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EDITORIAL

# Advances in cardiovascular MR imaging

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Despite advances in prevention and treatment, cardiovascular disease remains the number one cause of death worldwide [1]. Cardiovascular MR Imaging has become an indispensable tool in modern clinical practice for the diagnosis and clinical follow-up of a variety of conditions affecting the heart and vascular system. The ability of MR imaging to non-invasively probe anatomy, function and tissue structure not only enables physicians to take a "virtual biopsy", but it also enables quantitative evaluation of the cumulative effect of exposure to various risk factors. As such, cardiovascular MR imaging is a highly valuable diagnostic tool to derive a phenotypic signature of cardiovascular disease.

In this special issue of MAGMA, we present a state-of-the-art selection of original studies that present significant advancements in cardiovascular MR acquisition technology as well as a number of review papers on tissue characterization that highlight the high clinical impact as well as the pitfalls of this technique. The original contributions range from new hardware for cardiac imaging at 7T to methodology for faster and more comprehensive cardiac functional imaging, and tissue characterization. In addition, there are also various contributions focused on MR vessel wall imaging and a contribution on neurovascular imaging. Below, we highlight the novelty of the contributions to the special issue.

## Ultra-high field cardiac MR

Cardiovascular MRI can benefit from higher magnetic field strength (7T), provided hardware is available that permits RF transmission and reception with sufficient B1 homogeneity, while keeping tissue energy deposition within acceptable limits. Towards this goal, Steensma et al. [2] introduced a novel 7T RF cardiac coil with eight transmit channels and a 16-channel receive array and demonstrated its performance by cardiac cine MRI in healthy volunteers.

## Myocardial function

The current gold standard for assessing cardiac function requires a stack of 2-D CINE short-axis slices covering the ventricles. This requires multiple breath-holds, often leading to patient discomfort and sub-optimal imaging. Moreover, accurate planning of the short-axis slices requires time, as well as operator training and experience, although most vendors offer efficient automated planning tools these days. Nonetheless, there is a clear need for a 3-D cine technique capable of covering the whole heart volume in a single breath-hold. To that end, Wetzl et al. [3] introduce a 3-D CINE imaging technique capable of covering the left ventricle with nearly isotropic resolution in a single breath-hold of approximately 19 s. The sequence employs a Cartesian sampling strategy, which covers k-space very efficiently using a phyllotaxis trajectory and compressed sensing reconstruction. In the paper, the authors demonstrate in volunteers as well as patients that functional parameters derived using the new sequence did not differ significantly from the standard of reference acquisitions.

Tolouee et al. [4] address a key challenge of cardiac MRI, i.e., to reduce imaging acquisition time while maintaining image quality in terms of spatial and temporal resolution. Their approach involves a reconstruction of undersampled, accelerated data by a combination of compressed sensing and low-rank matrix completion. In the paper, a motion-estimation/motion-compensation (ME-MC) algorithm is introduced to the low-rank component to reconstruct cardiac CINE data with improved robustness to motion-related artifacts and minimal spatiotemporal blurring.

Patient discomfort and lack of compliance with multiple breath-holds, which are required in a standard cardiac MRI protocol, may give rise to significant respiratory motion

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artifacts in cine MRI. Piekarski and colleagues [5] have investigated whether a free-breathing protocol using a radial golden-angle k-space filling strategy and compressed sensing reconstruction can provide improved image quality in such cases. In an unselected patient population, they demonstrated improved image quality with the radial approach when breath-holds failed, although the radial acquisition was visually inferior to the standard CINE protocol when breath-holds were successful.

Detailed analysis of regional myocardial motion is of high potential value to better understand diseases affecting both the left and right ventricles, and to guide cardiac resynchronization therapy. Menza et al. [6] propose a number of modifications to cardiac tissue phase-mapping (TPM) which are essential for robust RV assessment: optimization of the black blood saturation pulse, navigator respiration control, and thorough post-processing and analysis of RV myocardial velocities. With their newly developed TPM protocol, measurements and subsequent quantitative biventricular analysis of velocities and timing were performed in a volunteer cohort.

In a further study focused on regional myocardial function, Lapinskas et al. [7] investigate the merits of a Dixon-type water/fat separation technique to better characterize patients with chronic myocardial infarction (MI). In their study, they demonstrate that this type of sequence ensures more detailed tissue characterization in patients with chronic MI without a relevant increase in imaging and post-processing time. They also demonstrate that fatty metaplasia may influence regional myocardial deformation, especially in myocardial segments adjacent to scar tissue.

One of the drawbacks of using phase-sensitive inversion recovery (PSIR) delayed enhancement imaging for detection of myocardial scars is the need to acquire a fully sampled reference scan. This effectively doubles the acquisition duration, limiting its use for whole heart delayed enhancement imaging in a single breath hold. In an attempt to address this issue, Liu et al. [8] developed a novel reconstruction method with independent phase estimation to directly reconstruct 3-D phase-sensitive images from complex IR T1-weighted images. They demonstrate that the novel reconstruction without using the reference acquisition provides similar image quality to PSIR reconstruction in half the acquisition duration.

## Myocardial tissue characterization

The longitudinal relaxation time T1 of the myocardium, with and without Gd contrast, is regarded as a useful imaging biomarker for cardiac pathology. Several MOLLI-based acquisition strategies are available for T1-mapping. In the paper by Vassiliou et al. [9] the authors investigated whether repeated averaging in basal and mid left ventricular myocardial levels improves precision and correlation with extracellular volume fraction (ECV) for a 11 heartbeat MOLLI T1-mapping sequence versus assessment at a single ventricular level. It was concluded that, particularly when small changes in native T1 or ECV are expected, repeated averaging improves precision and correlation with histology.

Zhang et al. [10] investigated the technical feasibility of a novel motion compensation method for myocardial T1- and extracellular volume fraction (ECV) mapping. A modified nonrigid, nonparametric image registration method was applied to generate motion-corrected modified look-locker image (MOLLI) series and subsequently to co-register native and post-contrast T1 maps. Although T1 and ECV values were not clinically significantly different before and after motion compensation, the investigators found improved intra- and inter-observer reproducibility after motion compensation, which will further support the introduction of mapping techniques in routine clinical practice.

The review by Piechnik et al. [11] addresses the potential utility of stress T1-mapping to unmask myocardial ischemia without the use of gadolinium contrast agents, which is a highly relevant topic in the era of heightened caution with regard to long-term side effects of gadolinium administration. The second review on parametric tissue mapping by Cameron et al. [12] provides a sorely needed comprehensive account of the technological and physiological pitfalls and possible solutions to guide the utility of T1-mapping in a clinical and research setting.

## Advances in vascular and vessel wall imaging

Transcatheter aortic valve replacement (TAVI) is a relatively new but widely used alternative to surgical aortic valve replacement. However, hemodynamic changes occurring after TAVI are known to play a crucial role for the outcome. To investigate this problem in more detail, Giese et al. [13] designed a pulsatile phantom to study velocities and turbulent kinetic energy values in five different TAVI implants. The presented setup enables comparison of different valve implants and could aid future novel valve designs.

In an effort to further understand the drivers of early atherosclerosis Eikendal et al. [14] evaluated associations of magnetic resonance imaging (MRI)-derived aortic wall area, wall thickness, and pulse wave velocity (PWV) with cardiovascular risk factors in asymptomatic, young adults and found that already in early adulthood, aortic wall geometry and stiffness vary by age, sex, body-mass index, and blood pressure.

Compressed sensing image reconstruction technology is revolutionizing cardiovascular MRI by making 3-D

imaging possible in clinically acceptable examination times. The study by Yuan et al. [15] is a good example of such developments. In their work, they employ a 3-D black-blood multi-contrast carotid artery imaging protocol moderately accelerated with compressed sensing (1.5 and 2×) and show that these measurements are robust by quantifying the inter/intra-observer reproducibility of lumen/wall area and carotid wall thickness measurements.

In the second contribution by Yuan et al. [16] the authors explore the relationship between carotid plaque surface morphology and ulceration and neovascularization using an innovative 4-D contrast-enhanced MRI technique that combines high temporal and spatial resolution in a single scan. Both ulceration and neovascularization are considered risk factors of plaque instability. The presented approach has several important advantages, including that only a single contrast injection is needed for the combined morphological and functional assessment of the plaques, and there is no need for registration of different scans. Application of the technique in 21 patients with significant carotid stenosis demonstrated a significant relationship between lumen morphology and neovascularization.

The final contribution on vessel wall imaging by Coolen et al. [17] gives a comprehensive account of the novel quantitative MRI methods for measuring vessel wall dimensions, plaque composition and permeability, endothelial shear stress and wall stiffness. Together, these methods show the versatility of non-invasive quantitative MRI for probing vascular disease at several stages.

Finally, the paper by Verbree and van Osch [18] addresses an important aspect of pseudocontinuous arterial spin labelling (pCASL) quantification, which has been lingering for many years, viz. how the cardiac cycle influences cerebral blood flow (CBF) quantification. Using simulations, the authors show that the pASL signal is only slightly variable with the time of triggering in the cardiac cycle. In vivo, this small variation did not lead to a detectable difference between triggered and non-triggered acquisitions, and; therefore, pCASL triggering can be considered not to have a practical implication.

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## Compliance with ethical standards

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