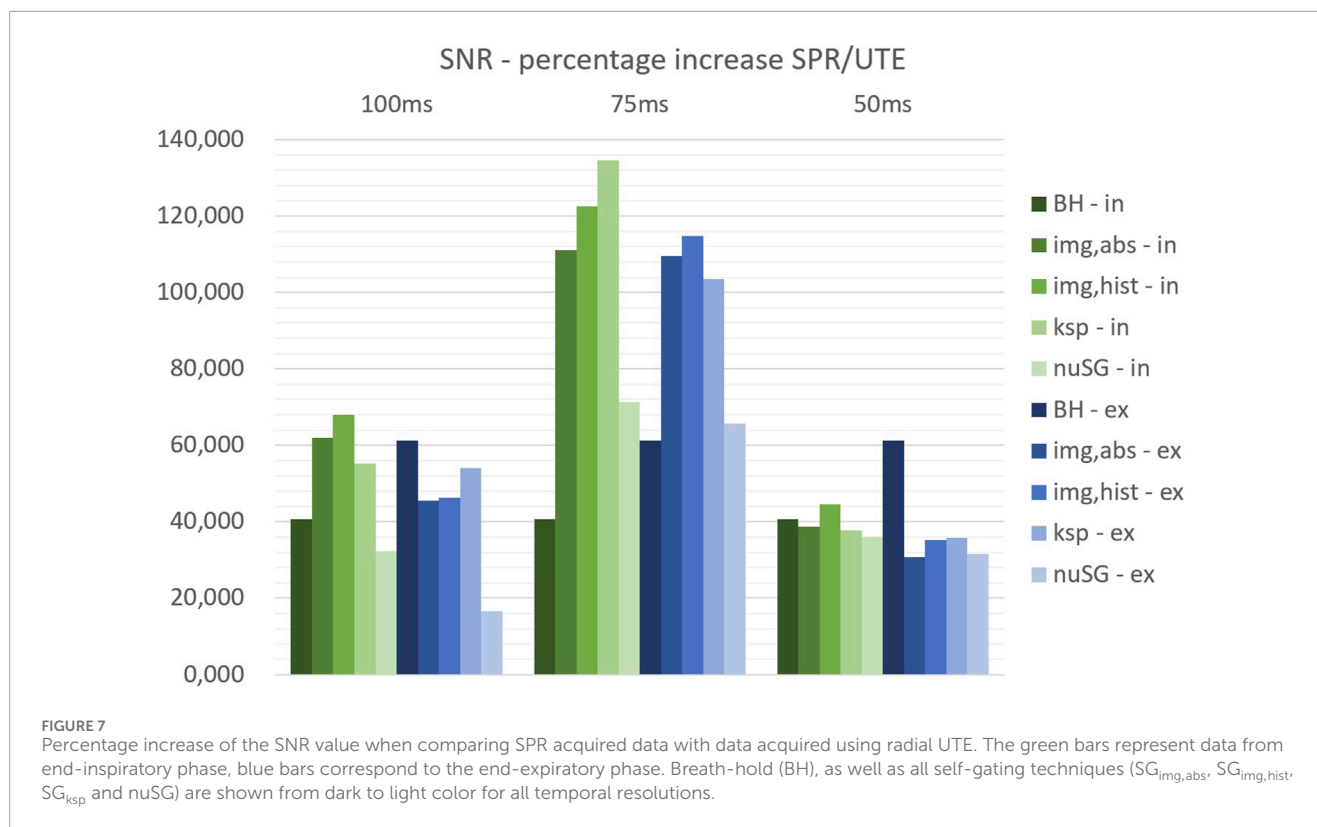
		BH	SG _{img,abs}	SG _{img,hist}	SG _{ksp}	nuSG
100 ms						
SPR	inspiration	2.2 ± 1.3	1.9 ± 0.9	2.0 ± 0.9	1.9 ± 0.9	2.0 ± 0.7
	expiration	2.8 ± 1.4	1.9 ± 0.8	2.0 ± 0.8	1.9 ± 0.8	2.1 ± 0.6
radial UTE	inspiration	1.7 ± 0.4	1.2 ± 0.4	1.2 ± 0.4	1.2 ± 0.4	1.6 ± 0.3
	expiration	1.8 ± 0.5	1.3 ± 0.5	1.3 ± 0.4	1.2 ± 0.4	1.8 ± 0.2
<i>p</i> -value	inspiration	0.53	0.04	0.04	0.04	0.14
	expiration	0.29	0.04	0.04	0.04	0.29
75 ms						
SPR	inspiration	2.2 ± 1.3	2.3 ± 0.7	2.5 ± 0.9	2.8 ± 1.1	2.3 ± 0.3
	expiration	2.8 ± 1.4	2.5 ± 0.9	2.6 ± 0.9	2.5 ± 0.8	2.8 ± 0.7
radial UTE	inspiration	1.7 ± 0.4	1.2 ± 0.3	1.2 ± 0.3	1.3 ± 0.3	1.4 ± 0.2
	expiration	1.8 ± 0.5	1.2 ± 0.3	1.3 ± 0.3	1.3 ± 0.4	1.7 ± 0.3
<i>p</i> -value	inspiration	0.53	0.04	0.04	0.04	0.04
	expiration	0.29	0.04	0.04	0.04	0.06
50 ms						
SPR	inspiration	2.2 ± 1.3	2.7 ± 1.0	2.7 ± 0.7	2.7 ± 0.9	2.4 ± 0.5
	expiration	2.8 ± 1.4	2.6 ± 0.9	2.7 ± 0.8	2.7 ± 0.9	2.5 ± 0.6
radial UTE	inspiration	1.7 ± 0.4	2.0 ± 1.0	2.0 ± 0.9	2.1 ± 0.9	1.8 ± 0.2
	expiration	1.8 ± 0.5	2.3 ± 1.4	2.2 ± 1.3	2.2 ± 1.3	1.7 ± 0.2
<i>p</i> -value	inspiration	0.53	0.04	0.04	0.04	0.06
	expiration	0.29	0.29	0.29	0.14	0.14

resolutions of 100 ms and even for SPR at 50 ms. The performance decrease correlated with temporal resolution is most noticeable for nuSG reconstruction. Artifacts start showing at temporal resolutions of 75 ms for SPR but still acceptable image quality can be achieved for 50 ms. For radial UTE, artifacts are already more prominent at a temporal resolution of 100 ms compared to SPR at a temporal resolution of 50 ms and decreasing for higher temporal resolutions.

The advantageous performance of the image-based gating techniques can especially be seen in the sharpness values. While for all gating techniques a percentage increase in sharpness can be found, when comparing SPR to radial UTE, especially image-based techniques show greatest improvement for a temporal resolution of 75 ms. For a temporal resolution of 100 ms the advantages of SPR are not as obvious, since radial UTE performs well enough. For a temporal resolution of 50 ms, while SPR still yields acceptable results, the overall decrease in gating performance is already noticeable.

A similar outcome is observed for SNR comparison between SPR and radial UTE. While for all gating techniques and all temporal resolutions, SPR yields higher SNR values compared to radial UTE, the improvements are highest for a temporal resolution of 75 ms, exceeding even the improvement found in breath-hold images. For a temporal resolution of 100 ms, the improvement found in breath-hold images is slightly superior for image-based and k-space based self-gating during end-inspiratory phase. For a temporal resolution of 50 ms the overall improvement is lowest, due to decreasing gating performance of SPR.

There is a huge body of recent publications on lung imaging. They can mainly be categorized in zero-echo time (ZTE) [28], ultra-short echo time [28] and conventional FLASH [29] imaging techniques. With ZTE being an intrinsically 3D sequence and as such yielding more SNR and superior isotropic spatial resolution as in the 2D approaches, its general application on clinical systems is limited, especially by the required rapid switch times between



transmit/receive mode of the frontend to avoid substantial loss of k-space center coverage. The conventional FLASH sequences have predominantly been applied to very low spatial resolution acquisitions, mainly providing mean intensity information of the parenchyma which is applied for deriving signal intensity changes over time to derive lung function information, rather than anatomic details. The suggested approach represents an efficient variant of the UTE techniques. UTE techniques have a high self-gating potential and in principle capable of trading spatial vs. temporal resolution and, as such, can be applied for high-resolution anatomic, as well as low-resolution functional assessment of the lung. Where the basic contrasts is still UTE-like, the main advantage of the presented trajectory results from the almost doubled temporal resolution of the low-resolution images applied for respiratory gating. The presented trajectory clearly improved the correct identification of the LLI during gating and results in a respective image sharpness improvement.

A major limitation of the study rises from the small cohort size. But even though only six volunteers were enrolled, a significant increase in SNR for the majority of SNR values and a clear trend to sharper LLI were already observed when compared to UTE. Further the feasibility of using a better temporal fidelity for the images applied to deriving the gating signal is already clearly appreciable from the provided data.

5 Conclusion

The higher efficiency in k-space sampling of the full-petal SPR images compared to radial UTE can be ideally exploited when

using full-petal data for low-spatial high-temporal resolution images as a base for image-based self-gating techniques. Since the final gated images can be reconstructed using only the center-out half of the SPR trajectory, the image contrast is equivalent to radial UTE images, leading to an easy comparison and interpretation of images in clinical settings.

The structure of undersampling artifacts, as well as higher liver signal due to longer read-out duration further improves the gating performance of image-based self-gating techniques.

For all temporal resolutions, SPR outperforms radial UTE. Image-based self-gating techniques show no apparent artifacts for temporal resolutions as low as 50 ms. This suggests that temporal resolutions of 50 ms are suitable for SPR data when using image-based self-gating techniques with image quality comparable to a temporal resolution of 100 ms of radial UTE.

A combination of SPR with retrospective self-gating has been proven suitable, making the trajectory an excellent candidate for further investigation of 3D lung imaging.

SPR further holds the intrinsic possibility of reconstructing images of different contrasts by using different parts of the petal. The full petal data benefit of a low-fat signal due to the position of the second echo, which could be beneficial, especially for cardiac applications.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by Ethikkommission der Universität Ulm. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

HF: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review and editing. VR: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review and editing.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fphy.2025.1611544/full#supplementary-material>

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