Non-contrast-enhanced 4D intracranial MR angiography: Optimizations using a variable flip angle approach

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INTRODUCTION: Recently, a new technique was presented for non-contrast-enhanced (NCE) 4D intracranial MR angiography (MRA) [1,2]. It uses a FAIR-type spin-labeling approach [3] together with an ECG-triggered CINE-like b-SSFP acquisition of multiple 3D phases, to sample the inversion recovery (IR) signal curves after selective and non-selective inversion, respectively. By subtraction of the two data series, the stationary signal is suppressed, while the difference between the signals of inflowing non-inverted and inverted blood provides dynamic vascular information. During the inflow, both inverted and non-inverted blood evolves towards the steady state, so that the difference between both decreases over time and vessels filling late in the inflow period are captured with lower signal. Both signal evolutions are dependent on the applied flip angle (FA), but it may be not obvious which flip angle is the optimum. It is the aim of this abstract to discuss this aspect, and to demonstrate that the technique can be substantially optimized by using a variable FA (VFA) evolution (first reported for b-SSFP in [4]) throughout the acquisition of the IR curve. This approach will be shown to yield a longer persistence of the blood signal when compared to an optimized constant FA (CFA) approach.

METHODS: The magnetization behavior was simulated (Matlab, The MathWorks Inc., USA) on basis of the Bloch equations for experiments with different CFA as well as for different VFA evolutions. For T1 and T2 of blood, values of 1390msec and 163msec were used (as reported for 3T in [5]), and effects due to imperfect slice profiles or off-resonance effects were neglected. The RR interval was assumed to be 1sec, and the b-SSFP signal acquisition extended over 950ms. For both acquisitions, the signal evolution of arterial magnetization that enters the slab right after inversion was assessed, since it is expected to travel the longest distance during the acquisition. In the selective IR experiment, the inflowing magnetization was assumed to enter the slice at its equilibrium. In the case of non-selective inversion, arterial magnetization outside the imaging slab was simulated with a history of non-selective inversions from four cardiac cycles. The sequence was implemented with different FA evolutions on a clinical 3T system (MAGNETOM Trio a Tim System, Siemens Healthcare, Germany). In-vivo experiments were performed in five healthy volunteers after obtaining informed consent. For signal reception, the standard 12-channel Tim Head Matrix coil of the system was used. Imaging parameters included FOV=220mmx165mm, matrix=240x175, 64 slices, 0.9mm thickness, TE/TR=2.0/4.5ms, BW=496Hz/Pix, 14 lines per phases, GRAPPA=2. With this protocol, a slab of 57.6mm was captured with an isotropic spatial resolution of 0.9mm and a temporal resolution of 63ms without any interpolation. The number of frames was adapted individually to the cardiac cycle of the subject. The average scan time was 7:31min ± 29sec. In each subject, signal values were taken from equivalent pixels within each of the two volunteer datasets: 30 pixels were placed within vessels that filled with blood in the last third of the cardiac cycle, and 10 pixels in the parenchyma.

RESULTS: For the CFA variant of the sequence, an FA of approx. 25° showed to be close to the optimum in terms of preserving high vessel signal until the end of the cardiac cycle. Hence, the length of the RF pulses was adjusted so that the protocol would not exceed maximum SAR limits at this FA in all volunteers. The corresponding simulated signal time courses of inverted and non-inverted blood, as well as the phase-sensitive difference are plotted in Fig.1a. For higher FA, stronger signals are created directly after inversion and the magnetization proceeds towards a larger b-SSFP steady state signal, but this approach takes place with faster apparent time constants, so that the difference between inverted and non-inverted blood is lost more quickly (Fig.1b). This behavior is consistent with the literature [6-9]. For the VFA case, a simple parabolic FA evolution showed to be well-suited to conserve a considerable signal difference during the RR interval, while still providing sufficiently high signal directly after inversion. Here, the nth FA of a total number of N RF pulses is calculated as FA(n) = FA1 + (FA2-FA1) * (n/N)^2, with FA1 and FA2 being the first and the last FA, respectively. With an FA evolution from 12° to 45°, which is associated with the identical overall power deposition as the corresponding protocol with a CFA of 25°, the blood signal in the subtracted data at the end of the cardiac cycle is expected to be 1.5-2 times higher than that of a CFA scan with otherwise same parameters (Fig.1c). In the in-vivo experiments, marked improvements were observed, in particular in the depiction of vessels reached by inflowing blood approx. 600ms after labeling or later. An overview of the signal analysis is shown in Fig.2. The ratio between the signal of late-filling vessels and the brain parenchyma increased about factors between 1.44 and 1.87, from the CFA to the VFA sequence. The last ten frames of a representative MIP time series for CFA = 25° and VFA = 12-45° are shown in Fig.3, zoomed and panned into the right temporoparietal lobe to demonstrate the improved spin label persistence with VFA.

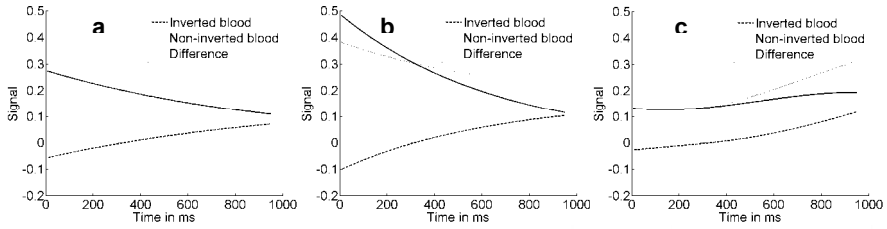

Fig.1: Simulated time signal courses for CFA = 25°(a), CFA = 45°(b), and VFA = 12°-45° (c).

Subject no.	1	2	3	4	5
CFA=25: S(Vessel)/S(Parench)	1.6±0.4	2.2±0.9	1.6±0.3	2.6±1.1	2.2±0.8
VFA=12-45: S(Vessel)/S(Parench)	2.6±0.7	3.2±1.2	3.0±0.8	4.3±1.8	3.5±1.5
Ratio CFA / VFA	1.59	1.44	1.87	1.63	1.63

Fig.2: Ratios between the signal of arteries filling late after spin labeling and that of background tissue, and the gain by using the VFA scheme instead of a CFA.

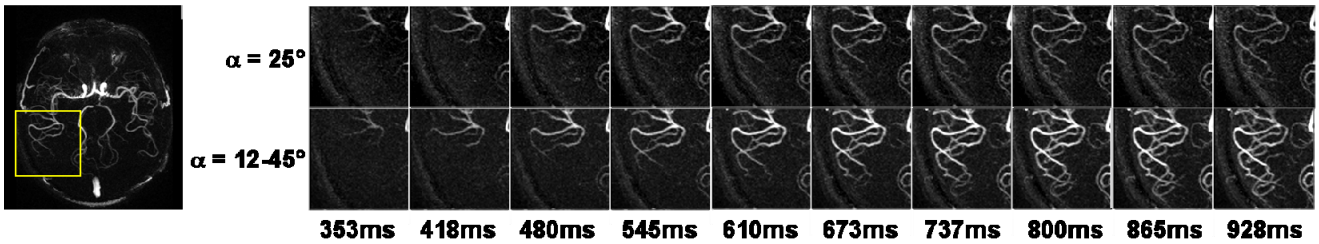

Fig.3.: Series of last ten MIPs for CFA = 25° (top) and VFA = 12°-45° (bottom). Note that distal vessels in late cardiac phases are better delineated using VFA as compared to those from CFA, indicating improved labeling persistence using VFA, in consistence with the simulation results.

DISCUSSION AND CONCLUSION: The VFL approach proved to be helpful for 4D non-CE MRA in that it prolongs the spin labeling period, and hence improves the visualization of late-filling vascular regions. It can be combined with any other means of achieving higher FA, such as using longer pulses or VERSE excitation. The concept represents a useful further degree of freedom for optimizations, in particular at higher field strengths. The evaluation in patients with vascular disease such as arteriovenous malformations is subject of further investigations.

REFERENCES: [1] Bi et al., 20th Ann Int Conf on MR Angiography, Graz, #2.2 (2008). [2] Bi et al., Proc Intl Soc Mag Reson Med 17, #3259 (2009). [3] Kim, Magn Reson Med 34: 293-301 (1995). [4] Hennig et al. Magn Reson Med 48: 801-809 (2002). [5] Dharmakumar et al. Magn Reson Med 53: 574–583 (2005). [6] Le Roux, J Magn Reson 163: 23-37 (2003). [7] Scheffler, Magn Reson Med 49: 781-783 (2003). [8] Ganter, Magn Reson Med 52: 368-375 (2004). [9] Schmitt et al., Magn Reson Med 55: 177-186 (2006).