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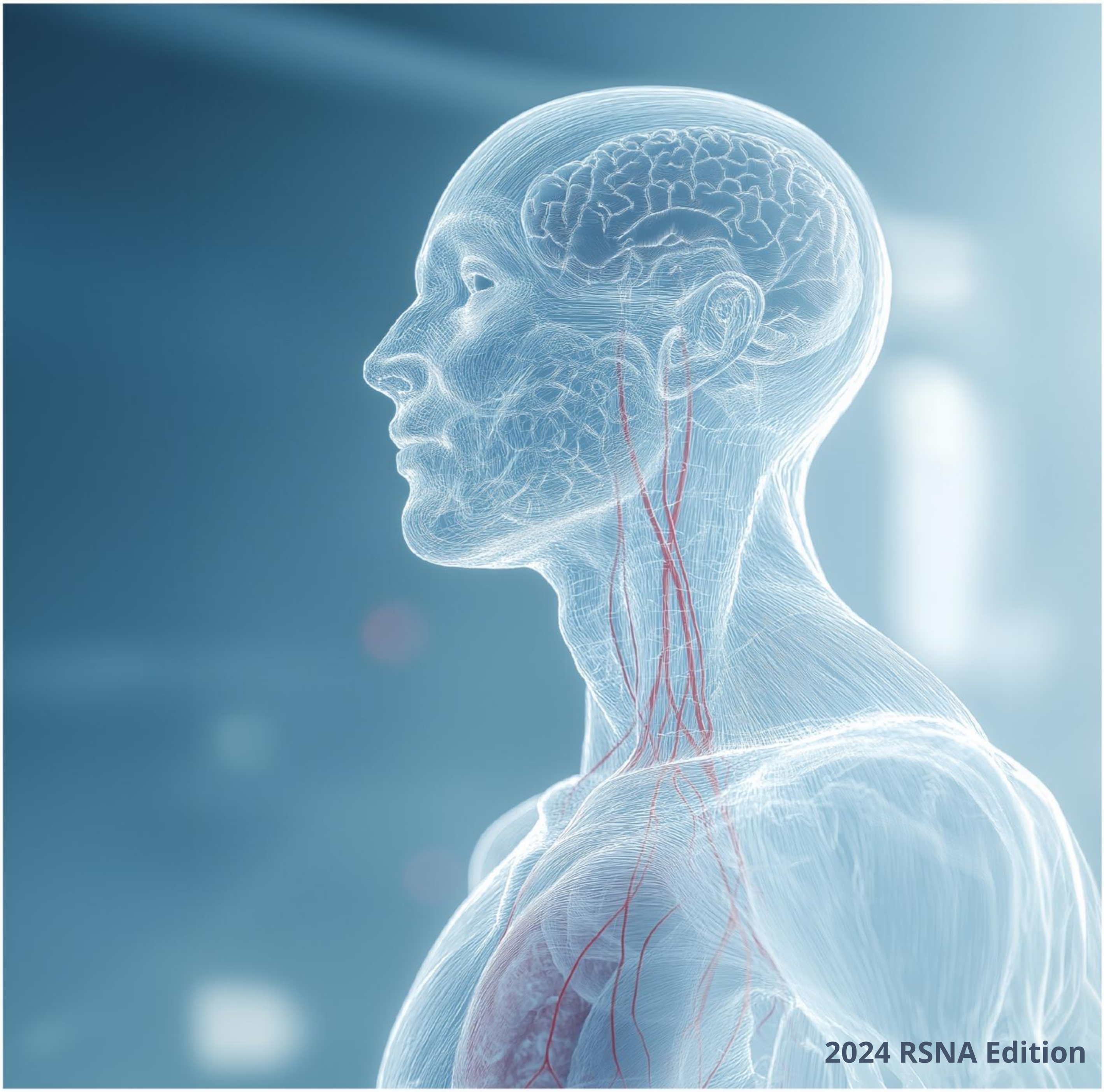

Issue Highlights

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Preliminary Application of 5T Whole Body Non-Contrast-Enhanced Magnetic Resonance Angiography

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1. Introduction

Non-contrast-enhanced magnetic resonance angiography (NCE-MRA) generates vascular images without the use of exogenous contrast agents, thus avoiding the risks associated with gadolinium-based contrast agents. It is widely used for vascular disease screening and assessment in various body regions.

Currently, clinical NCE-MRA scanning is primarily performed at 1.5T and 3T. Recent advancements in ultra-high field (field strength >3T) magnetic resonance equipment have enabled vascular imaging at higher field strengths. Increasing the main magnetic field strength is expected to bring many improvements to NCE-MRA, particularly in enhanced signal-to-noise ratio (SNR), resolution and acquisition efficiency. The 7.0T MR system, a typical ultra-high field MR, has shown significant advantages in intracerebral MRA compared to 1.5T and 3T (1). However, its use is limited by B1+/B0 inhomogeneity and the lack of body imaging coils, restricting it mostly to brain vessel scanning. Some pioneering studies have explored using custom transmit-receive coils for 7T body vascular imaging in the lower extremities (2, 3) and kidneys (4, 5), but these efforts face challenges like B1+ field inhomogeneity, causing blood signal loss and uneven image brightness (3, 5).

The uMR® Jupiter 5T is the first whole-body ultra-high field magnetic resonance imaging system, bringing new opportunities for ultra-high field whole-body NCE-MRA. This system features a large aperture 8-channel parallel transmit volume coil, combined with receiving coils suitable for multiple regions, enabling whole-body multi-regional scanning. Additionally, compared to 7.0T, the 5T field strength is expected to alleviate B1+ field inhomogeneity and RF heating issues, providing better suitability for body imaging. This article categorizes and reviews NCE-MRA methods, analyzes the advantages and challenges of NCE-MRA at ultra-high fields, and discusses NCE-MRA schemes applicable to different body regions using the 5T MR imaging platform.

2. Classification of NCE-MRA Techniques

Based on different principles, most NCE-MRA techniques can be divided into the following three categories:

2.1. Techniques Based on Inflow Enhancement Effect

NCE-MRA based on the inflow enhancement effect utilizes specific methods to suppress stationary tissue signals in the imaging region. Since the blood protons outside the imaging region are not yet excited, they generate high signal intensity relative to stationary tissues upon entering the imaging layer. Typical techniques include Time-of-Flight (TOF), inflow inversion recovery (IFIR) (6), quiescent interval single shot (QISS) (7), and arterial spin labeling (ASL).

TOF can be acquired in either 2D or 3D mode, using repeated excitation of RF pulses based on a gradient-echo sequence to saturate the static tissues within the imaging layer. IFIR and QISS utilize a 180°inversion recovery pulse and a 90° saturation pulse, respectively, to saturate the background signal in the imaging region and acquire MRA images after a predetermined wait time, allowing unsaturated blood to flow in. The former is suitable for observing renal and hepatic arteries, while the latter is commonly used for imaging the limbs and iliac arteries. ASL methods perform subtraction processing on images of labeled and unlabeled upstream blood to eliminate background signals, and are applicable for imaging blood vessels in the head (8), neck (9), chest, and abdomen (10).

2.2. Techniques Based on Spin-Phase Effect

Under the action of bipolar gradients, the stationary protons in background tissues experience no net phase shift, while the moving protons in the blood undergo a net phase shift proportional to their velocity, enabling NCE-MRA based on the spin-phase effect. Phase contrast (PC) can measure the net phase shifts of blood protons in three directions to obtain blood signals and calculate blood flow velocity, representing spin-phase effect NCE-MRA. Besides conventional 2D and 3D acquisition modes, PC can introduce a time dimension for cine or 4D flow imaging (11), facilitating dynamic blood flow monitoring.

Fresh blood imaging (FBI) (12) and flow-sensitized dephasing (FSD) (13, 14) can generate NCE-MRA images by subtracting arterial high-signal bright blood images (diastole) from arterial low-signal images based on the spin-phase effect (systole). FBI uses ECG gating and sets appropriate delay times based on differences in blood flow velocity and phase dispersion between diastole and systole, generating dark-bright blood images. FSD employs specially designed blood suppression pre-pulses to inhibit blood flow signals, effectively differentiating between arteries and veins (13, 15, 16).

2.3. Techniques Based on Blood T1/T2 Values

NCE-MRA based on inflow enhancement or spin-phase effects relies on blood flow, and its effects diminish in cases of slow blood flow or complex vasculature. In balanced steady-state free precession (bSSFP) sequence images, tissue signals are proportional to the tissue T2/T1 ratio. Blood, having a higher T2/T1 ratio, appears as a high signal in bSSFP sequences, enabling flow-independent NCE-MRA. Previous studies (17–19) have shown that combining bSSFP sequences with T2 preparation pulses, fat suppression pulses, and T1 contrast modulation pre-pulses helps to fully suppress background signals, making it suitable for coronary and aortic imaging.

The aforementioned three types of NCE-MRA techniques have different applicable scenarios. Existing research is mostly limited to MR equipment of 3T and below, lacking studies on the applicability of ultra-high-field imaging, especially body imaging. The unique environment of ultra-high-field MR poses higher demands on imaging techniques, necessitating the selection of the optimal NCE-MRA imaging and technical schemes based on the study area.

3. Analysis of Ultra-High Field Vascular Imaging Techniques

For vascular imaging, increasing the main magnetic field strength can bring the following advantages:

1. Improved Signal-to-Noise Ratio (SNR): The most direct advantage of increased signal strength at ultra-high fields, resulting in higher SNR and blood-to-background contrast-to-noise ratio.
2. Shortened Scan Time: Based on increased signal strength, ultra-high fields can achieve higher acceleration factors, reducing acquisition time.
3. Increased Resolution: Higher SNR and greater acceleration factors help improve spatial resolution, presenting vascular structures and pathological features more clearly within the same examination time.
4. Increased Blood-to-Background Contrast: As tissue T1 values increase with field strength, ultra-high fields can improve background suppression for inflow enhancement methods (such as TOF, IFIR, QISS) and enhance labeling efficiency for ASL methods.

Higher field strengths also bring many technical challenges to vascular imaging:

1. B1+ Field Inhomogeneity: The smaller RF wavelength at higher field strengths (3T: 27 cm, 5T: 16 cm, 7.0T: 12 cm) can cause standing wave effects due to insufficient penetration through the body, affecting B1+ field homogeneity. This effect can cause uneven image signals and blood signal loss, especially in body imaging (20, 21).
2. B0 Field Inhomogeneity: At ultra-high fields, the inhomogeneity of the main magnetic field (B0) is also more severe, potentially causing off-resonance artifacts and more severe blood signal dephasing. bSSFP sequences are particularly sensitive to these issues.
3. RF Heating Effects: The higher RF pulse energy at ultra-high fields increases patient energy deposition, raising the risk of thermal burns, further limiting the application of RF-intensive sequences like FSE.

4. Application of 5T MRA in Different Regions

The unique advantages and challenges of ultra-high-field imaging require researchers to select the most appropriate NCE-MRA imaging methods and techniques based on different anatomical regions. This section selects several typical body parts to demonstrate feasible technical schemes and example images.

4.1 Data Acquisition

The following 5T example images were acquired using the United Imaging uMR Jupiter 5T MRI scanner. Intracranial and foot vascular scans used a 48-channel head transmit-receive coil, while chest, abdominal, and lower limb vascular scans used a 48-channel spine receive coil and a 24-channel body receive coil. The 3T control images were acquired using the United Imaging uMR® 790 3T MRI scanner. This study has been approved by the Ethics Committee of the Institute of Brain Science and Technology, Fudan University (FE222691). All subjects were healthy volunteers who signed informed consent forms

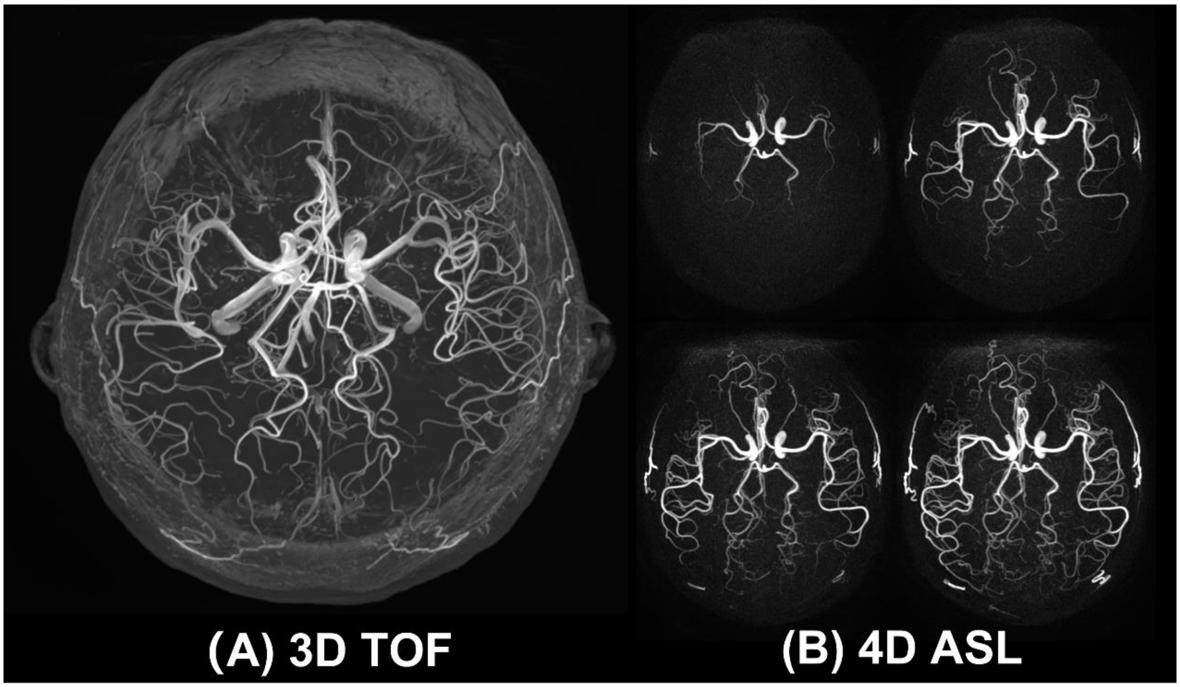

Figure 1. Examples of 5T intracranial MRA. A. 3D TOF maximum intensity projection (MIP) image (healthy male, 24 years old). B. 4D ASL MIP images at post-labeling delay times of 300, 600, 900 and 1500 ms(healthy male, 34 years old).

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4.2 Cerebral Vessels

3D TOF is the most commonly used method for intracranial MRA and shows good applicability at ultra-high fields (Figure 1A). Zhang et al. conducted a comprehensive quantitative evaluation of 3D TOF at 3T, 5T, and 7T field strengths, revealing that 5T TOF significantly outperforms 3T and that its quantitative results are consistent with those at 7T (22).

As a novel dynamic MRA technique, 4D ASL can capture dynamic changes in blood flow within the intracranial arterial system by acquiring images at different post-labeling delay times, allowing for the detection of arterial abnormalities such as stenosis, dilation, or thrombosis. Figure 1B shows example images of 5T 4D ASL at different post-labeling delay times.

4.3 Thoracic and abdominal Vessels

The IFIR technique based on the inflow effect can effectively be used for vascular imaging of thoracic and abdominal organs. Figure 2 shows 5T renal MRA obtained using the IFIR sequence (United Imaging: Flow-Inversion Nonenhanced (FINE) 3D). For imaging of the aorta and other chest vessels, the flow-independent bSSFP technique can be used. Additionally, 4D Flow technology, with high temporal resolution, can dynamically present blood flow changes and achieve quantitative flow measurements, showing potential for application at 5T ultra-high field.

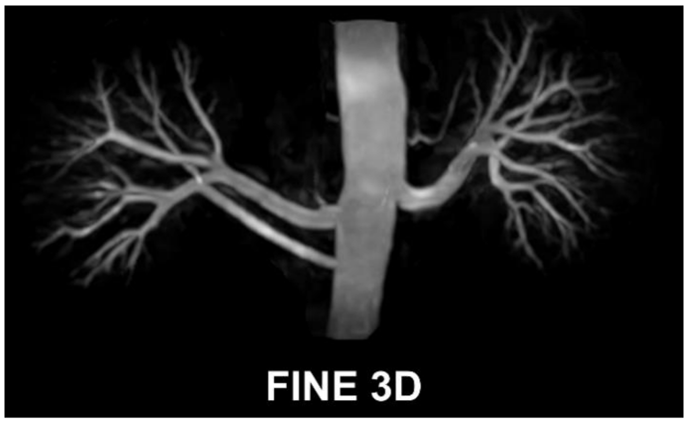

Figure 2. Example of 5T FINE 3D renal artery imaging (healthy male, 38 years old).

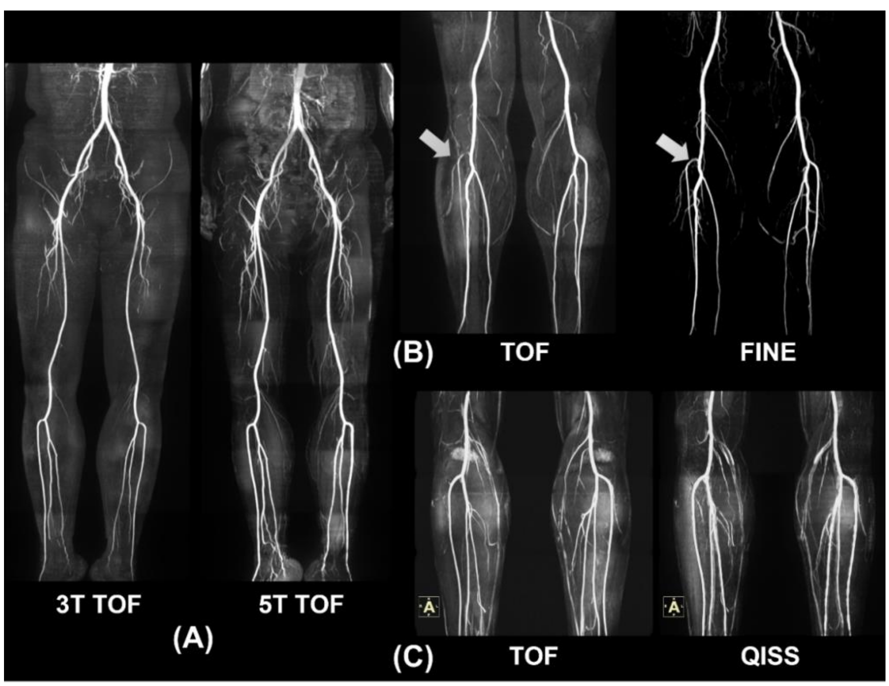

Figure 3. Examples of 5T lower limb MRA. A. Comparison of 2D TOF MIP images at 3T and 5T field strengths; B. Comparison of 2D TOF and FINE 2D, with arrows indicating missing signals in TOF; C. Comparison of 2D TOF and QISS, where the acquisition time required for QISS is one-third of that for 2D TOF. All images were acquired from healthy male volunteers aged 30-50, with each comparative image pair obtained from the same volunteer.

Figure 4. Example of 5T foot vascular imaging. Comparison of MIP images of 3D PC foot vascular imaging at 3T and 5T field strengths (same healthy volunteer, 48 years old).

4.4 Lower Limb Vessels

The vascular morphology and blood flow direction of the lower limbs generally follow a head-to-foot orientation and are relatively straight. NCE-MRA methods based on the inflow effect can achieve high-quality vascular images at ultra-high fields, such as TOF and QISS. Typically, 2D plane acquisitions in the transverse position are used to obtain strong inflow effects. During acquisitions, external ECG gating signals can be used to capture data during diastole and reduce pulsation artifacts. Figure 3A shows the performance of 2D TOF at 3T and 5T field strengths, demonstrating improved artery visualization at 5T.

The ASL method (United Imaging: FINE 2D) can achieve better background suppression by acquiring and subtracting images of arteries and veins separately. Figure 3B shows the imaging results of FINE 2D and 2D TOF in the calf, where FINE 2D shows enhanced background suppression and improved vessel delineation compared to 2D TOF.

The QISS method is another suitable NCE-MRA technique for lower limb vessels. Previous researchers have applied it to 7T but found it susceptible to B1 field issues, leading to blood signal loss and uneven image brightness (2, 3). The 5T field strength is expected to mitigate this defect. Figure 3C shows the imaging results of QISS in the calf. Compared to TOF, which completes layer acquisition every three heartbeats, QISS can reduce acquisition time from approximately 3 minutes per station to 1 minute per station using single-shot bSSFP acquisition.

Furthermore, FBI and FSD techniques based on 3D FSE or bSSFP acquisition can also be used for lower limb vascular imaging, but their application at 5T ultra-high field requires further research.

4.5 Foot Vessels

The slow blood flow in the foot presents significant challenges for NCE-MRA. TOF and QISS methods based on the inflow effect often fail to achieve ideal imaging results. Researchers have used FBI (23) and FSD (24) techniques to scan foot vessels, but these methods face challenges due to field inhomogeneity at ultra-high fields.

3D PC is a feasible technique that can achieve clear imaging of foot vessels by setting a small velocity encoding value (VENC) (25). Figure 4 shows the performance of 3D PC in the same healthy volunteer at 3T and 5T field strengths, demonstrating a significant improvement in vascular presentation at higher field strengths.

5. Conclusion

The advent of the uMR Jupiter 5T MRI platform brings new opportunities for ultra-high-field whole-body NCE-MRA research. Currently, the Jupiter 5T system preliminarily covers the full-body vascular scanning sequence. Existing research results indicate that traditional imaging techniques like TOF and PC demonstrate significantly superior vascular visualization at 5T compared to 3T (22, 25). The preliminary exploration results presented in this paper also suggest that more advanced techniques like ASL and QISS are feasible at 5T. Future research requires more in-depth studies to validate the applicability of various NCE-MRA techniques at 5T.

However, new opportunities come with more complex technical challenges. The technical issues faced by NCE-MRA at ultra-high fields are often a double-edged sword. For example, higher field strengths enhance signal, which can improve image SNR and resolution; however, more severe B1+ and B0 field inhomogeneities at ultra-high fields impose higher demands on NCE-MRA sequence design, especially for advanced techniques like FBI and FSD. Additionally, increased tissue T1 values at ultra-high fields result in longer signal recovery times, potentially leading to reduced image T1 contrast and extended scan times. However, for NCE-MRA, this phenomenon can be utilized to achieve higher blood-to-background contrast. Therefore, selecting imaging schemes suitable for ultra-high fields based on the morphology and blood flow characteristics of specific body parts and addressing challenges like field inhomogeneity through sequence optimization, coil design, and shimming techniques are crucial for ultra-high-field whole-body NCE-MRA research.

This paper only presents example images of NCE-MRA in various body regions and preliminarily discusses the technical characteristics and feasibility of 5T ultra-high-field whole-body vascular imaging. Future research plans will combine large-sample clinical scan data to conduct in-depth quantitative evaluations of various techniques in clinical applications, providing stronger support for their widespread use in medical imaging.

6. Image/Figure Courtesy

All images are the courtesy of The Institute of Science and Technology for Brain-inspired Intelligence, Fudan University, Shanghai, China and Department of Radiology, Zhongshan Hospital, Fudan University, Shanghai, China

7. References

1. Stamm AC, Wright CL, Knopp MV, Schmalbrock P, Heverhagen JT: Phase contrast and time-of-flight magnetic resonance angiography of the intracerebral arteries at 1.5, 3 and 7 T. Magnetic Resonance Imaging 2013; 31:545–549.

2. Raval SB, Britton CA, Zhao T, et al.: Ultra-high field upper extremity peripheral nerve and non-contrast enhanced vascular imaging. PLoS ONE 2017; 12:1–20.

3. Fischer A, Maderwald S, Johst S, et al.: Initial evaluation of non-contrast-enhanced magnetic resonance angiography in patients with peripheral arterial occlusive disease at 7 T. Investigative Radiology 2014; 49:331–338.

4. Umutlu L, Maderwald S, Kraff O, et al.: New look at renal vasculature: 7 tesla nonenhanced T1-weighted FLASH imaging. Journal of Magnetic Resonance Imaging 2012; 36:714–721.

5. Metzger GJ, Auerbach EJ, Akgun C, et al.: Dynamically applied B1+ shimming solutions for non-contrast enhanced renal angiography at 7.0 tesla. Magnetic Resonance in Medicine 2013; 69:114–126.

6. Glockner JF, Takahashi N, Kawashima A, et al.: Non-contrast renal artery MRA using an inflow inversion recovery steady state free precession technique (inhance): Comparison with 3D contrast-enhanced MRA. Journal of Magnetic Resonance Imaging 2010; 31:1411–1418.

7. Edelman RR, Sheehan JJ, Dunkle E, Schindler N, Carr J, Koktzoglou I: Quiescent-interval single-shot unenhanced magnetic resonance angiography of peripheral vascular disease: Technical considerations and clinical feasibility. Magnetic Resonance in Medicine 2010; 63:951–958.

8. Yan L, Wang S, Zhuo Y, et al.: Unenhanced dynamic MR angiography: High spatial and temporal resolution by using true FISP-based spin tagging with alternating radiofrequency. Radiology 2010; 256:270–279.

9. Koktzoglou I, Meyer JR, Ankenbrandt WJ, et al.: Nonenhanced arterial spin labeled carotid MR angiography using three-dimensional radial balanced steady-state free precession imaging. Journal of Magnetic Resonance Imaging 2015; 41:1150–1156.

10. Zhu D, Li W, Liu D, et al.: Non-contrast-enhanced abdominal MRA at 3 T using velocity-selective pulse trains. Magnetic Resonance in Medicine 2020; 84:1173–1183.

11. Markl M, Frydrychowicz A, Kozerke S, Hope M, Wieben O: 4D flow MRI. Journal of Magnetic Resonance Imaging 2012; 36:1015–1036.

12. 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; 227:890–896.

13. Priest AN, Taviani V, Graves MJ, Lomas DJ: Improved artery-vein separation with acceleration-dependent preparation for non-contrast-enhanced magnetic resonance angiography. Magnetic Resonance in Medicine 2014; 72:699–706.

14. Fan Z, Sheehan J, Bi X, Liu X, Carr J, Li D: 3D noncontrast MR angiography of the distal lower extremities using flow-sensitive dephasing (FSD)-prepared balanced SSFP. Magnetic resonance in medicine 2009; 62:1523–32.

15. Li H, Priest AN, Patterson I, Graves MJ, Lomas DJ: Subtractive non-contrast-enhanced MRI of lower limb veins using multiple flow-dependent preparation strategies. Magnetic Resonance in Medicine 2019; 81:1769–1783.

16. Xu F, Zhu D, Fan H, et al.: Magnetic resonance angiography and perfusion mapping by arterial spin labeling using Fourier transform–based velocity-selective pulse trains: Examination on a commercial perfusion phantom. Magnetic Resonance in Medicine 2021; 86:1360–1368.

17. Bangerter NK, Cukur T, Hargreaves BA, et al.: Three-dimensional fluid-suppressed T2-prep flow-independent peripheral angiography using balanced SSFP. Magnetic Resonance Imaging 2011; 29:1119–1124.

18. Stafford RB, Sabati M, Mahallati H, Frayne R: 3D non-contrast-enhanced MR angiography with balanced steady-state free precession dixon method. Magnetic Resonance in Medicine 2008; 59:430–433.

19. Edelman RR, Koktzoglou I: “Push-button” noncontrast MR angiography using balanced T1 relaxation-enhanced steady-state (bT1RESS). Magnetic Resonance in Medicine 2021; 85:1248–1257.

20. Miyazaki M, Akahane M: Non-contrast enhanced MR angiography: Established techniques. Journal of Magnetic Resonance Imaging 2012; 35:1–19.

21. Miyazaki M, Isoda H: Non-contrast-enhanced MR angiography of the abdomen. European Journal of Radiology 2011; 80:9–23.

22. Shi Z, Zhao X, Zhu S, et al.: Time-of-Flight Intracranial MRA at 3 T versus 5 T versus 7 T: Visualization of Distal Small Cerebral Arteries. Radiology 2023; 306:207–217.

23. Schubert T, Takes M, Aschwanden M, et al.: Non-enhanced, ECG-gated MR angiography of the pedal vasculature: comparison with contrast-enhanced MR angiography and digital subtraction angiography in peripheral arterial occlusive disease. European Radiology 2016; 26:2705–2713.

24. Liu X, Fan Z, Zhang N, et al.: Unenhanced MR Angiography of the Foot: Initial Experience of Using Flow-Sensitive Dephasing–prepared Steady-State Free Precession in Patients with Diabetes. Radiology 2014; 272:885–894.

25. Shi Z, Li H, Zeng M: Improved Visualization for Foot MRA by Warm Water Immersion. In Proceedings of Society for Magnetic Resonance Angiography 35th Annual International Conference; 2023.

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