Radiol Phys Technol (2014) 7:352–357
DOI 10.1007/s12194-014-0272-3

Separate pulmonary artery and vein magnetic resonance angiography by use of an arterial spin labeling method

Tomoyuki Okuaki · Tsuyoshi Ishimoto · Tosiaki Miyati · Satoshi Kobayashi · Masaru Ishihara · Momoe Kawakami · Tetsuo Ogino · Marc Van Cauteren

Received: 11 October 2013 / Revised: 18 May 2014 / Accepted: 18 May 2014 / Published online: 7 June 2014

Abstract A separate pulmonary vein (PV) is difficult to depict with the commonly used bright-blood magnetic resonance angiography method. Until now, no study has described the depiction of peripheral PVs without the artery. Our purpose in this study was to develop an arterial spin labeling (ASL)-based magnetic resonance angiography sequence to depict the pulmonary artery (PA) and vein separately. We developed such a sequence by using two inversion recovery pulses. The first pulse was non-selective, and the second pulse was selective and was applied to the aorta and heart. All studies were conducted on a 1.5-T clinical magnetic resonance system with six different inversion times for seven healthy volunteers. For evaluation, we categorized the inversion times by using visual scoring. Then, we used the magnitude image to evaluate the PA, and we used the real image to evaluate the PV. For the PA, an inversion time of 300 ms had the lowest score (1.43), and the score changed with increasing times; an inversion time of 1,100 ms had the highest score (3.85). For the PV, an inversion time of 300 ms had the highest score (2.68), and the score decreased with increasing times. The results indicated that the PA and vein could be depicted separately by the use of an ASL-based magnetic resonance angiography method. The optimal inversion times for the PV and artery were 300 and 1,100 ms, respectively.

Keywords Magnetic resonance imaging · Magnetic resonance angiography · Arterial spin labeling · Pulmonary artery · Pulmonary vein

1 Introduction

Magnetic resonance imaging (MRI) and angiography (MRA) sequencing techniques have improved, allowing broader clinical applications. In terms of non-contrast MRA studies, time-of-flight and phase contrast techniques are frequently applied for various clinical situations, such as brain artery

T. Okuaki · T. Ogino · M. Van Cauteren
Philips Healthcare, 2-13-37 Kohnan, Minato-ku, Tokyo 108-8507, Japan
e-mail: tetsuo.ogino@philips.com

M. Van Cauteren
e-mail: marc.van.cauteren@philips.com

T. Okuaki (✉) · T. Miyati · S. Kobayashi · T. Ogino
Division of Health Science, Graduate School of Medical Science, Kanazawa University, 5-11-80 Kodatsuno, Kanazawa 920-0942, Japan
e-mail: tomoyuki.okuaki@philips.com

T. Miyati
e-mail: ramiyati@mhs.mp.kanazawa-u.ac.jp

S. Kobayashi
e-mail: satoshik@staff.kanazawa-u.ac.jp

T. Ishimoto
Department of Radiology, Hyogo Cancer Center, 13-70 Kitaouji-cho, Akashi 673-8558, Japan
e-mail: ishimotohbhc@yahoo.co.jp

M. Ishihara
Department of Radiology, Hyogo Prefectural Amagasaki Hospital, 520 Saisho-ku, Himeji 670-0981, Japan
e-mail: hbhc_ishihara@yahoo.co.jp

M. Kawakami
Department of Radiology, Hyogo Prefectural Amagasaki Hospital, 1-1-1 Higashidaimoto-cho, Amagasaki 660-0828, Japan
e-mail: hamelnexit@yahoo.co.jp

scanning. Furthermore, the steady state sequence can depict blood as a high signal without an inflow effect and can therefore be used for whole-heart coronary MRA [1, 2]. Blood flow velocity in response to heart rate timing can be applied to peripheral MRA. During the systolic phase, arteries are depicted as low signals at maximum velocity because of flow void; however, during the systolic phase, arteries and veins are depicted as high signals at slow velocity. Therefore, the subtracted image can be shown only as an artery or vein [3–5]. Methods using the arterial spin labeling (ASL) technique have also been used for depiction of peripheral arteries and large vessels, such as the aorta [6–9].

Contrast-enhanced MRA has been utilized for delineation of the pulmonary artery (PA) [10, 11]. It is possible to separate the PA and pulmonary vein (PV) with an optimized scan parameter, though high time resolution and optimum scan timing are required [12–14]. Moreover, dynamic scan techniques with filling in of a low-frequency area in k-space at the time of contrast injection, and filling in of a high-frequency area after injection, can yield a high time resolution [15]. For non-contrast pulmonary MRA, a bright-blood method, in which turbo-spin-echo, a steady state sequence, and a phase contrast method are used, [16], or the ASL technique has been used [17].

Several studies have delineated the flow of blood in the PV and its branches [18, 19]. However, no study has described the depiction of peripheral PVs without the peripheral PAs. It is difficult to depict a separate PV with the bright-blood method in which an electrocardiogram trigger is used, because breathing and motion can hamper the generation of a subtracted image based on diastole and systole and can result in misregistration [4, 5]. Likewise, it is difficult to depict the PV by the ASL technique, because the inverted background signal by the inversion recovery (IR) pulse will be recovered by T_1 relaxation and the drop in contrast between the background signal and vein before the tagged spin arrives at the vein.

Therefore, our purpose in this study was to develop an ASL-based MRA sequence to depict the PA and PV separately.

2 Materials and methods

2.1 Theory of MR sequences

An ASL-based MRA technique was used. All signals in the field of view (FOV) were first inverted as a non-selective IR pulse. A second IR pulse as a selective IR was immediately added for blood in the superior vena cava (SVC), inferior vena cava (IVC), and right ventricle (RV) for spin tagging (Fig. 1). The blood tagged to be fully recovered by selective inversion pulse flows into the PA and PV to allow scanning of the lung area by the use of a turbo-spin-echo sequence after the inversion time (TI) (Fig. 2).

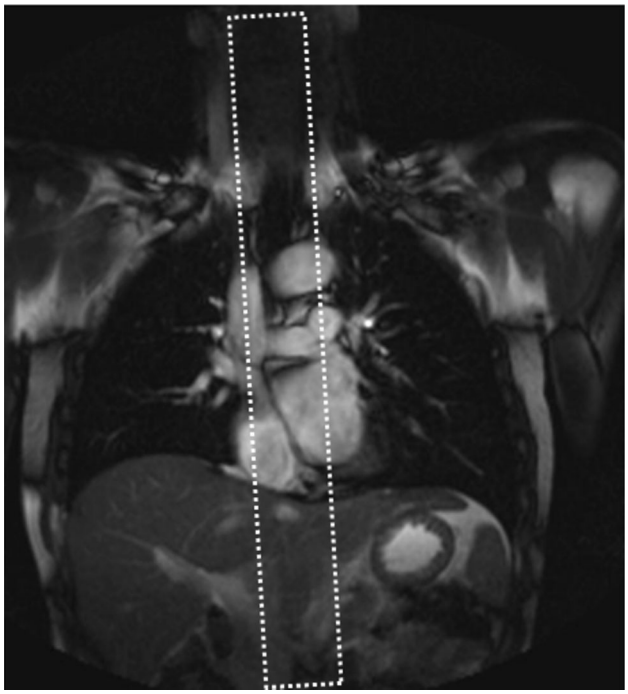

Fig. 1 Schema of magnetic resonance angiography-based arterial spin labeling. Setting position for selective inversion recovery pulse for tagging (*dotted white line*)

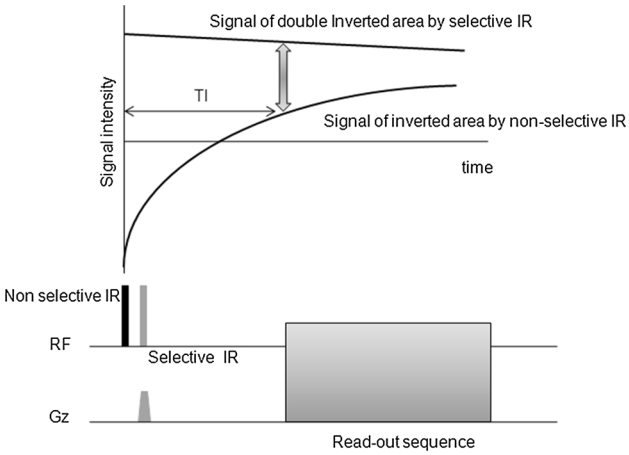

Fig. 2 Schema of magnetic resonance angiography-based arterial spin labeling. First inversion recovery (IR) pulse is non-selective pulse, and second IR pulse is selective pulse for tagging. Timing of readout sequence is after optimal inversion time that doubled the inverted blood flow into the target area

The contrast of the blood signal was decided on the basis of the background signal, which was considered T_1 relaxation after inversion by a non-selective IR pulse, and a tagged blood signal flowed into the target area. However, due to the T_1 relaxation, it was difficult to depict the PV, as mentioned above, because the contrast between the background and the PV decreased before the tagged blood travelled into the PV area.

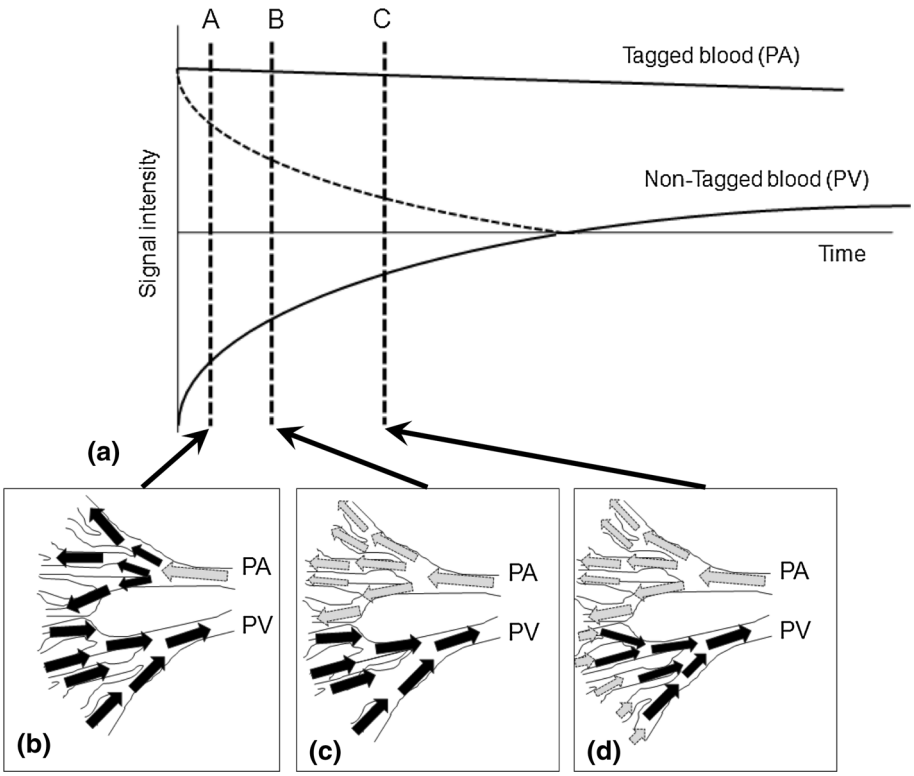

Fig. 3 Schema of (**a**) signal change and (**b–d**) tagged blood at *A*, *B*, and *C* in **a**. *Dotted and solid lines* in (**a**) are real and magnitude images, respectively. **b** Tagged blood travel to the pulmonary artery (PA), whose timing is immediately after the second inversion recovery (timing *A* in **a**). *Black arrows* in **b** are non-tagged blood, and gray arrow is tagged blood by double inversion. **c** Tagged blood fills in the PA, whose timing is a short inversion time (TI) (timing *B* in **a**). **d** Tagged blood arrival at the peripheral the pulmonary vein, whose timing is long TI (timing *C* in **a**)

MR images are usually shown as magnitude images, but the signal in the real image that is displayed in a gray scale from the most negative value to the most positive value changes as follows (Fig. 3a). The signal in the FOV was inverted by a non-selective IR pulse, and the tagged blood flowing into the lung area via the PA (Fig. 3b). The blood in the PV was still inverted at the time the tagged blood arrived in the peripheral PAs. When the real image at this time was inverted, tagged blood in the PA was depicted as a low signal, and blood in the PV was depicted as a high signal (Fig. 3c). A magnitude image was possible for depiction only of the PA as a high signal at the time the tagged blood filled the PA area (Fig. 3d).

2.2 Subjects

All studies were conducted on a 1.5-T clinical MR system (Achieva, Philips Healthcare, Best, the Netherlands) with a four-element body phased-array receiver coil. Written informed consent was obtained from seven volunteers (age range 24–38 years).

2.3 Scan parameters

All protocols were approved by our institutional review boards. Scanning was performed by the use of the following parameters with complex data: three-dimensional turbo-spin echo, TR/effective TE, 5,000/102 ms; matrix, 168*224 (512 reconstructions); FOV, 45 cm with fat suppression and flow compensation. Inversion times were 300, 500, 650, 800, 1,100, and 1,400 ms. The scan time was 4 min 40 s for each TI. The width of the second IR pulse was changed from 60 to 120 mm for each volunteer to set the optimal selective pulse, and the selective IR pulse was connected to the aorta and heart.

2.4 Visual scoring

MRIs were evaluated by one radiologist and four radiology technologists with 3–10-year experience in MR scanning.

The visual score was categorized as follows: The magnitude image was used for the evaluation of the PA, whereas the real image was used for the evaluation of the PV. We employed the one-way analysis of variance (one-way ANOVA) to compare the visual scoring between the image qualities of different TIs.

PA

Score 1, Poor	Did not visualize the PA or only depicted the beginning of the PA
Score 2, Fair	Both the PA and PV depicted
Score 3, Good	Only the PA depicted, but no depiction of the peripheral PAs
Score 4, Excellent	The PA was depicted well

PV

Score 1, Poor	Did not visualize the PV

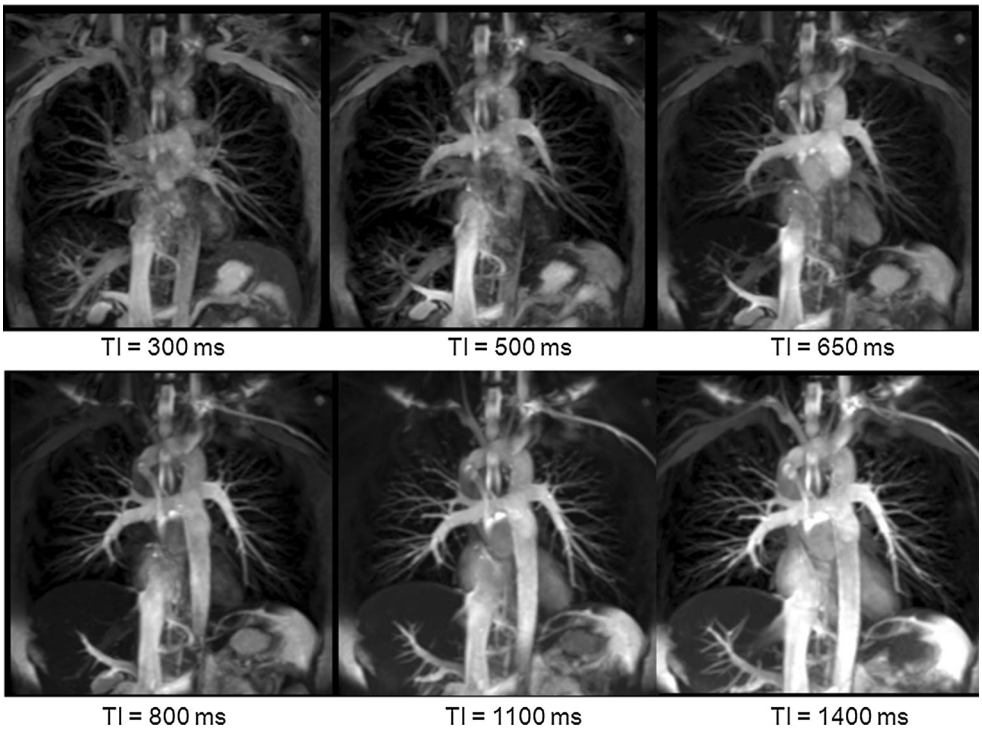

Fig. 4 Magnitude images of the pulmonary artery (PA) at each inversion time (TI). The PA is depicted well with a TI of 1,100 ms

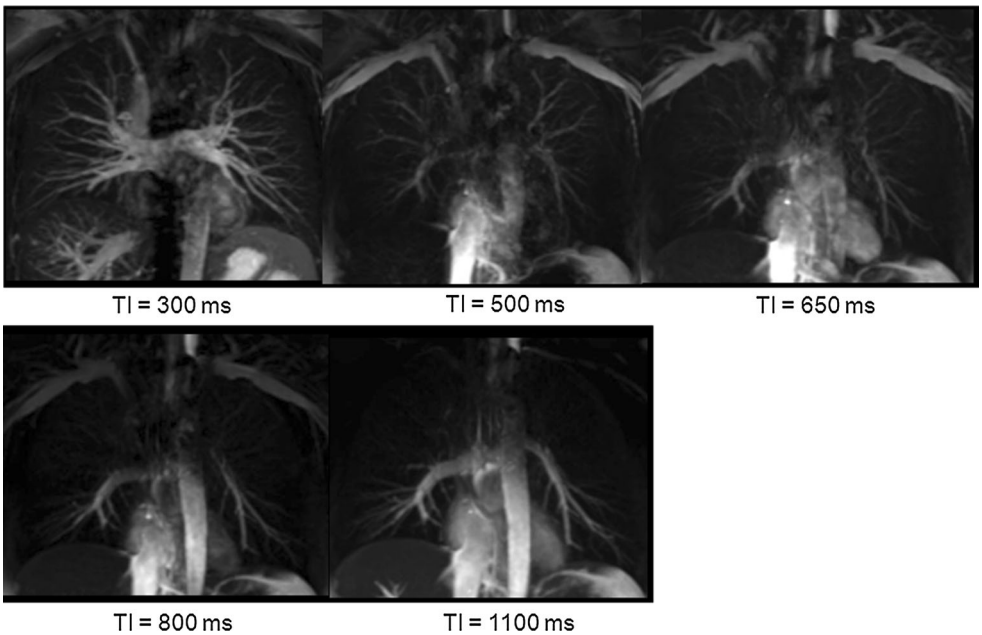

Fig. 5 Inverted real images of the pulmonary vein (PV) at each inversion time (TI). The PV is depicted well with a TI of 300 ms

Score 2, Fair	The PV was depicted, but it was unclear or the PA was also depicted
Score 3, Good	The PV was depicted, but only the beginning of the PV or only the peripheral PVs were depicted
Score 4, Excellent	The PV was well depicted

3 Results

Representative images are shown in Figs. 4 and 5, and a conventional turbo-spin-echo image (i.e., a non-tagged image) is shown for comparison in Fig. 6. Results of the average visual scoring are shown in Table 1. Significant differences were observed for different TIs (one-way ANOVA; $p < 0.0001$).

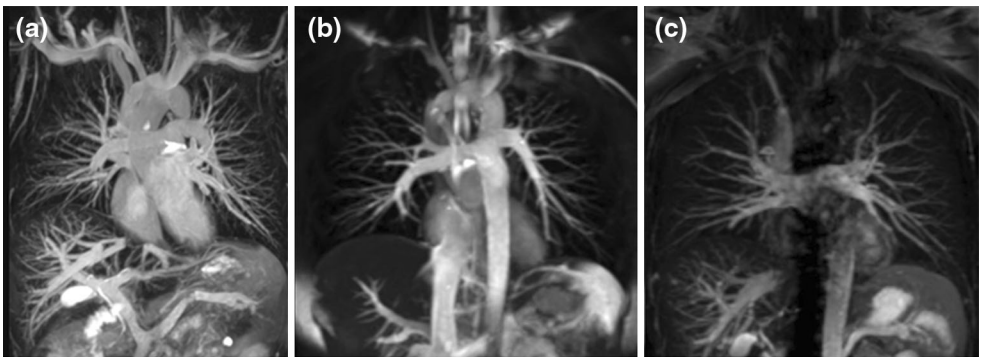

Fig. 6 Comparison among (**a**) conventional turbo-spin-echo image without tagging (**b**) magnitude pulmonary artery image with TI of 1,100 ms, and (**c**) inverted real pulmonary vein image with TI of 300 ms

Table 1 Results of visual scoring at each inversion time

TI (ms)	300	500	650	800	1,100	1,400
PA	1.43 ± 0.50	1.97 ± 0.30	2.17 ± 0.38	3.22 ± 0.65	3.85 ± 0.43	3.17 ± 0.75
PV	2.68 ± 1.18	2.43 ± 0.62	2.31 ± 0.64	1.88 ± 0.83	1.06 ± 0.25	1.06 ± 0.25

A TI of 1,100 ms is the highest score for PA imaging, whereas a TI of 300 ms is the highest score for PV imaging

TI inversion time, *PA* pulmonary artery, *PV* pulmonary vein

Significant differences were observed for different TIs (one-way ANOVA; $p < 0.0001$)

For the PA, the score for TI 300 ms was the lowest (1.43). The score changed with increasing TI; a TI of 1,100 ms had the highest score (3.85). The score for a TI of 1,400 ms was lower (3.17) than that for a TI of 1,100 ms.

PV images had a slightly low signal-to-noise ratio because of the real image; however, they were acceptable for evaluation. The score for a TI of 300 ms was highest (2.68), and the score decreased with increasing TI; the lowest score was 1.06.

4 Discussion

The PA and PV are vital structures for the lung, but it has been difficult to delineate these vessels separately in radiologic imaging. In the present study, we utilized an ASL-based technique and inverted real images to accomplish this delineation without using a subtraction method to depict the PV, thereby avoiding misregistration.

A selective IR pulse is a two-dimensional pulse, making it impossible to tag blood only in the RV. Therefore, one must be careful about setting the position of the selective IR pulse so that it tags only the SVC, IVC, and RV without the lung area, wherever possible. In this study, the pulse was positioned in accordance with the position of the vessels. Furthermore, the width of the pulse was optimized to cover the heart and aorta.

MRA using the ASL technique is affected by T_1 relaxation. This effect is related to the time at which the tagged blood arrives within the target area. The best result (depiction of the PA) was associated with a TI of 1,100 ms. It is difficult to depict only the PA, as its signal becomes low at a TI of >1,500 ms [17]. Some of the background signals, such as muscle and lung tissue, were relaxed, although this is not fully relaxation. If two scans, such as with and without tags, are performed with the subtraction technique, the background signal in the lung area is destroyed. This can result in misregistration and a long scan time. We did not consider visualizing signals besides the lung area, as our focus was only on the pulmonary vessels.

Information from real images has been used in our study. If it is assumed that the T_1 values of blood in the PV and lung tissue are 1,200 and 904 ms [20, 21], respectively, and the TR is 5,000 ms, then the null timing of the blood signal is around 830 ms. Thus, it is possible to detect the PV, even when the TI is 500 ms. Visualization of the PV was not perfect in this study (score: 2.68 ± 1.18 (mean ± SD) at a TI of 300 ms). This result means that the success rate was not high; in fact, the scores in two cases out of seven examinations were low.

The optimal TI was different for the depiction of the PA and PV. For scan timing, the best timing for PA detection was also the best timing for PV because tagged blood flowed into the PA area. ASL-based MRA images are

created by the use of signal contrast between tagged blood and background. Inverted signals by a non-selective IR pulse, such as background signals, are changed by T_1 relaxation. Therefore, the contrast between tagged blood and background worsens with longer TI on both magnitude and real images. For PA detection, an optimal TI resulted mainly for two reasons: the contrast between tagged blood and background, and the timing of the tagged blood flow into the peripheral PA area. For PV detection, an optimal TI resulted because of the contrast between non-tagged blood (PV) and tagged blood (PA) on real image, before the inverted non-tagged blood is relaxed at null timing. The timing that is a TI of 300 ms will be short, and tagged blood does not absolutely flow into the peripheral PA area. However, even TI of 300 ms, tagged blood flow into the PA is not small extent. Therefore, PV was depicted even the TI was 300 ms.

As a future work, phase compensation techniques will be needed for real images. And we focused on the development to depict the PA and PV separately. We scanned volunteer; thus, regarding optimal TI for the patients, it will be needed for more future work.

5 Conclusions

We developed an ASL-based MRA to depict the PA and PV separately.

In our study, the optimal TI for the PV in the inverted real image was 300 ms, whereas that for the PA in the magnitude, image was 1,100 ms.

Conflict of interest Tomoyuki Okuaki, Tetsuo Ogino, and Marc Van Cauteren are the employees of Philips Healthcare. Other authors do not have any conflict of interest associated with this study.

References

1. Jahnke C, Paetsch I, Schnackenburg B, Bornstedt A, Gebker R, Fleck E, Nagel E. Coronary MR angiography with steady-state free precession: individually adapted breath-hold technique versus free-breathing technique. Radiology. 2004;232:669–76.
2. Scheffler K, Lehnhardt S. Principles and applications of balanced SSFP techniques. Eur Radiol. 2003;13:2409–18.
3. Meuli RA, Wedeen VJ, Geller SC, Edelman RR, Frank LR, Brady TJ, Rosen BR. MR gated subtraction angiography: evaluation of lower extremities. Radiology. 1986;159:411–8.
4. Miyazaki M, Sugiura S, Tateishi F, Wada H, Kassai Y, Abe H. Non-contrast-enhanced MR angiography using 3D ECG-synchronized half-Fourier fast spin echo. J Magn Reson Imaging. 2000;12:776–83.
5. Miyazaki M, Takai H, Sugiura S, Wada H, Kuwahara R, Urata J. Peripheral MR angiography: separation of arteries from veins with flow-spoiled gradient pulses in electrocardiography-triggered three-dimensional half-Fourier fast spin-echo imaging. Radiology. 2003;227:890–6.
6. Edelman RR, Siewert B, Adamis M, Gaa J, Laub G, Wielopolski P. Signal targeting with alternating radiofrequency (STAR) sequences: application to MR angiography. Magn Reson Med. 1994;31:233–8.
7. Wielopolski PA, Adamis M, Prasad P, Gaa J, Edelman R. Breath-hold 3D STAR MR angiography of the renal arteries using segmented echo planar imaging. Magn Reson Med. 1995;33:432–8.
8. Nishimura DG, Macovski A, Pauly JM, Conolly SM. MR angiography by selective inversion recovery. Magn Reson Med. 1987;4:193–202.
9. Kanazawa H, Miyazaki M. Time-spatial labeling inversion tag (t-slit) using a selective IR-tag on/off pulse in 2D and 3D half-Fourier FSE as arterial spin labeling. In: Proceedings of the Tenth Meeting of the International Society for Magnetic Resonance in Medicine. Berkeley, Calif: International Society for Magnetic Resonance in Medicine, 2002. p. 140.
10. Du J. Contrast-enhanced MR angiography using time resolved interleaved projection sampling with three-dimensional Cartesian phase and slice encoding (TRIPPS). Magn Reson Med. 2009;61:918–24.
11. Du J, Bydder M. High-resolution time-resolved contrast-enhanced MR abdominal and pulmonary angiography using a spiral-tricks sequence. Magn Reson Med. 2007;58:631–5.
12. Wilman AH, Riederer SJ, King BF, Debbins JP, Rossman PJ, Ehman RL. Fluoroscopically triggered contrast-enhanced three-dimensional MR angiography with elliptical centric view order: application to the renal arteries. Radiology. 1997;205:137–46.
13. Earls JP, Rofsky NM, DeCorato DR, Krinsky GA, Weinreb JC. Breath-hold single-dose gadolinium-enhanced three-dimensional MR aortography: usefulness of a timing examination and MR power injector. Radiology. 1996;201:705–10.
14. Korosec FR, Frayne R, Grist TM, Mistretta CA. Time-resolved contrast-enhanced 3D MR angiography. Magn Reson Med. 1996;36:345–51.
15. Sodickson DK, McKenzie CA, Li W, Wolff S, Manning WJ, Edelman RR. Contrast-enhanced 3D MR angiography with simultaneous acquisition of spatial harmonics: a pilot study. Radiology. 2000;217:284–9.
16. Sanz J, Kuschnir P, Rius T, Salguero R, Sulica R, Einstein AJ, Dellegrottaglie S, Fuster V, Rajagopalan S, Poon M. Pulmonary arterial hypertension: noninvasive detection with phase-contrast MR imaging. Radiology. 2007;243:70–9.
17. Miyazaki M, Lee VS. Nonenhanced MR angiography. Radiology. 2008;248:20–43.
18. Hu P, Chuang ML, Kissinger KV, Goddu B, Goepfert LA, Rofsky NM, Manning WJ, Nezafat R. Non-contrast-enhanced pulmonary vein MRI with a spatially selective slab inversion preparation sequence. Magn Reson Med. 2010;63:530–6.
19. Hu P, Stoeck CT, Smink J, Peters DC, Ngo L, Goddu B, Kissinger KV, Goepfert LA, Chan J, Hauser TH, Rofsky NM, Manning WJ, Nezafat R. Noncontrast SSFP pulmonary vein magnetic resonance angiography: impact of off-resonance and flow. J Magn Reson Imaging. 2010;32:1255–61.
20. Simonetti O, Finn J, White R, et al. Black blood t2-weighted inversion recovery MR imaging of the heart. Radiology. 1996;199:49–57.
21. Stock KW, Chen Q, Morrin M, Hatabu H, Edelman RR. Oxygen-enhanced magnetic resonance ventilation imaging of the human lung at 0.2 and 1.5T. J Magn Reson Imaging. 1999;9:838–41.