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Non-contrast renal MRA using multi-shot gradient echo EPI at 3-T MRI

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Abstract

Objectives The purpose of this study was to investigate the feasibility of non-contrast renal MRA using multi-shot gradient echo planar imaging (MSG-EPI) with a 3-T MRI system.

Methods Seventeen healthy volunteers underwent non-contrast renal MRA using MSG-EPI and balanced steady-state free precession (b-SSFP) sequences on a 3-T MRI system. Two radiologists independently recorded the images' contrast, noise, sharpness, artifacts, and overall quality on 4-point scales. The signal-to-noise ratio (SNR) for the renal artery, the contrast ratio (CR) between the renal artery and erector spinae, and acquisition time were compared between the two sequences.

Results The SNR and CR were significantly higher with MSG-EPI than with the b-SSFP sequence (17.80 ± 3.67 vs. 10.84 ± 2.86 and 0.77 ± 0.05 and 0.66 ± 0.09, respectively; $p < 0.05$), and the acquisition time was significantly lower (164.5 ± 34.0 vs. 261.5 ± 39.3 s, respectively; $p < 0.05$). There were significant differences in image contrast, noise, sharpness, artifacts, and overall image quality between the two sequences ($p < 0.01$).

Conclusions The MSG-EPI sequence is a promising technique that can shorten the scan time and improve the image quality of non-contrast renal MRA with a 3-T MRI system.

Key Points

- *The multi-shot gradient echo planar imaging with an inversion pulse is a brand-new fast scan technique for an unenhanced renal MRA.*
- *The image quality of multi-shot gradient echo planar imaging is better than that of b-SSFP for an unenhanced renal MRA.*

Keywords Magnetic resonance imaging · Renal artery · Echo planar imaging

Abbreviations

3D	Three-dimensional
b-SSFP	Balanced steady-state free precession
CR	Contrast ratio
EPI	Echo planar imaging
MRA	Magnetic resonance angiography
MSG	Multi-shot gradient echo
PPU	Peripheral pulse unit
ProSet	Principle of selective excitation technique
ROI	Regions of interest
SD	Standard deviation
SI	Signal intensity
SNR	Signal-to-noise ratio
SPIR	Spectral presaturation with inversion recovery

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Introduction

Magnetic resonance angiography (MRA) has become a useful diagnostic tool for investigating arterial diseases because of its minimally invasive nature and lack of toxicity. The best-established approach for MRA is to use gadolinium-based contrast agents and T1-weighted imaging sequences. Although the contrast-enhanced approach has shown excellent diagnostic performance across diverse applications [1, 2], the intravenous administration of the contrast agent results in patient discomfort, increases examination costs, and limits the achievable spatial resolution and artery-to-background contrast because of the requirement for short acquisition at the optimal time after the injection. Recently, the MRI gadolinium-based contrast agents have been reported to cause the acute kidney failure especially at high doses in patients with pre-existing CKD and diabetic nephropathy [3, 4]. In addition, there remains some risk of nephrogenic systemic fibrosis in patients with renal failure, even though the risk can be significantly reduced through careful selection of the type and dose of contrast agent [5]. Because of a recently reported association between the use of gadolinium contrast agents and nephrogenic systemic fibrosis, there has been increasing interest in using non-contrast MRA techniques as an alternative, with promising data reported on using non-contrast MRA to evaluate the renal arteries [6–13]. The three-dimensional (3D) balanced steady-state free precession (b-SSFP) is a technique widely used in 1.5 T MRI [10, 11]; however, this technique has been reported to result in poor image quality due to the non-uniformity of the magnetic field in 3 T MRI [14].

Single-shot echo planar imaging (EPI) is the fastest method for acquiring MRI (100 ms/slice), but it has limited spatial resolution and is sensitive to off-resonance artifacts [15]. Multi-shot gradient echo (MSG)-EPI combines EPI scanning with SSFP [16] and results in fewer off-resonance artifacts than single-shot EPI. Previous reports have suggested that this technique cannot offer a sufficiently high signal-to-noise ratio (SNR) for clinical use without the use of contrast media [17, 18]; however, recent studies reported the feasibility of this technique for investigating coronary arteries and thoracic aorta [19, 20]. In addition, it has been reported that IR pulses applied immediately before signal acquisition can suppress the background signal and only collect signals in moving parts such as arterial blood [21]. We think that high-quality renal MRA can be achieved by combining these MSG-EPI and IR pulses. There have been no reports on non-contrast MRA of renal arteries with MSG-EPI and IR pulse using a 3-T MRI system.

In this study, we propose a short-time high-quality method for renal MRA that uses multi-shot EPI and an inversion pulse with a short inversion delay. We hypothesize that this technique can improve image quality in non-contrast renal MRA. The purpose of the study was to compare scan time, contrast ratio (CR), and image quality for MRA of the renal artery between MSG-EPI and b-SSFP sequences.

Material and methods

Populations

This prospective study received institutional review board approval, and prior informed consent to participate was obtained from 18 healthy volunteers. All underwent imaging consecutively in November and December 2017. Data for one volunteer were subsequently excluded because of a severe motion artifact. The age range of the 17 volunteers (16 men and one woman) was 26–44 years (mean 31.8 ± 5.7 years), their heart rate was 52–88 bpm (mean 70.4 ± 6.9 bpm), and their body weight was 52–100 kg (mean 68.8 ± 12.7 kg).

MRA acquisition

The subjects underwent imaging on a 3-T MRI scanner (Ingenia-CX, Philips Medical Systems) using a 32-element phased-array direct digital radio frequency receiver coil and peripheral pulse unit gating. During the same session, we acquired pulse and navigator echo-gated non-contrast-enhanced MRA using both MSG-EPI and b-SSFP sequences, with 3D imaging performed in the transverse plane. We set the image acquisition to occur during the systole of the peripheral pulse cycle. To obtain a bright blood signal, we applied an inversion pulse with the shortest delay time to the region of interest to enhance the contrast between flowing and static magnetization. This technique has been widely used for renal MRA with b-SSFP [21–24]. We tried to replicate the study parameters for the two sequences as much as possible; however, we used the water excitation technique (the principle of selective excitation technique, ProSet) for MSG-EPI and the spectral presaturation with inversion recovery (SPIR) for b-SSFP due to limitations of the MR scanner used in this study. Conventional spectrally selective fat suppression techniques cannot provide homogeneous fat suppression within the sampling time. We recorded the acquisition times for the 3D MSG-EPI and b-SSFP sequences.

Figure 1 shows schematics of the 3D MSG-EPI and b-SSFP sequences. The MSG-EPI sequence was similar to single-shot gradient-type EPI, except that several acquisitions were made rather than sampling the k-space completely with one shot. The MSG-EPI sequence allows many signals to be obtained with one radio frequency excitation; however, the signal acquisition time is limited by T2* relaxation. The acquisition of many k-space lines increases echo time and repetition time and results in reduced SNR and blurring. We therefore used an EPI factor of 7, which can yield seven echoes per excitation. The detailed scanning parameters are shown in Table 1.

Quantitative analysis

The quantitative image analysis of the source images was performed by a board-certified radiologist with 10 years of abdominal MRI experience. To minimize bias from single measurements, three circular regions of interest (ROIs) were placed on three sequential slices and the mean values were calculated. The mean signal intensities (SIs) of the right and

Table 1 Magnetic resonance imaging sequences and parameters

	b-SSFP	MSG-EPI
TR/TE (ms)	7.7/3.1	13.0/7.0
FOV (mm)	300	300
Slice thickness (mm)	1.8	1.8
Spatial resolution (mm^3)	1.17 × 1.32 × 1.8	1.17 × 1.55 × 1.8
Number slices	90	90
TFE factor	40	15
EPI factor	-	7
Shot duration (ms)	357.8	296.4
Flip angle	60	20
Fat suppression	SPIR	ProSet (1-2-1)
Pre-pulse	Invert (180°)	Invert (180°)
Pre-pulse delay	Shortest (196.7 ms)	Shortest (213.7–219.5 ms)
Averages	1	2
SENSE factor	2.0 × 1.0	2.0 × 1.0
Trigger	Navigator echo + PPU	Navigator echo + PPU

b-SSFP, balanced steady-state free precession sequence; *MSG-EPI*, multi-shot gradient echo planar imaging; *TR*, repetition time; *TE*, echo time; *FOV*, field of view; *TFE*, turbo field echo; *PPU*, peripheral pulse unit

left renal arteries within the ROIs were measured. The mean SI of the renal artery was also measured. The ROIs to measure the SIs of the right and left renal arteries (ROI_{renal}) were selected so that they did not affect per-pixel variability and excluded the vessel walls and perivascular fat as far as possible. In addition, the mean SI of the erector spinae (ROI_{muscle}) and the mean standard deviation of the SI of the abdominal aortic artery (SD_{aorta}) were measured. The SNR and CR of the renal artery were calculated as follows: $SNR = ROI_{renal}/SD_{aorta}$; $CR = (ROI_{renal} - ROI_{muscle})/(ROI_{renal} + ROI_{muscle})$.

Qualitative image analysis

The image quality obtained with the different sequences was evaluated by qualitative image analysis on a PACS viewer (View R, version 1.09.15, Yokogawa Electronic). Two board-certified radiologists, both with 13 years of experience of cardiac and great vessel MRI, independently graded image contrast, noise, artifacts, sharpness, and overall image quality.

The MRI datasets were randomized, and the readers were blinded to the acquisition parameters. Using a subjective 4-point scale, they independently graded image contrast and overall image quality (1 = unacceptable, 2 = acceptable, 3 = good, or 4 = excellent). Image noise and artifacts were similarly recorded as grade 1 (present and unacceptable), 2 (present and interfering with the depiction of adjacent structures), 3 (present without interfering with the depiction of adjacent structures), or 4 (no noise or artifact). Image sharpness was determined by evaluating the aortic wall sharpness as grade 1 (blurry), 2 (poorer than average), 3 (better than average), and 4 (sharp). Any disagreement between the readers was settled by consensus.

Statistical analysis

Statistical analyses were performed using Python programing software (version 3.7; available at: https://www.python.org/). The Wilcoxon signed-rank test was employed for the quantitative and qualitative MRI image comparisons. Differences with $p < 0.05$ were considered statistically significant.

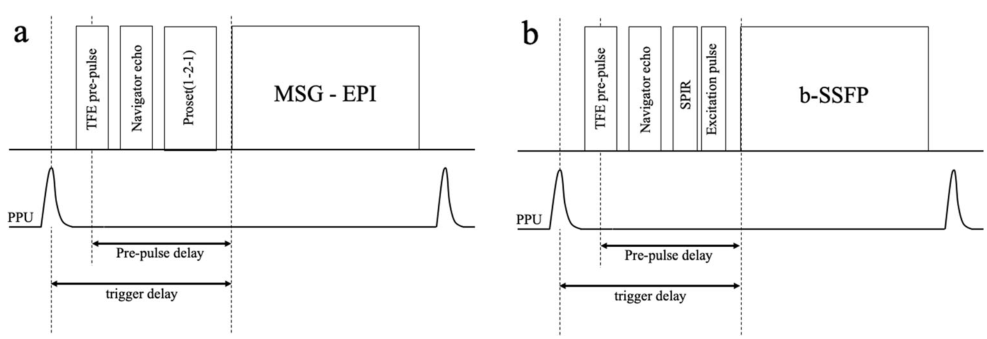

Fig. 1 Pulse sequence scheme. A respiratory- and a peripheral pulse navigator-gated 3D MSG-EPI (**a**) and b-SSFP (**b**) sequences were used for renal artery MRA. PPU, peripheral pulse unit

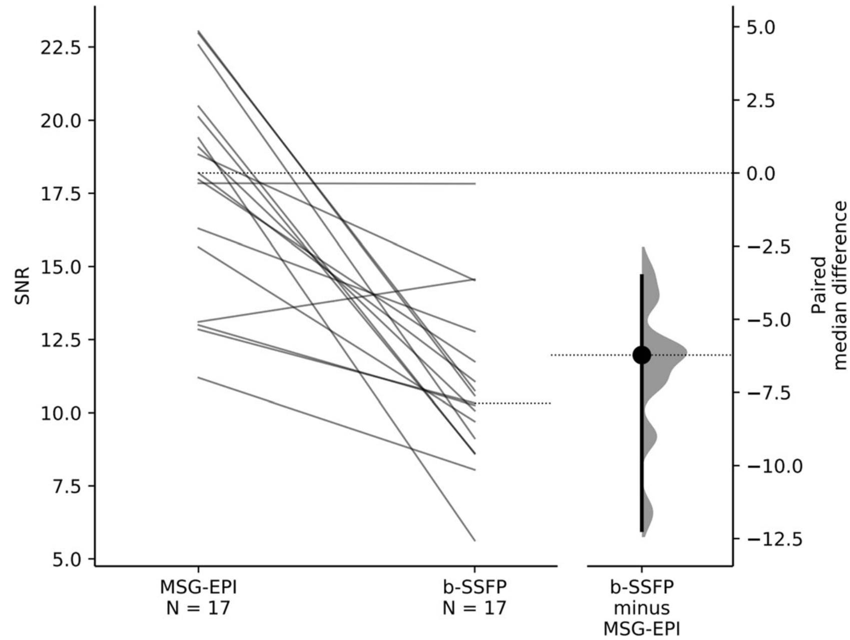

Fig. 2 Tufte slope graph shows SNR of renal artery for b-SSFP and MSG-EPI sequences. The SNR was significantly higher in MSG-EPI than in b-SSFP ($p < 0.01$)

Results

Figures 2 and 3 show the results of our quantitative analyses. The SNR was significantly higher with MSG-EPI than with the b-SSFP sequence (17.80 ± 3.67 vs. 10.84 ± 2.86; $p < 0.01$) (Fig. 2). The CR was significantly higher with MSG-EPI than with b-SSFP (0.66 ± 0.09 vs. 0.77 ± 0.05; $p < 0.01$) (Fig. 3). The total scan time was 39% shorter for MSG-EPI than for b-SSFP (164.5 ± 34.0 vs. 261.5 ± 34.3 s, $p < 0.01$) (Fig. 4).

Table 2 summarizes the qualitative analysis. The qualitative scores for image contrast, noise, sharpness, artifacts, and overall image quality were significantly higher for MSG-EPI than for b-SSFP ($p < 0.01$).

Representative cases are shown in Fig. 5. The MSG-EPI sequences showed homogenous renal artery SI without flow artifacts. However, signal intensity of renal artery is inhomogeneous in b-SSFP because of the presence of flow artifacts. In the qualitative image analysis, all the image quality scores were higher for MSG-EPI than for b-SSFP. The inflow effect appeared as blood signal intensity from none RF excitation area in Fig. 5 (white arrow), because the RF pulse was excited to only the imaging area.

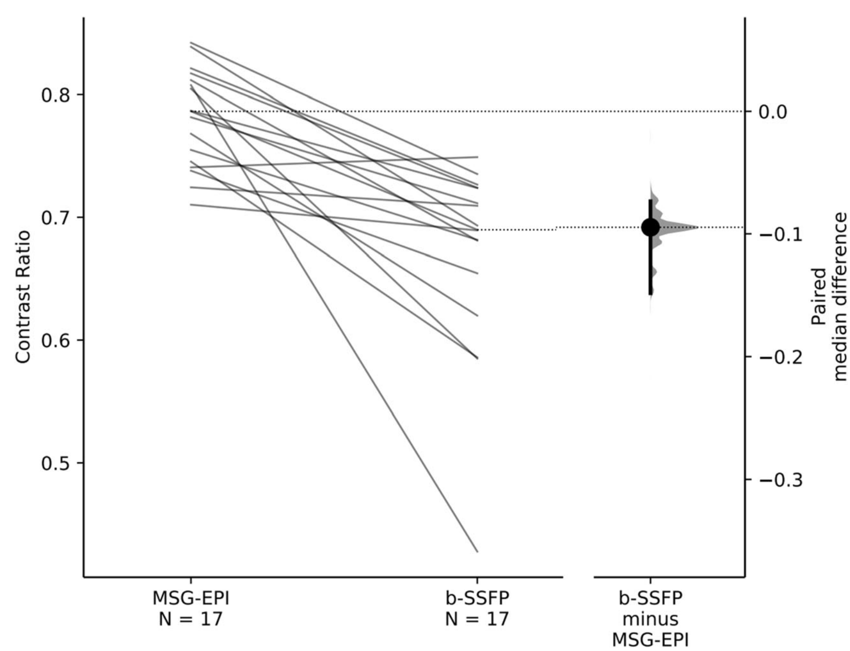

Fig. 3 Tufte slope graph shows the contrast of renal artery for b-SSFP and MSG-EPI sequences. The contrast was significantly higher in MSG-EPI than in b-SSFP ($p < 0.01$)

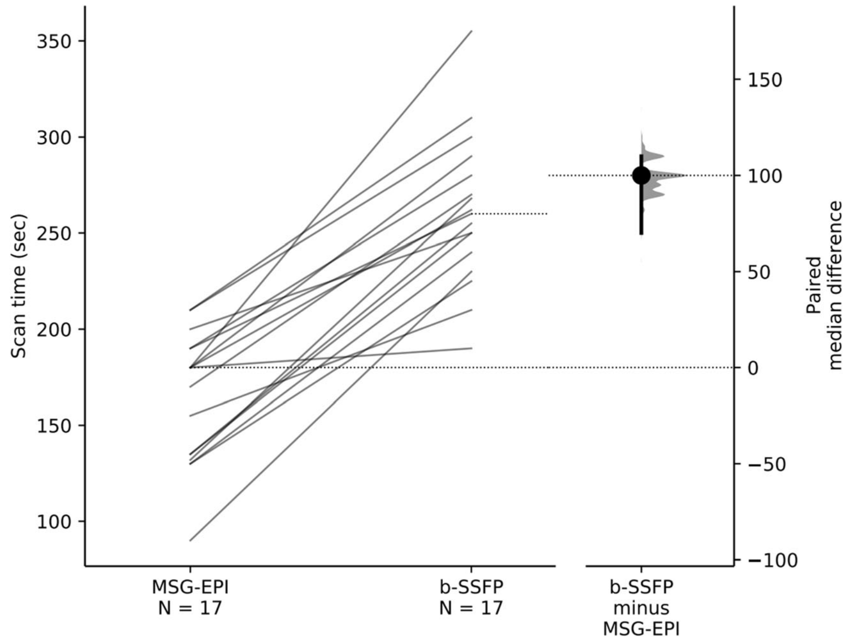

Fig. 4 Tufte slope graph shows the total scan time of b-SSFP and MSG-EPI sequences. The total scan time was 39% shorter for MSG-EPI than b-SSFP ($p < 0.01$)

Discussion

The results of this study suggest that the MSG-EPI sequence yields a more homogeneous SI in the renal arteries and allows a shorter acquisition time compared with the b-SSFP sequence for non-contrast renal MRA. In the qualitative image analysis, the MSG-EPI sequence provided significantly higher image quality than the b-SSFP sequence.

In general, the b-SSFP sequence yields a high SNR with a short repetition time, but it is sensitive to off-resonance interference by B0 field inhomogeneities. Previous report suggested non-contrast MRA using inversion recovery pre-pulse and 3D b-SSFP under regulated breathing or respiratory triggering provides acceptable diagnostic performance for detecting significant renal artery stenosis, with sensitivity and specificity values in the range 72–98% [10, 11]. However, b-SSFP also has a problem in 3 T MRI due to banding artifacts caused by non-uniformity of the magnetic field [14]. The MSG-EPI sequence proposed in this study, which combines non-balanced-SSFP turbo field echo and EPI techniques, is less sensitive than b-SSFP to banding artifacts and image inhomogeneity due to B0 field inhomogeneity. The basic idea of MSG-EPI is to fill the k-space in a single-shot with a read-out gradient during a single T2* decay or in multiple shots using multiple excitations. Thus, changing the number of EPI factors can reduce the scan time significantly for the same repetition time. Our results suggested that, compared with the b-SSFP sequence, the MSG-EPI sequence with an EPI factor of 7 can provide a shorter scan time with more homogeneous renal artery SI without a decrease in the SNR for non-contrast MRA of the renal arteries at 3 T. MSG-EPI has also been reported to have great potential for enabling high spatial resolution imaging [25].

Commonly, renal non-contrast MRA techniques apply a spatially selective inversion pulse with a long inversion delay to maximize the inflow signal inside the renal arteries. A recent paper reported the effectiveness of background signal suppression by this subtraction method; however, there is a problem of increased imaging time with double imaging and deterioration of image quality due to mis-registration [22]. In this study, we suppressed the background signals effectively by applying an inversion pulse with a short inversion delay rather than a long delay [10] and by using a ProSet pulse for fat suppression. Consequently, we succeeded in depicting the renal arteries with high contrast against the background signals, although this was mostly due to the differences in relaxation times and was independent of inflow effects. Because this technique is less sensitive to flow speed, exact inversion delay settings are not needed. This suggests that the

Table 2 Qualitative analysis

	b-SSFP	MSG-EPI	*p*
Image contrast	2.6 ± 0.5	3.8 ± 0.5	< 0.01
Image noise	2.6 ± 0.6	3.6 ± 0.5	< 0.01
Artifact	2.4 ± 0.6	3.7 ± 0.5	< 0.01
Image sharpness	2.7 ± 0.6	3.7 ± 0.6	< 0.01
Overall image quality	2.5 ± 0.6	3.7 ± 0.5	< 0.01

Data are mean ± standard deviation. *b-SSFP*, balanced steady-state free precession sequence; *MSG-EPI*, multi-shot gradient echo planar imaging

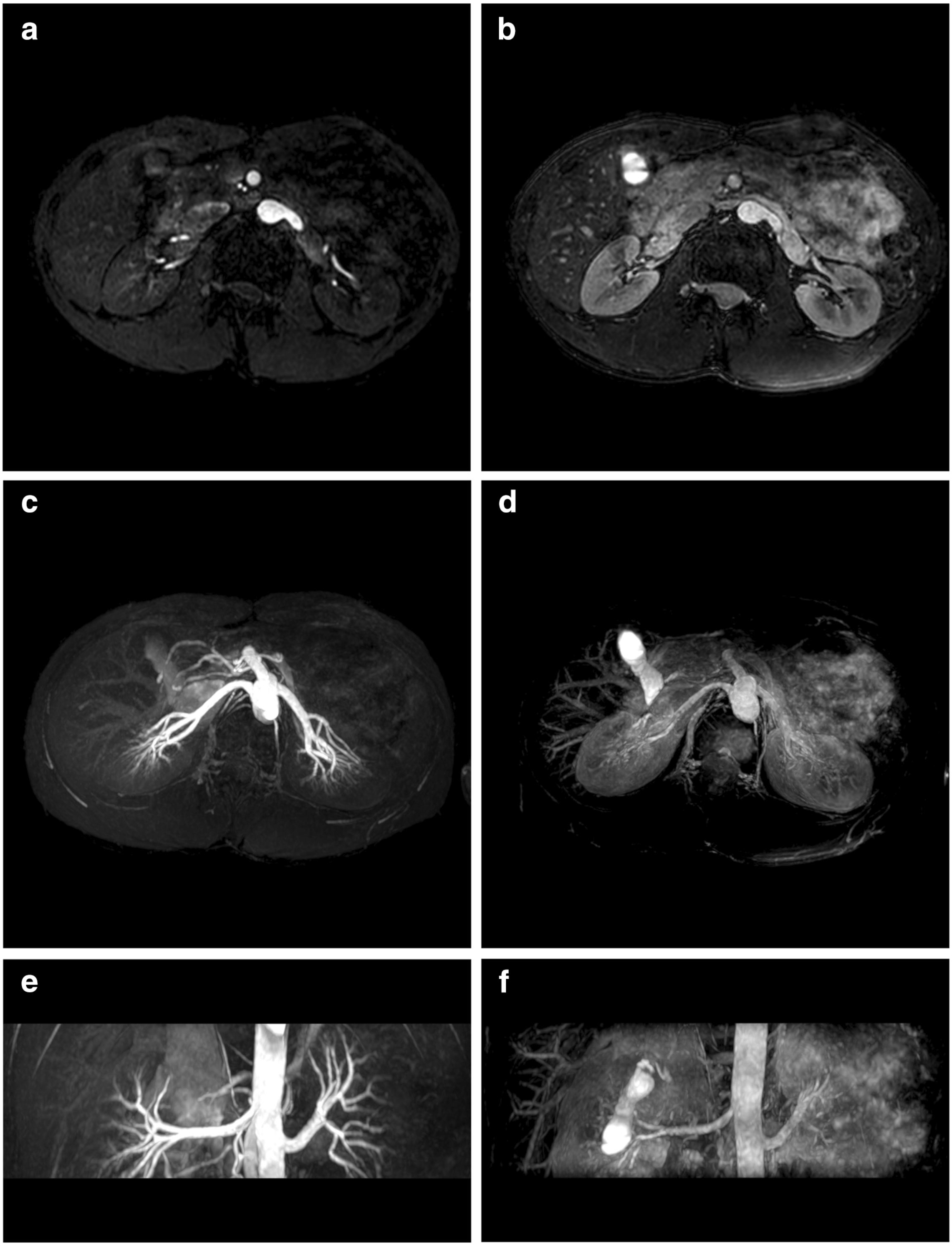

Fig. 5 Representative images of a 28-year-old man imaged with MSG-EPI and b-SSFP for three-dimensional renal artery MRA. His heart rate was 66 bpm, and the scan times for MSG-EPI and b-SSFP were 130 and 225 s, respectively. The panels show transverse images for the source and maximum intensity projection for MSG-EPI (**a**, **c**, **e**) and b-SSFP (**b**, **d**, **f**) sequences

technique can yield more robust results compared with inflow-based methods, regardless of the patient conditions. Furthermore, using a short inversion delay allows the scan time to be kept relatively short, such as for a breath-holding scan, which can result in reduced motion artifacts compared to conventional free-breathing inflow techniques.

Our study had some limitations. It included only 17 volunteers, all of whom were healthy, so the results do not necessarily demonstrate that the MSG-EPI sequence would yield non-inferior image quality to other sequences for patients with suspected renal artery disease, who tend to manifest breathing pattern drifts. In addition, we did not evaluate the diagnostic accuracy of MSG-EPI for renal artery MRA. Further studies are needed to evaluate its diagnostic performance for patients with suspected renal artery disease. This was a preliminary study to optimize the scan parameters of MSG-EPI for renal arteries and to demonstrate the feasibility of this technique; we did not compare with other techniques such as Time-SLIP [21] and RAVEL [26]. Further clinical investigation of MSG-EPI for renal arteries, including comparisons with other techniques, is needed. We evaluated only one scan setting for MSG-EPI sequence; it might be needed to optimize such as numbers of EPI factor and flip angle for MSG-EPI sequence [19, 20]. In this study, we focused to compare MSG-EPI with b-SSFP as a read-out sequence using the same pre-pulse. Then, further studies that compared this sequence to major renal MRA techniques are needed to verify the clinical usefulness of this sequence in daily clinical examinations. Finally, we manipulated only one renal artery MRA parameter. Other parameters, such as the EPI and turbo field echo factors and half-Fourier scanning, might change the image quality and scan time of MSG-EPI. Studies are underway to optimize the MSG-EPI sequence for renal artery MRA.

Conclusions

The MSG-EPI sequence for renal MRA at 3 T can yield more homogenous image quality compared with the b-SSFP sequence. This technique is a promising method that could reduce the acquisition time of 3D non-contrast renal MRA.

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Compliance with ethical standards

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Conflict of interest Masami Yoneyama is an employee of Philips Japan. The other authors declare no conflicts of interest in regard to the products under investigation or the subject matter discussed in this manuscript.

Statistics and biometry No complex statistical methods were necessary for this paper.

Informed consent Written informed consent was obtained from all subjects (volunteers) in this study.

Ethical approval Institutional Review Board approval was obtained.

Methodology
• prospective
• experimental
• performed at one institution

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