Cardiovascular MRI at 3T & Beyond

Ultra-high field imaging techniques for MRA

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Highlights

- Performing magnetic resonance angiography (MRA) at higher fields has been demonstrated to improve the signal to noise and contrast to noise in both the brain and body applications.
- Direct implementation of standard clinical protocols and acquisitions methods at 7T are insufficient to obtain the best results as increased B0 and B1+ inhomogeneity, local SAR and limited peak power present roadblocks to their success.
- Through the availability of multi-element transmit arrays and with expanded flexibility made possible through multiple independent RF amplifiers, B1+ (or RF) shimming has been developed to address some of these challenges.
- The use of contrast agents have been demonstrated to improve MRA in the brain and body at 7T, however their use needs to be optimized taking into consideration the impact on both longitudinal and transverse relaxation properties of blood.

Target Audience: This contribution is focused on clinician and basic researchers interested in overcoming the challenges of performing MRA at increasing static magnetic fields (B0) in order to realize the potential benefits of increased SNR, contrast and resolution.

Objectives: The goal of this session to expose the audience to the complexities and advantages of translating MRA methods from high to ultrahigh field (7T), to understand the potential challenges and to present possible solutions in the context of existing work and future developments.

Purpose: The increased longitudinal relaxation times (T1), higher signal-to-noise ratio (SNR) and increased parallel imaging performance at ultrahigh fields promise to improve contrast-to-noise as well as spatial and/or temporal resolution. However, when translating existing MRA methods to systems with higher B0, a number of *roadblocks* arise. These include the increasingly non-uniform electromagnetic fields resulting in local RF heating concerns, tradeoffs between transmit B1 (B1+) efficiency and homogeneity as well as limitations in achievable peak B1+ and increasing B0 inhomogeneity. In addition, if exogenous contrast agents are desired, the greatly increasing r2* relaxivity with nearly constant r1 relaxivity can limit the typically desired enhancement expected through T1 shortening of standard paramagnetic contrast agents. Navigating this maze of roadblocks requires the continuous development of novel hardware, RF pulses, acquisition methods and/or injection strategies.

Methods / Results: While by no means exhaustive, the following section highlights developments needed to navigate around the multiple *roadblocks* to performing MRA studies in the brain and body at ultrahigh field as well as studies which investigate the advantages of 7T MRA compared to lower field strengths.

Dealing with complex transmit B1 (B1+) fields: Several different methods have been proposed and implemented to handle the complex and inhomogeneous transmit fields present at ultrahigh fields. In addition to the very important multi-channel transmit array coil and independent RF amplifier setups that drive them, there are the methods by which the RF amplitudes and phases are manipulated between the array channels to affect transmit homogeneity, efficiency and even local power deposition. One such method (TIAMO – time interleaved acquisition of modes) involves acquiring data with different transmit modes which effectively produce complimentary excitation profiles across the object (1). When combined the two acquisitions can produce images with uniform contrast despite the vastly inhomogeneous excitation profiles of each individual transmit mode. This strategy was successfully used in performing non-enhanced vascular imaging of the lower extremities at 7T (2).

Another method to handle the complex electromagnetic fields at 7T is B1+ shimming which was demonstrated to produce an efficient and homogeneous B1+ over a smaller localized region by performing targeted, subject-dependent optimization of the transmit phases (3). The transmit phases within the target region were modified so that they would, on average, constructively interfere thus increase transmit efficiency. Increased efficiency greatly reduces the power needed to generate a given B1+ and also reduces E-fields leading to lower local and global specific absorption rates (SAR) (4). The type of shimming used in these initial studies falls into a class we now refer to as "static B1+ shimming" as a single B1+ shim solution is used throughout the entire RF pulse sequence.

Dynamically Applied static B1+ Shimming: The original static B1+ shimming method described above was simple and both efficient and relatively homogenous for small regions of interest in the head (5,6) and body (3,7). Additional flexibility was made available for subject dependent, static B1+ shimming by the implementation of algorithms to optimize for B1+ homogeneity as well as efficiency or a balance between the two (8). Even with these advances however, in larger targets and/or for imaging methods that require RF pulses applied with varying coverage and spatial locations, this simple approach was inadequate. In such cases, it was realized that imaging sequences could benefit from unique B1+ shim solutions tailored for each RF pulse. A similar idea was demonstrated by Hetherington et al. in the head (9), where different B1+ shim solutions optimizing homogeneity were used for performing outer volume suppression and spectroscopic localization.

Time-of-flight (TOF) Imaging of Intracranial Vessels: Earlier on (i.e. 2006), time-of-flight angiography was used to image the intracranial arteries and demonstrated a contrast-to-noise advantage and improved visualization of distal vessels at 7T compared to 3T (10). These initial attempts at 7T provided some optimization of acquisition parameters to accommodate for the increased T1 of arterial blood. However, the methods employed were simply a direct extension of those provided for lower field strength clinical systems. To further improve CNR, it is common practice to perform magnetization transfer contrast (MTC) preparation at standard clinical field strengths. If applied in a standard way, every TR, the power deposition at 7T would be too high when using MTC resulting in local SAR levels which exceed guidelines defined by the IEC (4). Improved TOF results were obtained at 7T by employing MTC preparation but only during readout segments covering the center of k-space (11), a modification of common acquisition methods to accommodate the limitations at 7T. These studies were facilitated by using multi-channel transmit coils and RF hardware and employed a dynamically applied static B1+ shimming approach where different B1+ shimming solutions for each imaging slab were used.

Time-Resolved Angiography of Intracranial Arteries: Non-contrast enhanced time-resolved 4D MRA has been shown to be a valuable method for simultaneously assessing anatomic structure and dynamic filling of cerebral arteries (12,13). With these methods, vessel contrast is obtained by subtracting a labeled volume with a control similar to methods used for arterial spin label (ASL) perfusion imaging. Using blood as an endogenous tracer eliminates the need for exogenous contrast agents important for patients with contraindications. The longer T1s at higher field result in more persistent labeling allowing for improved visualization of distal vessels, especially in conditions of reduced flow. A strategy for performing time-resolved MRA in the human brain at 7T demonstrated persistent labeling and excellent visualization of distal arteries. Dynamic B1+ shimming used a more efficient solution for inferior spin labeling and homogeneous solution over the imaging volume for RF excitation (14).

Non-enhanced Coronary and Renal MRA: Similar to studies in the brain, improved signal to noise (SNR) and contrast to noise ratio (CNR) resulted when performing right coronary artery imaging at 7T compared to 3T (15). These initial studies demonstrated the potential of 7T for CMRA, however reaching the deeper left coronary artery was more challenging. The deeper left coronary artery (LCA) was later imaged by using a multi-channel transmit array and dynamic RF shimming (16). This strategy allowed the LCA to be imaged at 7T with similar contrast to that achieved in the RCA but with lower SNR due to the increased distance from the RF coil. Similar methods were used for imaging the renal arteries. More efficient B1+ shimming solutions were used for adiabatic inversion pulses, performing the job of background suppression, while more homogeneous B1+ shim solutions were used for the gradient echo excitation pulses for uniform excitation of the intravascular signals (8).

Contrast Enhanced Studies at UHF: Some studies have been performed in the brain and kidneys investigating the potential role of contrast agents in MRA at 7T (17,18). It is well accepted that reduced concentrations of the standard paramagnetic contrast agents are needed to produce a similar T1-weighted enhancement at higher field. This reduction is not as a result of improved relaxivity but more a function of the prolonged T1s in the body, therefore a similar relaxivity has a more pronounced effect on contrast. While this is true, the tremendous spin dephasing as a result of blood being a multi-compartment system is typically ignored. Contrast only has direct access to the plasma volume, not the water space in red blood cells which make up approximately 40% of the blood's volume. Susceptibility induced dephasing greatly increases the R2* (i.e. 1/T2*). For Gadolinium-DTPA, the R1 relaxivity (r1) was shown to be relatively constant from 3T to 7T while the R2* relaxivity (r2*) increased four-fold (19). Based on these results, sub-millisecond T_2^* relaxation times at 7T are possible with Gd-DTPA concentrations ([GaD]) of 5 mM in the blood. Such concentrations can easily be reached *in-vivo* when injection rates of 3 ml/s are used (20). These effects could negatively impact contrast enhanced studies when performed at 7T if not accounted for in the sequence optimization and/or injection strategies.

Discussion: Other RF and SAR management routines and hardware can be used to further expand MRA applications at UHF. For example, the optimization of B1+ can be performed while explicitly taking into account local SAR such as in the virtual observation point (VOP) technique (21). Subject dependent prediction of E-fields, SAR and temperature would further increase confidence in pushing the limits in terms of power deposition, currently an area of active investigation by many groups (22). Parallel transmit systems, which permit the generation of channel dependent RF waveforms, will provide even further flexibility in RF and SAR management.

Explicit SAR optimization, subject dependent SAR determination, and parallel transmit systems can be used to improve individual RF shim solutions which again can be used

dynamically within an MRI pulse sequence to provide ever increasing flexibility to manage, arguably, the biggest challenge facing imaging studies at ultrahigh magnetic fields.

Conclusion: Performing MRA at increasing static magnetic fields has been demonstrated to increase both SNR and CNR resulting in improved anatomic and hemodynamic evaluations of the brain and body vasculature. However, the number of roadblocks and increasing complexity of these studies cannot be ignored. As strategies to manage local power deposition and increased B0 and B1 inhomogeneity are continuously developed, ways to streamline the implementation of these solutions on the scanner are needed to make them viable for more general use. This is an active area of investigation at multiple centers.

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