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Introduction

Contrast-enhanced MR angiography (CE-MRA) has become a non-invasive modality of choice for detecting arterial disease across various vascular regions. However, patients with renal insufficiency who receive gadolinium-based agents are at risk for developing a debilitating and potentially fatal disease known as nephrogenic systemic fibrosis (NSF) [1, 2]. As a result, a substantial population in need for this radiation-free, non-invasive diagnostic tool. Furthermore, with CE-MRA, short contrast first-pass window in arteries often limits the imaging coverage and/or spatial resolution, and venous contamination may be present at distal run-off vessels. All limitations above, along with added complexity and cost of contrast agent, have triggered a renaissance of interest in non-contrast MRA (NC-MRA).

Time-of-flight and phase-contrast are two original NC-MRA techniques, but not widely accepted for imaging peripheral arteries, primarily due to the limited spatial coverage (or time inefficiency) as well as well-known flow artifacts associated with complex flow [3]. Recently, a group of NC-MRA techniques, such as fast spin-echo based fresh blood imaging (FBI) methods (also known as NATIVE SPACE on Siemens systems) [4], quiescent interval single-shot (QISS) [5] or Ghost [6], have been developed as an alternative to CE-MRA for peripheral MRA. Among them, balanced steady-state free precession (SSFP) using flow-sensitive dephasing (FSD) magnetization preparation is a non-contrast approach that provides several unique features including high arterial blood signal-to-noise ratio (SNR) and blood-tissue contrast, isotropic features including high arterial blood sensitivity dephasing (FSD) magnetization preparation* is a non-contrast method that provides several unique features including high arterial blood sensitivity dephasing (FSD) magnetization preparation, which are removed by the bipolar-gradient FSD module. This method can introduce a spatial signal modulation in static tissues, as shown below, if the center 180° RF pulse frequency response is spatially inhomogeneous.

where M_r is the longitudinal magnetization right after FSD-preparation, M_0 is the equilibrium magnetization, Ω is the actual flip angle of the 180° pulse, Ω is the phase the static spins accumulate during the FSD gradient before the 180°-pulse, which is dependent on the gradient’s net area A_r is the static signal modulation in static tissues, as shown below, if the center 180° RF pulse frequency response is spatially inhomogeneous.

Technical considerations

FSD gradient waveform

The FSD pulse sequence is a 90°, 180°, 90°, driven equilibrium Fourier transform diffusion preparation module, and identical field gradients are applied symmetrically around the 180° radio-frequency (RF) pulse [15]. Analysis based on the Bloch equation reveals that conventional unipolar-gradient pulses (Fig. 2A) in the FSD module can introduce a spatial signal modulation in static tissues, as shown below, if the center 180° RF pulse frequency response is spatially inhomogeneous.

A simple solution to circumventing the issue is to have Φ_r = A_r = 0. A bipolar-gradient scheme (Fig. 2B) becomes a natural choice to achieve this goal. Example images using the two gradient waveforms are shown in figures 2C and D.
An unnecessarily large $m_1$ value may adequate $m_1$ value. Consequently, sub-segments may result from an inadequate diffusion effect, whereas static background tissues due to the venous blood and, potentially, other entail signal contamination from or false diagnosis in FSD MRA.

Quality, overestimation of stenosis, optimal $m_1$ tends to cause poor image quality, or false diagnosis in FSD MRA. In case of FSD-prepared MRA, the signal of a coherent flow that is perpendicular to this direction will not be effectively nullified. Thus, the conventional FSD module may result in a suboptimal vessel segment depiction on MR angiograms.

To achieve signal suppression of multi-directional blood flow, we proposed a multi-directional FSD preparative scheme. Specifically, two (or three for three-dimensional flow) conventional FSD preparative modules are applied in series, with balanced FSD gradients aligned along the RD direction in the first module and along the PE direction in the second one (Fig. 3) [21]. The spoiler gradients applied at the end of the preceding FSD module ensure that dephased flow spin components will not be rephased in the subsequent one. Thus, flow components along individual directions can be suppressed independently by their corresponding modules. Figure 3 shows an example whereby certain signal loss on MIP MRA was observed at several arterial segments when using the conventional single FSD module. Such signal defects mimicking vessel narrowing can be markedlyameliorated by the two-module FSD preparation.

**Clinical applications**

Clinical feasibility of using the FSD-based NC-MRA technique has been demonstrated in multiple arterial stations, including lower legs [8, 9], feet [10], and hands [11, 12]. In all previous studies, CE-MRA was used as a comparison reference, reflecting the fact that invasive x-ray angiography is not commonly performed in clinical diagnostic imaging routines.

At lower legs, Lim et al. [8] showed that FSD-based NC-MRA is more robust to arterial flow variations than fast spin-echo based techniques and “can be performed first line at 1.5T where exogenous contrast agents are undesirable or contraindicated”. In this work, FSD-based MRA demonstrated satisfactory image quality, excellent negative predictive value (91.7%), and good sensitivity (80.3%), specificity (81.7%), and diagnostic accuracy (81.3%) for hemodynamically significant (≥50%) stenosis. Another study by Liu et al. [9] showed that the number of diagnostic segments is not significant between FSD-based NC-MRA and CE-MRA, although the image quality of NC-MRA is slightly lower with significance reached. Similarly, high diagnostic accuracy was obtained using the NC-MRA technique. An example case from [9] is shown in figure 4.

Pedal arteries present a few challenges to NC-MRA techniques, including smaller caliber size, relatively slow flow, and more tortuous anatomy. FSD-based NC-MRA has recently been successfully applied to diabetic patients who have foot vascular complications [10]. This work demonstrated that the NC-MRA technique can yield a significantly higher number of diagnostic arterial segments.
A clinical case from this work is shown in figure 6.

Conclusion

FSD-based balanced SSFP is a promising NC-MRA approach to the diagnosis of peripheral arterial disease in various vascular regions. This method eliminates the intravenous injection of contrast medium and prevents adverse contrast reaction and complications while reducing the medical expense. Most importantly, the use of this approach in clinical practice will greatly lessen patient radiation exposure and kidney function. Preliminary patient studies have demonstrated very promising clinical value. However, this technique still awaits clinical validation with large-size patient populations.

Acknowledgements

The authors are grateful to the colleagues from Siemens Healthcare, especially Renate Jerecic, Sven Zuehlsdorff, and Gehard Laub.

References

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