Non-contrast coronary magnetic resonance angiography: current frontiers and future horizons

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Abstract
Coronary magnetic resonance angiography (coronary MRA) is advantageous in its ability to assess coronary artery morphology and function without ionizing radiation or contrast media. However, technical limitations including reduced spatial resolution, long acquisition times, and low signal-to-noise ratios prevent it from clinical routine utilization. Nonetheless, each of these limitations can be specifically addressed by a combination of novel technologies including super-resolution imaging, compressed sensing, and deep-learning reconstruction. In this paper, we first review the current clinical use and motivations for non-contrast coronary MRA, discuss currently available coronary MRA techniques, and highlight current technical developments that hold unique potential to optimize coronary MRA image acquisition and post-processing. In the final section, we examine the various research-based coronary MRA methods and metrics that can be leveraged to assess coronary stenosis severity, physiological function, and atherosclerotic plaque characterization. We specifically discuss how such technologies may contribute to the clinical translation of coronary MRA into a robust modality for routine clinical use.

Keywords Magnetic resonance coronary angiography · Image acceleration technique · Image denoising · Review article

Abbreviations

| MRA | Magnetic resonance angiography |
| CAD | Coronary artery disease |
| CTA | Computed tomography angiography |
| CAG | Coronary angiography |
| LGE | Late gadolinium enhancement |
| ECG | Electrocardiography |
| SSFP | Steady-state free precession |
| RCA | Right coronary artery |
| SNR | Signal-to-noise ratio |
| CNR | Contrast-to-noise ratio |
| bSSFP | Balanced steady-state free precession imaging |
| FLASH | Fast low angle shots |
| MRI | Magnetic resonance imaging |
| SR | Super-resolution |
| BM3D | Block matching and 3-D filtering |
| TNRD | Trainable nonlinear reaction diffusion |
| DnCNNs | Denoising convolutional neural networks |
| PI | Parallel imaging |
| CS | Compressed sensing |
| SENSE | Sensitivity encoding |
| iGRASP | Iterative golden-angle radial sparse parallel MRI |
| SPIRiT | Self-consistent parallel imaging reconstruction |
| ESPIRiT | Eigenvector maps self-consistent parallel imaging reconstruction |
| tGA | Tiny golden radial |
| DLR | Deep learning reconstruction |
| XD-GRASP | Extra-dimensional GRASP |
| PC | Phase contrast |
| CBF | Coronary blood flow |
| LAD | Left anterior descending |
| LCX | Left circumflex |
| CFR | Coronary flow reserve |
Background

The diagnosis and management of coronary artery disease (CAD) and consequent myocardial ischemia are central to the prevention of future cardiac events. In this regard, the main advantage of non-contrast coronary magnetic resonance angiography (coronary MRA) is its ability to assess coronary artery morphology and function without ionizing radiation or contrast media. Despite the early recognition of such extraordinary potential [1], significant technical limitations including reduced spatial resolution, long acquisition time, and low signal-to-noise ratio impairing image quality have caused coronary MRA to be less preferred than competing non-invasive techniques such as coronary computed tomography angiography (CTA), and prevented it from routine clinical utilization [2, 3]. However, despite these technical limitations, coronary MRA has contributed significantly to our current understanding of CAD pathophysiology [4, 5] by providing insights into coronary artery distensibility in response to stress [6], plaque characteristics [7], and plaque inflammation [8]. Its usefulness as a non-invasive research method to assess CAD in different groups of patients has been demonstrated not only in single center clinical investigations [9, 10], but also in multi-center studies [11, 12]. Moreover, coronary MRA has proven to be important in the delineation of congenital coronary abnormalities, for which it is recommended as the clinical modality of choice, particularly when there is concern about the use of radiation and contrast [13, 14]. Recent developments in magnetic resonance imaging are poised to specifically impact coronary MRA in its ability to assess coronary anatomy and function in patients with chest pain or other clinical manifestations that suggest the presence of CAD [15–18]. More recently, the possibility of using deep learning techniques to enhance image quality in applications characterized by low signal-to-noise ratios has opened additional avenues of potential development in coronary MRA imaging [19, 20]. In this paper, we will first review the current clinical status of non-contrast coronary MRA, and then discuss current technical efforts to optimize coronary MRA image acquisition and post-processing. In the last section of this paper, we will discuss the various techniques of coronary anatomical and functional assessment on MRI that when combined together promise diagnostic and prognostic performance boost. Through these discussions, we hope to guide the readers to realize the promise of coronary MRA as a diagnostic tool for clinical use.

Current status of non-contrast coronary MRA

Motivations for the clinical use of non-contrast coronary MRA

CAD remains the leading cause of death in the world [21]. Catheter-based X-ray coronary angiography (CAG) is the current gold standard for the diagnosis of significant (> 50% diameter stenosis) CAD. However, around half of the patients referred for diagnostic CAG do not have significant stenosis [22–24], yet are exposed to ionizing radiation and contrast media as well as the potential risks associated with this invasive procedure [25]. The discomfort of patients during the invasive procedure is also not negligible. Non-contrast coronary MRA is an attractive option for anatomical coronary artery assessment in this regard, albeit relatively underdeveloped compared to coronary CTA. However, there are advantages non-contrast coronary MRA holds over CTA that may be leveraged as the technique matures including: (1) “one-stop-shop-test” by combining it with additional anatomical and functional MRI methods, (2) robustness to the calcium “blooming” that hampers CTA assessment, and (3) absence of ionizing radiation or contrast media exposure [9].

There are several well-defined patient populations that benefit from these advantages. Pediatric congenital heart disease patients frequently present for evaluation of coronary anatomy post-surgery or suspected coronary anomaly. These pediatric patients require multiple follow-up examinations and thus are good candidates for non-contrast coronary MRA [26]. Albrecht et al. have reported that in a pediatric population with suspected anomalous coronary arteries, coronary MRA provided comparable diagnostic accuracy with coronary CTA in the detection of findings that occurs in proximal to mid main coronary arteries like anomalies, high origin, and inter-arterial course of the coronary arteries, admitting superior visualization with CTA in distal coronary arteries [27]. Meanwhile, drawbacks for coronary MRA in pediatric patients include smaller coronary diameter, high resting heart rate, and difficulty of keeping the same position for a long time as compared to adults. Cardiac MRI with sedation or coronary CTA with its inherently higher spatial resolution may be considered appropriate in some cases [28, 29]. Evaluation of Kawasaki disease is another accepted indication for which coronary MRA is reported to be equivalent to CAG (Fig. 1) [30, 31]. Indeed, coronary MRA is recommended as the clinical modality of choice for these populations in which repeated radiation and contrast exposure are major concerns [13, 14]. The Japanese Circulation Society guidelines for Kawasaki disease in 2013 stipulate

| MPRAGE | Magnetization-prepared rapid acquisition with gradient echo |
| HIP    | High-intensity plaque                                      |
| UTE    | Ultrashort echo time                                       |
that coronary MRA is preferred over coronary CTA, as it allows repeated imaging while heart rate control is not required, which enables infants and young children to undergo the examination during sleep [32]. On the other hand, while the European Society of Cardiology guidelines for adult congenital disease published in 2010 recommend regular usage of cardiovascular magnetic resonance when considered superior to echocardiography, these guidelines do admit that CT is superior for non-invasive coronary angiography [33].

In chronic kidney disease (CKD) patients, contrast administration is a major concern due to the risk of post-contrast acute kidney injury after iodine-based contrast media injection [34, 35] or nephrogenic systemic fibrosis after gadolinium-based contrast media [36]. Moreover, these patients often require multiple follow-ups since they frequently present with severely calcified plaques in the coronary arteries. Not only does non-contrast MRCA take away the risk of further kidney injury by contrast injection, but it also allows for coronary lumen visualization without blooming artifacts from calcium as seen in coronary CTA. In MRI, calcifications present very low signal both on T1 and T2 images due to their low proton density. As a result, coronary calcifications do not obscure the coronary lumen in MRI. Indeed, coronary MRA has been shown to have a better performance in the detection of significant stenosis in patients with moderate to severe calcifications than CTA (Fig. 2) [37].

The principal idea for the treatment strategy of stable CAD is 1) invasive revascularization for the left main stenosis and 2) invasive revascularization when symptoms such as chest pain remain despite optimal medical therapy. Coronary MRA provides information on the distribution and severity of stenotic lesions, which is helpful to assess left main lesions, or when deciding the treatment strategy between percutaneous catheter intervention (PCI) and coronary artery bypass graft (CABG) surgery.

Another recent concern is the possibility of gadolinium depositions in the brain. This phenomenon has been correlated with the number of previous examinations involving gadolinium-based contrast administration [38] and has also been reported in subjects without severe renal dysfunction [39]. Although the long-term effects are not clear, the general consensus is that when possible, reduced exposure to gadolinium is preferable. Non-contrast coronary MRA is in line with this principle.

Meanwhile, coronary MRA has a few major limitations including (1) time-consuming image acquisition which takes around 10–20 min, (2) low spatial resolution (around 1-2 mm) compared to coronary CTA (around 0.5 mm) or CAG(< 0.3 mm), (3) poor visualization of coronary stents or calcified plaque due to the low proton density of these elements and limited visibility of the stent lumen due to radiofrequency (RF) shielding effects [40], susceptibility artifacts by diamagnetic (calcium) or ferromagnetic (stent) effect (though manageable with short echo time setting [41]), and (4) no consensus on coronary MRA post-processing and analysis methodology.

As these challenges are tackled and the technique matures, integrated protocols in which coronary MRA is added to other cardiac MRI examinations as a “one-stop-shop-test” are likely to improve the diagnostic and prognostic performance of the MRI examination. For example, the addition of free-breathing whole heart contrast-enhanced coronary MRA at 3 T to the combination of stress/rest myocardial perfusion imaging and late gadolinium enhancement (LGE) image significantly

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**Fig. 1** Coronary MRA (a) and CAG (b) image of a left anterior descending coronary artery aneurysm (LAD an) in a patient with Kawasaki disease. **MRA** magnetic resonance angiography, **CAG** coronary angiography, **LAD** left anterior descending, **LV** left ventricle, **R. Atrium** right atrium, **RCA** right coronary artery. (Reprinted with permission from Mavrogeni et al. [30], Copyright © 2004 by the American College of Cardiology Foundation)
improved the sensitivity and diagnostic accuracy of detection of ≥50% stenosis as diagnosed by CAG (per-patient bases, sensitivity 100% vs. 76.5%, \( p < 0.01 \), accuracy 89.1% vs. 73.9%, \( p < 0.01 \)) [42]. Although not specifically shown, a similar benefit of non-contrast coronary MRA is highly expected. Interestingly, the additive value of coronary MRA was not significant in another study that evaluated the integration of non-contrast coronary MRA with myocardial perfusion imaging (MPI) and LGE at 1.5 T for the detection of hemodynamically significant stenosis, defined as either a severe lesion of ≥90% luminal narrowing/occlusion or flow reserve ≤0.80 [43]. This result suggests that the diagnostic performance of MPI and LGE for the detection of physiological ischemia is already saturated and therefore there is less room for the contribution of the morphological assessment to significantly improve the diagnostic performance. The potential additive value of MRCA remains in excluding three-vessel disease in the differential diagnosis with microvascular disease, which was not assessed in this study.

Prognostication of cardiac events is a primary contribution of non-contrast coronary MRA by itself or in combination with other cardiac MRI phenotypes as a “one-stop-shop-test”. Yoon et al. have reported during a median follow-up of 25 months of 207 patients that the presence of significant stenosis detected on 1.5 T non-contrast coronary MRA was significantly associated with all cardiac events (hazard ratio = 20.78, \( p = 0.001 \)) [44].

**Preparation for the clinical coronary MRA acquisition**

The current acquisition standard for coronary MRA—three-dimensional (3D) free-breathing whole-heart coverage coronary MRA, requires several preparatory techniques such as electrocardiography (ECG) and respiratory gating [45]. A patient-specific acquisition window is set based on ECG gating during either the diastolic or systolic phase, corresponding to the phase with the least coronary artery motion. For the static phase selection, transaxial cine MR images with a steady-state free precession (SSFP) sequence are acquired prior to the coronary MRA acquisition to evaluate the motion pattern of the right coronary artery (RCA). The dome of the right hemidiaphragm is the preferred location of the respiratory navigator, while the details of navigator implementation tend to be vendor specific [45]. Although the image gets sharper when the ECG and respiratory gating width are narrowed, the inherent disadvantages of narrow windows are a reduction in the data acquisition success rate and a corresponding increase in the image acquisition time, potentially leading to more disturbance from patient motion. In the respiratory navigator, the current general setting of a small gating window of 5–6 mm leads to a low imaging efficiency (30–50%) [46]. In the absence of overt contraindications, the administration of sublingual nitroglycerin (NTG) is recommended to improve luminal visualization in terms of signal-to-noise ratio (SNR), vessel diameter, and vessel sharpness of the coronary MRA [47]. Heer et al. have reported that the significant increase in coronary diameter and visible vessel length observed with sublingual NTG administration result in improved sensitivity, specificity, and diagnostic accuracy for the detection of >50% coronary stenosis on 1.5 T non-contrast coronary MRA [48].
1.5 T vs. 3 T coronary MRA

Coronary MRA at higher magnetic field strengths has been an area of active research given the potential benefits in SNR and contrast-to-noise ratio (CNR) as well as higher spatial and temporal resolutions. The optimal non-contrast coronary MRA imaging technique differs between 1.5 T MRI and 3 T MRI. In 1.5 T-MRI, balanced steady-state free precession imaging (bSSFP) is the most commonly used sequence [12, 45, 49]. However, the applicability of bSSFP to 3 T MRI is limited for a variety of reasons including (1) more pronounced B0 and B1 field inhomogeneities than 1.5 T, (2) degraded image quality and increased magnetic field heterogeneity from RF pulse-induced dielectric effects, and (3) increased power deposition in the human body at 3 T limits the use of large flip angles for SSFP imaging [50]. To address the above-mentioned challenges, spoiled gradient echo sequences are used [51, 52]. Despite somewhat limited by lower SNR and CNR than SSFP, spoiled gradient echo sequencing, ECG- and diaphragm navigator gating, and fat suppression have become the standard acquisition protocol for non-contrast coronary MRA at 3 T [15]. In a study that investigated the image quality between SSFP and gradient echo sequence for coronary MRA at 3 T, the image quality was higher and the measured vessel length was longer in gradient echo sequence [53]. When performed with the same sequence, 3 T coronary MRA is not inferior to 1.5 T coronary MRA both in image quality and diagnostic accuracy for the detection of coronary stenosis [54].

Figure 3 shows a representative non-contrast coronary MRA case acquired in 3 T MRI with the conventional image acquisition acceleration method of parallel imaging (PI).

Non-contrast vs. contrast-enhanced coronary MRA

Non-contrast coronary MRA leverages the natural T2 differences between the blood and the surrounding architectures. Techniques such as fat saturation pre-pulses, magnetization pre-pulses, and T2 preparatory pulses augment the relative signal of the coronary arteries. These pre-pulses differentiate oxygenated blood in coronary arteries from the surrounding short T2 relaxation tissues such as cardiac muscle.

Fig. 3 A representative case of a non-contrast coronary MRA with a conventional technique. A non-contrast coronary MRA acquired in 3 T scanner with the conventional image acquisition acceleration method of parallel imaging (PI) is presented. A spoiled gradient echo sequence with ECG gating, diaphragm navigator gating, and fat suppression with spectral attenuated inversion recovery was used for the image acquisition. The MRI acquisition parameters were FOV = 350 × 350 mm, matrix = 224 × 232, slice thickness = 1.5 mm, slice number = 80, acceleration factor = 2.0 × 2.0, TR = 4.9 ms, TE = 1.9 ms, flip angle = 12°, bandwidth = 326 Hz/pix, acquisition voxel size = 1.6 × 1.5 × 1.5 mm, reconstructed voxel size = 0.80 × 0.80 × 0.75, navigator gating window = 5 mm. a, b Volume rendering images. Arrowheads: LAD, dashed arrows: LCX, and solid line arrows: RCA. c–e Curved MPR images of c LAD, d LCX, and e RCA. MRA magnetic resonance angiography, LAD left anterior descending, LCX left circumflex, RCA right coronary artery.
deoxygenated blood in cardiac veins, and epicardial fat [55, 56]. Dixon water–fat separation [57] and lipid insensitive binomial off-resonant excitation (LIBRE) [58, 59] (Fig. 4) are also available options for fat suppression on coronary MRA. Another approach to fat suppression, the fast interrupted steady-state (FISS) sequence, uses an RF excitation pulse to natively suppress the fat signal without the need for periodical application of fat suppression and ramp-up pulses, and is reported to present a strong suppression of pericardial fat signal [60, 61]. The fat suppression technique is more challenging in radial imaging with higher magnetic field strengths, since the field inhomogeneities are typically accentuated. At the current stage, there is no conclusion on which fat suppression technique is the best for the current coronary MRA imaging technique. In comparison to the SSFP sequence acquisition in 1.5 T MRI, the T1 differences between blood and myocardium are smaller in 3 T MRI with gradient echo sequence acquisition. Therefore, contrast-enhanced coronary MRA was preferred during the period that 3 T coronary MRA acquisition was under development. With the maturation of the technique, the non-contrast coronary MRA image is more feasible and preferred in 3 T MRI.

The diagnostic performance of coronary MRA varies between studies, likely a result of the presence or absence of contrast administration, heterogeneity of the acquisition sequences, and the analytic methods used. A meta-analysis of 1638 patients in 24 studies including 1.5 T and 3 T coronary MRA studies reported the estimated sensitivity and specificity for detecting > 50% stenosis is 95% and 77% for contrast coronary MRA, while those values were 87% and 69%, respectively, for non-contrast coronary MRA [3]. The diagnostic performance of 1.5 T non-contrast coronary MRA to detect > 50% stenosis, with CAG serving as the reference standard, was reported by Kato et al. in a multicenter trial of 137 patients across seven hospitals in Japan. On a per-patient level, the observed sensitivity and specificity were 88% and 72%, respectively [12]. Hamdan et al. compared the performance of 3 T non-contrast coronary MRA against 64-slice coronary CTA to detect significant CAD, using quantitative coronary angiography as the gold standard. On a per-patient basis, the observed sensitivities and specificities were 87% and 77% for non-contrast coronary MRA versus 90% and 83% for CTA, respectively [10]. Despite the trend toward higher diagnostic accuracy values for CTA, both techniques

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**Fig. 4** Comparison of the different fat saturation methods on radial trajectories coronary MRA at 3 T in healthy subjects. Coronary MRA images show the left and right coronary artery system depicting the RCA and the LAD in several subjects. Using the LIBRE pulse the visualization of the RCA and LAD was improved (yellow arrow), as well as fat suppression (orange arrows) compared with FS and WE. Vessel sharpness as well as imaged vessel length was significantly increased using LIBRE. Window and level are identical in images acquired in each volunteer. MRA magnetic resonance artery, RCA right coronary artery, LAD left anterior descending artery, LIBRE lipid insensitive binomial off-resonant excitation, FS fat saturation, WE water excitation. (Reprinted with permission from Batiaansen et al. [59] Copyright © 2019 by the Authors)
were equal in their ability to identify patients who subsequently underwent revascularization. Current diagnostic performance of non-contrast coronary MRA is encouraging, but not as high as contrast coronary MRA and coronary CTA. However, as discussed earlier, the various advantages of non-contrast coronary MRA make it exceedingly attractive in many clinical situations. Technical developments provide further promise to improve the diagnostic performance of non-contrast coronary MRA.

Current in-progress topics in coronary MRA

The major challenges of current coronary MRA sequences remain in: (1) unpredictable and long scan times mainly due to low gating efficiency which need image acquisition acceleration techniques including trajectory design, sparse sampling, and reconstruction; (2) residual respiratory motion artifacts due to simplified motion models and translational motion correction only. Advanced non-rigid motion correction techniques can address not only the motion artifacts but the low gating efficiency problem by allowing for 100% scan efficiency; and (3) overall image quality problems including those that may be solved by resolution improvement and denoising. Table 1 is a summary of the current technical challenges facing wider adoption of coronary MRA and corresponding solutions offered by current techniques and promising techniques under development which are discussed in the following paragraphs.

Image acquisition acceleration technique (1): trajectory design and sparse sampling

Trajectory design of k-space sampling method is the first step of the image acquisition acceleration strategy and it is closely related with the subsequent reconstruction strategy. Cartesian k-space sampling is the most widely used trajectory design in current MRI image and in coronary MRA.

| Problems                                    | Current techniques                      | Promising techniques                  |
|---------------------------------------------|-----------------------------------------|----------------------------------------|
| 1. Time-consuming image acquisition         | Parallel imaging (PI) [80–84]           | Compressed Sensing (CS) [15, 16, 85, 86]|
|                                             | Well-established method Limitation of the acceleration factor Characteristic artifacts | Potentially more effective in higher-dimensional image (3D > 2D) which is ideal for 3D coronary MRA acquisition Further techniques that combine PI and CS [65, 78, 88–91] or sparse k-space acquisition and DL [92, 93] are potentially available |
| 2. Low scan efficiency from respiratory and ECG gating | Respiratory and ECG gating are the current standard technique | Self-gating with motion correction [17, 46, 75, 94–98] Golden-angle image acquisition and reconstruction [18, 71, 72, 91] |
|                                             | Strict gating gives better image quality but trade-off with long acquisition time | No need for respiratory gating or ECG gating Simultaneously acquired CINE images Time consuming for the reconstruction |
| 3. Low resolution                            | Sub-millimeter spatial resolution acquisition [84] | Super-resolution with inter-slice reconstruction [99] Super-resolution based on overcomplete dictionaries [100, 104] Super-resolution based on deep learning [101, 102] |
|                                             | Trade-off with SNR                       | Inter-slice reconstruction method works well with 2D images |
| 4. Noise                                     | Mathematical denoising [108, 109]       | DL denoising [19, 20, 113–116, 140]    |
|                                             | No generally accepted standard for clinical use for any commercial filter | Better preservation of the edge Potentially works well with specific situation such as coronary MRA-dedicated denoising |

MRA magnetic resonance angiography, SNR signal-to-noise ratio, DL deep learning, PI parallel imaging, CS compressed sensing, ECG electrocardiography
as well. The conversion from k-space domain to the image domain is simple with the inverse fast Fourier transform (FFT). Meanwhile, other types of non-Cartesian trajectory designs like radial and spiral trajectories have several advantages in the aspect of accelerated image acquisition and are of great interest. Reconstruction from non-Cartesian trajectories generally use filtered back-projection or interpolation to the Cartesian grid k-space so that the conversion to the image domain is more complicated.

Radial and spiral-like Cartesian trajectories have undersampling properties to create incoherent noise-like artifacts, which are a requirement for compressed sensing (CS) or low-rank reconstructions while still allowing for much shorter reconstruction times compared to non-Cartesian trajectories. These techniques have been extensively used in recent coronary MRA studies.

Non-Cartesian trajectories can sample denser in the center of the k-space referring their design. This is preferable to image coronary MRA (1) to achieve faster acquisition with sparse k-space sampling and (2) to address motion artifact by average effect or (3) to extract motion with sparse k-space sampling and (2) to address motion.

The key components of CS are: (1) image sparsity or transform sparsity, (2) pseudo-random undersampling, and (3) iterative nonlinear reconstruction. CS reconstructions require prior optimization of a regularization parameter, or data consistency tuning constant, to find the best trade-off between the data consistency and sparsity terms. Sparse and random sampling in multi-dimensional data sets result in ‘noise-like’ incoherence artifacts unlike coherence artifacts seen in PI without random sampling. These incoherence artifacts can be reduced within the CS reconstruction, providing an ideal condition for 3D coronary MRA image acquisition. Coronary MRA acquired with CS has shown comparable image quality with PI-corporary MRA, yet with shortened image acquisition time. Akçakaya et al. have compared conventional PI and CS combined with LOST de-aliasing strategy for sub-millimeter whole-heart coronary MRA. Overall image quality and perceived (semi-quantitative) SNR of the CS images were significantly higher than those of conventional PI.

Further image acceleration methods which combine CS with PI such as the k-t sparse technique with sensitivity encoding (SENSE) reconstruction, iterative Golden-angle RAdial Sparse Parallel MRI (iGRASP), self-consistent parallel imaging reconstruction (SPIRiT), and parallel imaging using eigenvector maps (ESPIRiT) are areas of active research. SPIRiT and ESPIRiT are able to incorporate an L1-norm minimization term to additionally enforce sparsity in a transform domain, which has the same underlying theory as CS. Haris et al. have reported high quality of images with iGRASP in comparison to the PI-based real-time imaging in the cardiac and extra-cardiac structure visibility in fetal cardiac examinations.

**Image acquisition acceleration technique (2): reconstruction (parallel imaging and compressed sensing)**

Sparse k-space sampling which violates the Nyquist sampling theorem is central to accelerated image acquisition. Two major reconstruction methods are parallel imaging (PI) and CS, which are in practice combined to achieve highly accelerated acquisition.

Parallel imaging (PI) is currently the most widely used method for image acquisition acceleration. PI approaches share the following characteristics: (1) undersampled k-space data in the phase-encoding direction (and partition-encoding direction in 3D imaging), (2) data acquisition with an array of independent receiver channels instead of using a large homogeneous volume receive coil, and (3) usage of a dedicated algorithm, which requires some knowledge of the individual coil sensitivities, to combine the undersampled data.

CS is a promising image acquisition acceleration method that works more efficiently in higher dimensional images such as 3D images or images with a temporal dimension. The key components of CS are: (1) image sparsity or transform sparsity, (2) pseudo-random undersampling, and (3) iterative nonlinear reconstruction. CS reconstructions require prior optimization of a regularization parameter, or data consistency tuning constant, to find the best trade-off between the data consistency and sparsity terms. Sparse and random sampling in multi-dimensional data sets result in ‘noise-like’ incoherence artifacts unlike coherence artifacts seen in PI without random sampling. These incoherence artifacts can be reduced within the CS reconstruction, providing an ideal condition for 3D coronary MRA image acquisition. Coronary MRA acquired with CS has shown comparable image quality with PI-corporary MRA, yet with shortened image acquisition time. Akçakaya et al. have compared conventional PI and CS combined with LOST de-aliasing strategy for sub-millimeter whole-heart coronary MRA. Overall image quality and perceived (semi-quantitative) SNR of the CS images were significantly higher than those of conventional PI.

Another approach is deep learning reconstruction from the subsampled k-space data. In a recent CS combined with DL.
approach, successful reconstruction was achieved from 29% of the k-space data with comparable image quality to fully sampled MRI reconstructions [92]. Combining tiny golden-angle radial sampling (tGA) with DL resulted in more than five times faster overall reconstruction time, superior image quality, and better accuracy of biventricular volumes than iGRASP when compared in short axis cine image. The total reconstruction time for all the short axis cine slices was 22.0 s with this method, which allowed for the real-time image reconstruction [93]. These advanced techniques all hold great potential for use in coronary MRA image acquisition acceleration and reconstruction, although there is no current consensus on which technique is most favorable. The central thesis is that the combination of PI and CS is expected to afford high spatial resolution while reducing the total time of acquisition. Additionally, deep learning reconstruction (DLR) promises effective denoising to improve SNR and CNR. Figure 5 shows a comparison between PI, CS, and CS processed with DLR.

Motion correction

ECG gating and respiratory gating is the most widely used motion correction method. Its drawbacks are the low efficiency of data acquisition resulting in unpredictable and long scan times despite the need for expert planning. This respiratory gating method prospectively corrects for translational motion of the heart in the superior–inferior direction, while it does not account for remaining directions, or rotations or nonrigid deformations.

Several promising techniques are being investigated that aim to improve the motion artifact as well as the scan efficiency. One promising approach is a self-navigator derived from the imaging data itself [73]. Such self-gating methods including 2D and 3D image navigators have been first introduced for 3D single heart phase coronary MRA [94, 95].

When combined with 3D affine or 3D non-rigid reconstruction, this approach can achieve 100% scan efficiency [17, 46, 96–98] (Fig. 6). Bhat et al. have investigated a whole-heart coronary MRA acquisition method with 100% scan efficiency reconstructed with respiratory motion correction. They used the navigator signal as a reference respiratory signal to segment the data into six respiratory bins. The reconstruction of low-resolution undersampled images for each respiratory bin was enabled from the 3D projection reconstruction k-space acquisition, which samples data on a spiral path running on the surface of a sphere. The data from different respiratory bins were retrospectively combined after motion correction based on the affine transform. When compared with a traditional navigator gating approach, their method reduced scan time by a factor of 2.5 while image quality was preserved [46]. Piccini et al. have reported that respiratory self-navigation with 100% acceptance rate significantly reduced the acquisition time from $16.23 \pm 6.28$ to $6.07 \pm 0.57$ min ($p < 0.01$) when compared with the navigator-gated coronary MRA acquisition [96]. In addition, the authors reported that the end-expiratory reference position significantly improved the image quality as compared to using end inspiration as a reference [97].

Another promising approach toward motion correction is the continuous 3D golden-angle radial sampling and reconstruction of separated cardiac and respiratory dimensions [18, 71, 72]. These methods have the advantage

![Fig. 5](image-url) 

**Fig. 5** Coronary MRA images of PI, CS, and CS with deep learning reconstruction. Three MPR images with identical resolution yet different image acceleration methods and post-processing are shown. a PI, b CS, c CS with deep learning reconstruction post-processing. c The best image quality among the three images. The PI and CS images were acquired with a spoiled gradient echo sequence with ECG-gating, diaphragm navigator gating, and fat suppression with spectral attenuated inversion recovery. The MRI acquisition parameters were FOV = 380 × 380 mm, Matrix = 392 × 384, slice thickness = 1.0 mm, slice number = 152, acceleration factor = 2.0 × 2.1, TR = 5.3 ms, TE = 2.0 ms, flip angle = 12 degree, bandwidth = 279 Hz/pix, acquisition voxel size = 1.0 × 1.0 × 1.0 mm, reconstructed voxel size = 0.5 × 0.5 × 0.5 mm, navigator gating window = 4 mm. For the DLR technique, see Refs. [116, 140]. MRA magnetic resonance angiography, PI parallel imaging, CS compressed sensing, MPR multiplanar reconstruction.
that coronary MRA images can be reconstructed with different temporal resolutions, or, since the images are acquired over the entire cardiac cycle, cine images of other structures can be derived from the same image data [17]. Another advantage is time reduction through elimination of the respiratory gating preparation. Feng et al. used a framework called eXtra-Dimensional GRASP (XD-GRASP) [71] which combines a continuous 3D golden-angle radial sampling scheme with a multidimensional compressed sensing technique to reconstruct separated cardiac and respiratory dimensions. The proposed method resulted in higher image quality in the myocardium and coronary arteries, better coronary sharpness, and longer coronary length visualized than respiratory motion-corrected 3D and 4D whole-heart imaging [18]. Haji-Valizadeh et al. have scanned the aorta with an accelerated coronary MRA sequence with stack-of-stars k-space sampling and GRASP reconstruction, achieving comparable image quality as contrast-enhanced conventional imaging with significant scan time reduction (5.55 ± 0.48 min vs. 6.56 ± 2.10 min). The mean off-line image reconstruction time was 4 h 41 min and 13 s [72].

While these methods look promising, their robustness in daily practice with respect to reconstruction with clinically acceptable reconstruction time and motion correction is an ongoing area of research [17].
Image quality improvement (1): high-resolution coronary MRA acquisition/super-resolution coronary MRA post-processing

Coronary MRA image acquisition under free breathing offers the opportunity for improved spatial resolution including sub-millimeter coronary MRA, while there are drawbacks such as increased acquisition times and lower SNR. Gharib et al. acquired high-resolution coronary MRA using 3 T magnetic resonance imaging (MRI) with a voxel size as small as 0.35×0.35×1.5 mm³ and compared the images with coronary MRA images having 0.7×1×3 mm³ voxel size. The higher resolution images showed a 47% improvement in vessel sharpness, although image acquisition times were longer and SNR and CNR reduced as compared to the lower-resolution coronary MRA [84]. Super-resolution (SR) is a different approach than voxel size adjustment and has been already utilized in brain imaging. There are several methods reported such as inter-slice reconstruction applied to 2D multislice MRI [99], image domain SR via patch-based sparse representation using overcomplete dictionaries [100], and deep learning-based SR [101–103]. In coronary MRA images, dictionary-based super-resolution applied to 1.5 T non-contrast coronary MRA was reported by Ishida et al. [104]. Their SR technique showed significant improvement in the detection of coronary artery stenosis as compared to conventional resolution coronary MRA. Further improvements in acquisition and reconstruction methods are likely to lead to routine high-resolution coronary MRA images.

Image quality improvement (2): denoising/smoothing

Coronary MRA image quality is not merely assessed using SNR or image resolution measures. Other metrics are also considered, such as overall visual image quality allowing meaningful clinical diagnosis, the visually recognizable coronary length, and the crispness/sharpness (conspicuity) of the coronary wall edges [15]. Such a comprehensive image quality assessment has traditionally relied on experienced observers, but initial results from deep learning architecture for automated image quality assessment are promising. Efforts are already ongoing in other domains such as liver MRI [105] and in other modalities such as coronary CTA [106], and these developments may be applicable to coronary MRA as well.

Image denoising is an indispensable first step in many practical applications including coronary MRA. It aims to preserve edges while smoothing out the noise. Oversmoothing renders the image blurry, which is problematic in coronary MRA for the interpretation of clinically meaningful findings such as intensity change in the coronary lumen or fine anatomies like distal coronary arteries or branches. Noise may be roughly categorized into additive white Gaussian noise, multiplicable noise (speckle noise), impulse noise (salt and pepper noise), and shot noise (Poisson noise). In MR images, the predominant noise is actually non-Gaussian such as a Rician distribution [107], yet it is a common practice to assume noise as Gaussian since Rician noise asymptotically becomes Gaussian for high SNR [107]. Some denoising techniques aim to cover a wide range of noise models such as Gaussian and non-Gaussian noise [108, 109]. In the paragraphs below we discuss two denoising approaches, namely (1) conventional methods and (2) deep learning approaches applicable for coronary MRA imaging.

Conventional methods

There is no generally accepted standard for clinical/commercial application of any denoising filter. Denoising filters applied to coronary MRA images need to be carefully considered, with regard to the balance between preserving the detailed coronary information and strength of denoising. Most traditional spatial filtering techniques directly operate on pixels in the image (or spatial) domain and have a tendency to blur the edges, which is not preferred in coronary imaging. In contrast, transform domain filtering operates on the wavelet transformed data and then transforms it back to the spatial domain, leading to faster computation and preserved edge-detail fidelity based on at least one prior report [110]. Most filtering techniques assume an equal noise distribution across the image, although spatially varying noise levels occur such as those obtained by parallel imaging. In such cases, spatially adaptive non-local denoising may provide better results [108]. One example of such denoising methods and the current state of the-art is block matching and 3-D filtering (BM3D) [109]. That method groups similar patches into blocks, transforms them to wavelet coefficients, then thresholds to obtain an optimal representation, and transforms back. BM3D can be adapted to various noise models such as additive noise and non-Gaussian noise.

Deep learning approaches

Deep learning reconstruction does not require modeling of noise. It has the ability to perform improved denoising through efficient optimization of the denoising level and good edge preservation based on the characteristics of “learning noise” strategy, which works well on coronary MRA images (Fig. 7). Consequently, denoising with deep learning may achieve higher SNR values than conventional filters (Fig. 7). Another characteristic is its flexibility with various frameworks, including application to the image domain as well as the k-space domain to create either denoised spatial images or denoised k-space data [111, 112].
Learning a specific type of noise in advance such as in a trainable nonlinear reaction diffusion (TNRD) model [113] would restrict its performance to the specified forms of prior learning and accordingly be limited in blind image denoising. To overcome this problem, feedforward denoising convolutional neural networks (DnCNNs) were proposed by Zhang et al., which are capable of handling Gaussian denoising with unknown noise levels [114]. Isogawa et al. proposed an adaptive approach by using soft shrinkage for the activation function of deep CNN resulting in a noise adaptive algorithm [115]. Furthermore, in one implementation [116], the application of 7 × 7 discrete cosine transform (DCT) convolution to extract higher frequency components followed by deep learning-based CNN using soft shrinkage for adaptive denoising successfully removed noise regardless of SNR parameters such as contrast settings, matrix size, 2D and 3D, among other variables.

While still in its infancy, the use of deep learning strategies shows promise in denoising coronary MRA images, where fine anatomical images require good edge preservation and high SNR [19, 20]. Its flexibility with various noise levels and noise types is a great advantage when scanning patients with different body sizes. Its potential application to different frameworks may be valuable when combined with image acquisition acceleration techniques. However, care must be taken with regard to the application of deep learning reconstruction methods, since inappropriate denoising may cause artificial image manipulation leading to a loss of accuracy in image interpretation and reported clinical findings. Further validation is therefore necessary before adoption.
Opportunities for utilization from research-based modality to clinically utilized modality

At present, there is no standardization of coronary MRA assessment methods. Currently available research-based methods are summarized in Table 2, and will be discussed in the following.

Software development for the assessment of coronary MRA images

While there are many multipurpose cardiovascular analysis packages, there are few dedicated non-contrast coronary MRA assessment tools commercially available or widely used. Coronary tree tracking and stenosis assessment remain a labor-intensive and time-consuming process. There are several specific reasons for this: (1) low SNR of the coronary lumen, (2) vulnerability of the coronary MRA images to artifacts that hamper autotracking of the vessels, and (3) rather low resolution of the image that prevents tracking of the smaller side branches. Attempts such as the “soap-bubble method” which assumed the coronary tree distribution on a relatively smooth 3D surface of a soap bubble to derive the final 2D maximum intensity projection image [117] or coronary MRA vessel centerline tracking and boundary segmentation based on geometric deformable models and optimized energy forces [118] have been previously reported. However, the application of these techniques in different clinical settings as well as their robustness remains untested.

Coronary MRA stenosis assessment by signal intensity (SI) drop quantification

Coronary MRA interpretation is usually performed visually, but its quantification is important for the generalization of the method. A previous study investigated the signal intensity (SI) profile across the coronary artery and reported an SI drop of 35% corresponding to significant stenosis by CAG (Fig. 8) [119]. Notably, this SI drop was not observed in chronic total obstruction cases [120]. One possible explanation is that the SI is affected not only by the stenosis severity, but also by the plaque characteristics.

Plaque assessment

Various sequences have been investigated for plaque assessment, though none of these techniques are currently viable clinically. T1-weighted magnetization-prepared rapid acquisition with gradient echo (MPRAGE) (Fig. 9) [121–123] and T2* [124, 125] images describe iron accumulation in the vulnerable plaque. Noguchi et al. have reported that the presence of high-intensity plaque (HIP) on MPRAGE image was significantly associated with coronary events (p < 0.0001, HR = 3.15) [122]. HIP detection prior to PCI was reported to be clinically relevant to avoid no-reflow phenomenon [123]. Ultrashort echo time (UTE) [126, 127] and susceptibility weighted imaging [128] are used to improve the visualization of calcified plaque. The distribution of iron and calcium is under research interest, since iron is suspected to accelerate the progression of atherosclerotic lesions while suppressing its calcification, and alternatively calcification could defend against atherosclerotic progression by excluding iron [129].

Physiological assessment of the coronary arteries

Physiological coronary function assessment by MRI uses phase-contrast (PC) imaging to quantify the blood flow through the coronary arteries. Sakuma et al. have reported in their canine study that the coronary blood flow (CBF) measured with the PC technique correlated well with flowmeter measurements [130]. Flow in the coronary sinus, which represents 96% of the total myocardial blood flow [131], has also been assessed [132, 133]. Lund et al. have reported

| Table 2  | Summary of research-based coronary MRA assessment methods |
|-----------------|----------------------------------------------------------|
| Target of the assessment | Methods |
| 1. Stenosis severity | Signal intensity drop quantification [119, 120] |
| 2. Plaque characteristics | MPRAGE [122, 123, 141] and T2* [124, 125] images for the iron accumulation detection in vulnerable plaques, Ultrashort TE (UTE) for fibrosis and calcification detection [126, 127], Susceptibility weighted imaging for calcification detection [128] |
| 3. Physiological function | Phase contrast-based coronary blood flow, coronary sinus flow, and coronary flow reserve measurement [130, 132–137], Pressure gradient along the stenotic lesion [138], 4D flow [139] |

*MRA* magnetic resonance angiography, *MPRAGE* magnetization-prepared rapid acquisition with gradient echo, *UTE* ultrashort echo time
in a canine model that CBF measured in the left anterior descending (LAD) and left circumflex (LCX) showed excellent correlation with the flow of coronary sinus ($r = 0.98$, $p < 0.001$) [132]. Coronary flow reserve (CFR) which is the fractional CBF increase induced by stress agent is another target. Sakuma et al. have reported that the CFR measured in LAD in healthy subjects was significantly higher than that in patients with significant LAD stenosis [134]. Kato et al. have reported that in patients with suspected coronary artery disease, CFR assessed on the coronary sinus flow showed higher hazard ratio (HR) for the prediction of major adverse cardiac events than the presence of > 10% ischemia on stress perfusion cardiac magnetic resonance (HR: 14.16 vs 6.50, respectively) [133]. These physiological measurements estimate the severity and extent of atherosclerotic burden, including the presence of multi-vessel disease or microvascular dysfunction [135, 136]. The prognostic value of CFR [133, 135–137] is noted and it can be a good candidate for a “non-contrast one-stop-shop-test” to be combined with coronary MRA.

Meanwhile, another measurement of coronary flow, the functional flow ratio (FFR), is still under development. Direct assessment of the pressure gradient ($\Delta P$) along the stenotic coronary artery with PC imaging was reported by Deng et al., who observed a significant increase in $\Delta P$ in suspected coronary stenosis lesions than in controls (6.40 ± 4.33 mmHg vs. 0.70 ± 0.57 mmHg, $p = 0.025$) [138]. Current technical problems related to this PC application are the partial volume effects at stenotic regions, possible impact from turbulence on the accuracy of PC-MRI velocity measurements, and the need to cope with cardiac and respiratory motion [138]. 4D flow is an advanced promising technique.
of PC with flow encoding in all three dimensions of space, plus time along the cardiac cycle. The current typical spatial resolution of 4D flow is $1.5 \times 1.5 \times 1.5$ to $3 \times 3 \times 3$ mm$^3$ [139], which is not enough for coronary artery imaging. Further developments with higher resolution are expected.

**Conclusions**

Non-contrast coronary MRA is a non-invasive, non-ionizing radiation modality that is particularly unique, as it does not require contrast use to enhance intra-luminal blood flow. These characteristics have great potential for routine clinical applications. We reviewed the current clinical use and the in-progress technical developments that could significantly impact coronary MRA prospectively. The central thesis is that the combination of PI and CS is expected to maintain high spatial resolution while reducing the total time of acquisition, and application of DLR is promising for effective denoizing to improve SNR and CNR. Research-based coronary MRA assessment methods of stenosis severity, physiological function, and plaque characteristics are being developed to transform coronary MRA into a robust non-invasive imaging modality to be used routinely for clinical decision making in cardiovascular medicine.

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**Author contributions** YK performed the literature search, data analysis and interpretation, drafting, and critical revision of the work. BAV, SC, and JACL performed the study conception and the critical revision. YK and LK helped in the acquisition of the data, analysis, interpretation of the data, and the critical revision. JS and KK helped in critical revision. All authors contributed to the idea for the article. All authors read and approved the final manuscript.

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Compliance with ethical standards

Conflict of interest Author Joao A.C. Lima has received research grants from Canon Medical Systems Corporation, Yoshimori Kasai, Larry Kasuboski, Joanne Schijf, and Shelton Caruthers are Canon Medical Systems employees in research and development roles. This work represents ongoing R&D between our group at Johns Hopkins Hospital and Canon Medical Systems. We have been particularly careful at eliminating any perception of bias. The remaining authors declare that he/she has no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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References

1. Manning WJ, Li W, Edelman RR (1993) A preliminary report comparing magnetic resonance coronary angiography with conventional angiography. N Engl J Med 328:828–832
2. Dewey M (2011) Coronary CT versus MR angiography: pro CT—the role of CT angiography. Radiology 258:329–339
3. Di Leo G, Fisci E, Secchi F, Ali M, Ambrogi F, Sconfienza LM, Sardanelli F (2016) Diagnostic accuracy of magnetic resonance angiography for detection of coronary artery disease: a systematic review and meta-analysis. Eur Radiol 26:3706–3718
4. Kelle S, Hays AG, Hirsch GA, Gerstenblith G, Miller JM, Steinblith G, Kelle S (2011) Coronary artery distensibility assessed by 3.0 Tesla coronary magnetic resonance imaging in subjects with and without coronary artery disease. Am J Cardiol 108:491–497
5. Nguyen PK, Meyer C, Engvall J, Yang P, McConnell MV (2008) Noninvasive assessment of coronary vasodilation using cardiovascular magnetic resonance imaging in patients at high risk for coronary artery disease. J Cardiovasc Magn Reson 10:28
6. Hays AG, Stuber M, Hirsch GA, Yu J, Schär M, Weiss RG, Gerstenblith G, Kelle S (2013) Non-invasive detection of coronary endothelial response to sequential handgrip exercise in coronary artery disease patients and healthy adults. PLoS ONE 8:1–8
7. Botnar RM, Stuber M, Kissinger KV, Kim WY, Spuentrup E, Manning WJ (2000) Noninvasive coronary vessel wall and plaque imaging with magnetic resonance imaging. Circulation 102:2582–2587
8. Yeon SB, Sabir A, Clouse M, Martinezclark PO, Peters DC, Hauser TH, Gibson CM, Nezafat R, Maintz D, Manning WJ, Botnar RM (2007) Delayed-enhancement cardiovascular magnetic resonance coronary artery wall imaging: comparison with multislice computed tomography and quantitative coronary angiography. J Am Coll Cardiol 50:441–447
9. Sakuma H, Ichikawa Y, Suzawa N, Hirano T, Makino K, Koyama N, Van Cauteren M, Takeda K (2005) Assessment of coronary arteries with total study time of less than 30 minutes by using whole-heart coronary MR angiography. Radiology 237:316–321
10. Hamdan A, Asbach P, Wellnhöfer E, Klein C, Gebker R, Kelle S, Killian H, Huppertz A, Fleck E (2011) A prospective study for comparison of MR and CT imaging for detection of coronary artery stenosis. JACC Cardiovasc Imaging 4:50–61
11. Kim WY, Danias PG, Stuber M, Flamm SD, Plein S, Nagel E, Langeraek SE, Weber OM, Pedersen EM, Schmidt M, Botnar RM, Manning WN (2001) Coronary magnetic resonance angiography for the detection of coronary stenoses. N Engl J Med 345:1863–1869
12. Kato S, Kitagawa K, Ishida N, Ishida M, Nagata M, Ichikawa Y, Katahira K, Matsumoto Y, Seo K, Ochiai R, Kobayashi Y, Sakuma H (2010) Assessment of coronary artery disease using magnetic resonance coronary angiography: a national multicenter trial. J Am Coll Cardiol 56:983–991
13. Bluemke DA, Achenbach S, Budoff M, Gerber TC, Gersh B, Hillis LD, Hundley WG, Manning WN, Printz BF, Stuber M, Woodward PK (2008) Noninvasive coronary artery imaging: magnetic resonance angiography and multidetector computed tomography angiography: a scientific statement from the american heart association committee on cardiovascular imaging and intervention of the council on cardiology. Circulation 118:586–606
14. Hundley WG, Bluemke DA, Finn JP, Flamm SD, Fogel MA, Friedrich MG, Ho VB, Jerosch-Herold M, Kramer CM, Manning WN, Patel M, Pohost GM, Stillman AE, White RD, Woodward PK (2010) ACCF/ACR/AHA/NASCI/SCMR 2010 expert consensus document on cardiovascular magnetic resonance. A report of the American College of Cardiology Foundation Task Force on Expert Consensus Documents. J Am Coll Cardiol 55:2614–2662
15. Nakamura M, Kido T, Kido T, Watanabe K, Schmidt M, For- man C, Mochizuki T (2018) Non-contrast compressed sensing whole-heart coronary magnetic resonance angiography at 3T: a comparison with conventional imaging. Eur J Radiol 104:43–48
16. Akgaykaya M, Basha TA, Chan RH, Manning WN, Nezafat R (2014) Accelerated isotropic sub-millimeter whole-heart coronary MRA: compressed sensing versus parallel imaging. Magn Reson Med 71:815–822
17. Pang J, Sharif B, Fan Z, Bi X, Arsanjani R, Berman DS, Li D (2014) ECG and navigator-free four-dimensional whole-heart coronary MRA for simultaneous visualization of cardiac anatomy and function. Magn Reson Med 71:1208–1217
18. Feng L, Coppo S, Piccini D, Yerly J, Lim RP, Maschi PG, Stuber M, Dodick DK, Otazo R (2018) 5D whole-heart sparse MRA. Magn Reson Med 79:826–838
19. Kato Y, Ambale-venkatesh B, Kassai Y, Pitts J, Kasuboski L, Ortman J, Caruthers S, Lima JAC (2019) Application of deep learning reconstruction for denoising of compressed sensing non-contrast coronary MRA images to achieve improved diagnostic confidence. ISMRM 2019 Abstr
20. Takahashi S, Machida H, Kariyasu T, Niitsu R, Miyazaki I, Yoshimori K, Kusahara H, Matsuoka Y, Kitamura M, Yamamoto T, Yokoyama K (2019) Improved vessel delineation in whole-heart coronary MRA with sub-millimeter isotropic resolution using deep learning reconstruction compared with routine whole-heart coronary MRA. ISMRM 2019 Abstr
management of grown-up congenital heart disease (new version 2010). Eur Heart J 31:2915–2957
34. Molen AJ Van Der, Reimer P, Dekkers IA, Bongartz G, Bellin M (2018) Post-contrast acute kidney injury—Part I: Definition, clinical features, incidence, role of contrast medium and risk factors. Am Coll Radiol 2845–2855
35. van der Molen AJ, Reimer P, Dekkers IA, Bongartz G, Bellin M-F, Bertolotto M, Clement O, Heinz-Peer G, Stacul F, Webb JAWW, Thomsen HS (2018) Post-contrast acute kidney injury. Part 2: risk stratification, role of hydration and other prophylactic measures, patients taking metformin and chronic dialysis patients: recommendations for updated ESUR Contrast Medium Safety Committee guidelines. Eur Radiol 28:2856–2869
36. Thomsen HS, Morcos SK, Almén T, Bellin MF, Bertolotto M, Bongartz G, Clement O, Leander P, Heinz-Peer G, Reimer P, Stacul F, Van Der Molen A, Webb IA (2013) Nephrogenic systemic fibrosis and gadolinium-based contrast media: updated ESUR Contrast Medium Safety Committee guidelines. Eur Radiol 23:307–318
37. Liu X, Zhao X, Huang J, Francois CJ, Tuite D, Bi X, Li D, Carr JC (2007) Comparison of 3D free-breathing coronary MR angiography and 64-MDCT angiography for detection of coronary stenosis in patients with high calcium scores. Am J Roentgenol 189:1326–1332
38. Kanda T, Ishii K, Kawaguchi H, Kitajima K, Takenaka D (2014) High signal intensity in the dentate nucleus and globus pallidus on unenhanced T1-weighted MR images: relationship with increasing cumulative dose of a gadolinium-based contrast material. Radiology 270:834–841
39. Kanda T, Fukusato T, Matsuda M, Toyoda K, Oba H, Kotoku J, Haruyama T, Kitajima K, Furui S (2015) Gadolinium-based contrast agent accumulates in the brain even in subjects without severe renal dysfunction: evaluation of autopsy brain specimens with inductively coupled plasma mass spectroscopy. Radiology 276:228–232
40. Klemm T, Duda S, Machann J, Seekamp-Rahn K, Schniedr L, Claussn SD, Schick F (2000) MR imaging in the presence of vascular stents: A systematic assessment of artifacts for various stent orientations, sequence types, and field strengths. J Magn Reson Imaging 12:606–615
41. Czervionke LF, Daniels DL, Wehrli FW, Mark LP, Hendrix LE, Strandt JA, Williams AL, Haughton VM (1988) Magnetic susceptibility artifacts in gradient-recalled echo MR imaging. AJNR Am J Neuroradiol 9:1149–1155
42. Zhang L, Song X, Dong L, Li J, Dou R, Fan Z, An J, Li D (2018) Additive value of 3T cardiovascular magnetic resonance coronary angiography for detecting coronary artery disease. J Cardiovasc Magn Reson 20:1–8
43. Bettencourt NF, Ferreira N, Chihibiri A, Schuster A, Sampao F, Santos L, Melica B, Rodrigues A, Braga P, Teixeira M, Leite-Moreira A, Silva-Cardoso J, Portugal P, Gama V, Nagel E (2013) Additive value of magnetic resonance coronary angiography in a comprehensive cardiac magnetic resonance stress-rest protocol for detection of functionally significant coronary artery disease a pilot study. Circ Cardiovasc Imaging 6:730–738
44. Yoon YE, Kitagawa K, Kato S, Ishida M, Nakajima H, Kurita T, Ito M, Sakuma H (2012) Prognostic value of coronary magnetic resonance angiography in patients with suspected coronary artery disease. J Am Coll Cardiol 60:2316–2322
45. Spuentrup E, Manning WJ, Botnar RM, Kissinger KV, Stuber M (2002) Impact of navigator timing on free-breathing submillimeter 3D coronary magnetic resonance angiography. Magn Reson Med 47:196–201
46. Bhat H, Ge L, Nielles-Vallespin S, Zuehlsdorff S, Li D (2011) 3D radial sampling and 3D affine transform-based respiratory motion correction technique for free-breathing whole-heart coronary MRA with 100% imaging efficiency. Magn Reson Med 65:1269–1277
47. Hu P, Chuang HL, Ngo LH, Stock CE, Peters DC, Kissinger KV, Goddu S, Goeppert LA, Manning WJ, Nezafat R (2010) Coronary MR imaging: Effect of timing and dose of isosorbide dinitrate administration. Radiology 254:401–409
48. Heer T, Reiter S, Trißler M, Höfling B, von Knobelsdorff-Brenkenhoff F, Pilz G (2017) Effect of nitroglycerin on the performance of MR coronary angiography. J Magn Reson Imaging 45:1419–1428
49. Deshpande VS, Shear SM, Laub G, Simonetti OP, Finn JP, Li D (2001) 3D magnetization-prepared true-FISP: A new technique for imaging coronary arteries. Magn Reson Med 46:494–502
50. Bi X, Deshpande V, Simonetti O, Laub G, Li D (2005) Three-dimensional breathhold SSFP coronary MRA: a comparison between 1.5T and 3.0T. J Magn Reson Imaging 22:206–212
51. Haase A, Frahm J, Matthaei D, Hänckel W, Merboldt K-D (1986) FLASH imaging: rapid NMR imaging using low flip-angle pulses. 1986. J Magn Reson 67:258–266
52. Liu X, Bi X, Huang J, Jerecic R, Carr J, Li D (2008) Contrast-enhanced whole-heart coronary magnetic resonance angiography at 3.0 T. Invest Radiol 43:663–668
53. Kaul MG, Stork A, Bansmann PM, Nolte-Ernsting C, Lund GK, Weber C, Adam G (2004) Evaluation of balanced steady-state free precession (TrueFISP) and k-space segmented gradient echo sequences for 3D coronary MR angiography with navigator gating at 3 Tesla. RoFo Fortschritte auf dem Gebiet der Rontgenstrahlen und der Bildgeb Verfahren 176:1560–1565
54. Sommer T, Hackenbroch M, Hofer U, Schmiedel A, Willinek WA, Flacke S, Gieseke J, Träber F, Fimmers R, Litt H, Schild H (2005) Coronary MR angiography at 3.0 T versus that at 1.5 T: initial results in patients suspected of having coronary artery disease. Radiology 234:718–725
55. Brittain JH, Hu BS, Wright GA, Meyer CH, Macovski A, Nishimura DG (1995) Coronary angiography with magnetization-prepared T2 contrast. Magn Reson Med 33:689–696
56. Botnar RM, Stuber M, Danias PG, Kissinger KV, Manning WJ (1999) Improved coronary artery definition with T2-weighted, free-breathing, three-dimensional coronary MRA. Circulation 99:3139–3148
57. Nezafat M, Henningsson M, Ripley DP, Greil G, Greenwood JP, Börnert P, Plein S, Botnar RM (2016) Coronary MR angiography at 3T: fat suppression versus water-fat separation. Magn Reson Med 79:733–738
58. Bastiaansen JAM, Botnar GM (2018) Flexible water excitation for fat-free MRI at 3T using lipid insensitive binomial off-resonant RF excitation (LIBRE) pulses. Magn Reson Med 79:3007–3017
59. Bastiaansen JAM, van Heeswijk RB, Stuber M, Piccini D (2019) Noncontrast free-breathing respiratory self-navigated coronary artery cardiovascular magnetic resonance angiography at 3 T using lipid insensitive binomial off-resonant excitation (LIBRE). J Cardiovasc Magn Reson 21:38
60. Koktzoglou I, Edelman RR (2018) Radial fast interrupted steady-state (FISS) magnetic resonance imaging. Magn Reson Med 79:2077–2086
61. Bastiaansen JAM, Piccini D, Di Sopra L, Roy CW, Heerfordt J, Edelman RR, Koktzoglou I, Yerly J, Stuber M (2020) Natively fat-suppressed 3D whole-heart MRI with a radial free-running fast-interrupted steady-state (FISS) sequence at 1.5T and 3T. Magn Reson Med 63:45–55
62. Mistretta CA, Wieben O, Velikina J, Block W, Perry J, Wu Y, Johnson K, Wu Y (2006) Highly constrained backprojection for time-resolved MRI. Magn Reson Med 55:30–40
63. Fessler JA, Sutton BP (2003) Nonuniform fast Fourier transforms using min-max interpolation. IEEE Trans Signal Process 51:560–574

64. Smith DS, Sengupta S, Smith SA, Brian Welch E (2019) Trajectory optimized NUFFT: faster non-Cartesian MRI reconstruction through prior knowledge and parallel architectures. Magn Reson Med 81:2064–2071

65. Lustig M, Pauly JM (2010) SPIRIT: Iterative self-consistent parallel imaging reconstruction from arbitrary k-space. Magn Reson Med 64:457–471

66. Nam S, Aşçıkaya M, Basha T, Stenhing C, Manning WJ, Tarokh V, Nezafat R (2013) Compressed sensing reconstruction for whole-heart imaging with 3D radial trajectories: a graphics processing unit implementation. Magn Reson Med 69:91–102

67. Liu J, Saloner D (2014) Accelerated MRI with CIRCular Cartesian UnderSampling (CIRCUS): a variable density Cartesian sampling strategy for compressed sensing and parallel imaging. Quant Imaging Med Surg 4:57–67

68. Prieto C, Doneva M, Usman M, Henningsson M, Greil G, Schaeffter T, Botnar RM (2015) Highly efficient respiratory motion compensated free-breathing coronary MRA using golden-step Cartesian acquisition. J Magn Reson Imaging 41:738–746

69. Bustin A, Ginami G, Cruz G, Correia T, Ismail TF, Rashid I, Neji R, Botnar RM, Prieto C (2019) Five-minute whole-heart coronary MRA with sub-millimeter isotropic resolution, 100% respiratory scan efficiency, and 3D-PFROST reconstruction. Magn Reson Med 81:102–115

70. Pipe JG (1999) Motion correction with PROPELLER MRI: Application to head motion and free-breathing cardiac imaging. Magn Reson Med 42:963–969

71. Feng L, Axel L, Chandarana H, Block KT, Sodickson DK, Otazo R (2016) XD-GRASP: Golden-angle radial MRI with reconstruction of extra motion-state dimensions using compressed sensing. Magn Reson Med 75:775–788

72. Haji-Valizadeh H, Collins JD, Aoudj PJ, Serhal AM, Lindley MD, Pang J, Naresh NK, Carr JC, Kim D (2019) Accelerated, free-breathing, noncontrast, electrocardiograph-triggered, thoracic MR angiography with stack-of-stars k-space sampling and GRASP reconstruction. Magn Reson Med 81:524–532

73. Larsson AC, White RD, Laub G, McVeigh ER, Li D, Simoni et al. (2004) Self-gated cardiac cine MRI. Magn Reson Med 51:93–102

74. Liu J, Spincemaille P, Codella NCF, Nguyen TD, Prince MR, Wang Y (2010) Respiratory and cardiac self-gated free-breathing cardiac CINE imaging with multicoil 3D hybrid radial SSFP acquisition. Magn Reson Med 63:1230–1237

75. Stehning C, Börnert P, Nehurke K, Eggers H, Stuber M (2005) Free-breathing whole-heart coronary MRA with 3D radial SSFP and self-navigated image reconstruction. Magn Reson Med 54:476–480

76. Winkelmann S, Schaeffter T, Koehler T, Eggers H, Doessel O (2007) An optimal radial profile order based on the golden ratio for time-resolved MRI. IEEE Trans Med Imaging 26:68–76

77. Feng L, Bendker T, Block KT, Sodickson DK, Otazo R, Chandarana H (2017) Compressed sensing for body MRI. J Magn Reson Imaging 45:966–987

78. Feng L, Grimm R, Block KT, Chandarana H, Kim S, Xu J, Axel L, Sodickson DK, Otazo R (2014) Golden-angle radial sparse parallel MRI: combination of compressed sensing, parallel imaging, and golden-angle radial sampling for fast and flexible dynamic volumetric MRI. Magn Reson Med 72:707–717

79. Chandarana H, Block TK, Rosenkranz AB, Lim RP, Kim D, Mosa DJ, Babb JS, Kiefer B, Lee VS (2011) Free-breathing radial 3D fat-suppressed T1-weighted gradient echo sequence: a viable alternative for contrast-enhanced liver imaging in patients unable to suspend respiration. Invest Radiol 46:648–653

80. Pruessmann KP, Weiger M, Scheidegger MB, Boesiger P (1999) SENSE: sensitivity encoding for fast MRI. Magn Reson Med 42:952–962

81. Sodickson DK, Manning WJ (1997) Simultaneous acquisition of spatial harmonics (SMASH): fast imaging with radiofrequency coil arrays. Magn Reson Med 38:591–603

82. Griswold MA, Jakob PM, Heidemann RM, Nittka M, Jellus V, Wang J, Kiefer B, Haase A (2002) Generalized autocalibrating partially parallel acquisitions (GRAPPA). Magn Reson Med 47:1202–1210

83. Deshmam E, Gulani V, Griswold MA, Seiberlich N (2012) Parallel MR imaging. J Magn Reson Imaging 36:55–72

84. Ghahri M, Abd-Elmoniem KZ, Ho VB, Födi E, Herzka DA, Ohayon J, Stuber M, Pettigrew RI (2012) The feasibility of 350 μm spatial resolution coronary magnetic resonance angiography at 3 T in humans. Invest Radiol 47:339–345

85. Lustig M, Donoho D, Pauly JM (2007) Sparse MRI: The application of compressed sensing for rapid MR imaging. Magn Reson Med 58:1182–1195

86. Lustig M, Donoho D (2008) Compressed sensing MRI. Signal Process Mag 25:72–82

87. Aşçıkaya M, Basha TA, Goddu B, Goeppert LA, Kissinger KV, Tarokh V, Manning WJ, Nezafat R (2011) Low-dimensional-structure self-learning and thresholding: regularization beyond compressed sensing for MRI reconstruction. Magn Reson Med 66:756–767

88. Otazo R, Kim D, Axel L, Sodickson DK (2010) Combination of compressed sensing and parallel imaging for highly accelerated first-pass cardiac perfusion MRI. Magn Reson Med 64:767–776

89. Uecker M, Lai P, Murphy MJ, Virtue P, Elad M, Pauly JM, Vasanawala SS, Lustig M (2014) ESPIRiT—a new algorithm approach to autocalibrating parallel MRI: where SENSE meets GRAPPA. Magn Reson Med 71:990–1001

90. Hollingsworth KG (2015) Reducing acquisition time in clinical MRI by data undersampling and compressed sensing reconstruction. Phys Med Biol 60:R297–R322

91. Haris K, Hedström E, Bidhult S, Testud F, Maglaveras N, Heiberg E, Hansson SR, Arheden H, Aletras AH (2017) Self-gated fast cardiac MRI with tiny golden angle iGRASP: a feasibility study. J Magn Reson Imaging 46:207–217

92. Hyun CM, Kim HP, Lee SM, Lee S, Soo JK (2018) Deep learning for undersampled MRI reconstruction. Phys Med Biol 63:135007

93. Hauptmann A, Arridge S, Lucka F, Muthurangu V, Steeden JA (2018) Real-time cardiovascular MR with spatio-temporal artifact suppression using deep learning—proof of concept in congenital heart disease. Magn Reson Med 1143–1156

94. Aitken AP, Henningsson M, Botnar RM, Schaeffter T, Prieto C (2015) 100% Efficient three-dimensional coronary MRI angiography with two-dimensional beat-to-beat translational and bin-to-bin affine motion correction. Magn Reson Med 74:756–764

95. Addy NO, Ingle RR, Luo J, Baron CA, Yang PC, Hu BS, Nishimura DG (2017) 3D image-based navigators for coronary MR angiography. Magn Reson Med 77:1874–1883

96. Piccini D, Littmann A, Nielles-Vallespin S, Zenge MO (2012) Respiratory self-navigation for whole-heart bright-blood coronary MR angiography. Magn Reson Med 77:1143–1156

97. Frieden J, Prieto C, Kiefer B, Kiefer B, Lee VS (2011) Free-breathing, noncontrast, electrocardiograph-triggered, thoracic MR angiography with two-dimensional beat-to-beat translational and bin-to-bin affine motion correction. Magn Reson Med 74:756–764

98. Dang V, Ingle RR, Luo J, Baron CA, Yang PC, Hu BS, Nishimura DG (2017) 3D image-based navigators for coronary MR angiography. Magn Reson Med 77:1874–1883

99. Piccini D, Littmann A, Nielles-Vallespin S, Zenge MO (2012) Respiratory self-navigation for whole-heart bright-blood coronary MRI: Methods for robust isolation and automatic segmentation of the blood pool. Magn Reson Med 68:571–579

100. Piccini D, Bonanno G, Ginami G, Littmann A, Zenge MO, Stuber M (2016) Is there an optimal respiratory reference position for self-navigated whole-heart coronary MR angiography? J Magn Reson Imaging 43:426–433

101. Pang J, Bhat H, Sharif B, Fan Z, Thomson LEJ, Labounty T, Friedman JD, Min J, Berman DS, Li D (2014) Whole-heart coronary MRA with 100% respiratory gating efficiency:
self-navigated three-dimensional retrospective image-based motion correction (TRIM). Magn Reson Med 71:67–74
99. Greenspan H, Peled S, Oz G, Kiryati N (2001) MRI inter-slice reconstruction using super-resolution. Lect Notes Comput Sci (including Subser Lect Notes Artif Intell Lect Notes Bioinformatics) 2208:1204–1206
100. Rueda A, Malpica N, Romero E (2013) Single-image super-resolution of brain MR images using overcomplete dictionaries. Med Image Anal 17:113–132
101. Chen Y, Xie Y, Zhou Z, Shi F, Christodoulou AG, Li D (2018) Brain MRI super resolution using 3D densely connected neural networks. Proc—Int Symp Biomed Imaging 2018-April:739–742
102. Chen Y, Shi F, Christodoulou AG, Xie Y, Zhou Z, Li D (2018) Efficient and accurate MRI super-resolution using a generative adversarial network and 3D multi-level densely connected network. Med Image Comput Comput Assist Interv 91–99
103. Chen Y, Shaw JL, Xie Y, Li D, Christodoulou AG (2019) Deep learning within a priori temporal feature spaces for large-scale dynamic MR image reconstruction: application to 5-D cardiac MR Multitasking 1–9
104. Ishida M, Nakayama R, Uno M, Ito T, Goto Y, Ichikawa Y, Nagata M, Kitagawa K, Nakamori S, Dohi K, Ito M, Sakuma H (2014) Learning-based super-resolution technique significantly improves detection of coronary artery stenoses on 1.5T whole-heart coronary MRA. J Cardiovasc Magn Reson 16:P218
105. Esses SJ, Lu X, Zhao T, Shanbhogue K, Dane B, Bruno M, Chandarana H (2018) Automated image quality evaluation of T2-weighted liver MRI utilizing deep learning architecture. J Magn Reson Imaging 47:723–728
106. Nakaniishi R, Sankaran S, Grady L, Malpese J, Yousfi R, Osawa K, Ceponiene I, Nazarat N, Rahmani S, Kessel K, Jayawardena E, Dailing C, Zarins C, Koo BK, Min JK, Taylor CA, Budoff MJ (2018) Automated estimation of image quality for coronary computed tomographic angiography using machine learning. Eur Radiol 28:4018–4026
107. Guddbjartsson H, Patz S (1995) The Rician distribution of noisy MRI data. Magn Reson Med 34:910–914
108. Manjón JV, Coupé P, Martí-Bonmatí L, Collins DL, Robles M (2010) Adaptive non-local means denoising of MR images with spatially varying noise levels. J Magn Reson Imaging 31:192–203
109. Dabov K, Foi A, Katkovnik V, Egiazarian K (2007) Image denoising by sparse 3-D transform-domain collaborative filtering. IEEE Trans Image Process 16:2080–2095
110. Gupta SM (2018) A review and comprehensive comparison of image de-noising techniques. In: 2017 6th Int Conf Reliab Infocom Technol Optim Trends Futur Dir ICRITO 2017 2018-Infocom Technol Optim Trends Futur Dir ICRITO 2017 2018-6:466–474
111. Zhu B, Liu JZ, Cauley SF, Rosen BR, Rosen MS (2018) Image reconstruction by domain-transform manifold learning. Nature 555:487–492
112. Han Y, Ye JC (2018) k-space deep learning for accelerated. MRI. 1–11
113. Chen Y, Pock T (2017) Trainable nonlinear reaction diffusion: a flexible framework for fast and effective image restoration. IEEE Trans Pattern Anal Mach Intell 39:1256–1272
114. Zhang K, Zuo W, Chen Y, Meng D, Zhang L (2017) Beyond a Gaussian denoiser: residual learning of deep CNN for image denoising. IEEE Trans Image Process 26:3142–3155
115. Isogawa K, Ida T, Shiodera T, Takeguchi T (2018) Deep shrinkage convolutional neural network for adaptive noise reduction. IEEE Signal Process Lett 25:224–228
116. Kidoh M, Shinoda K, Kitajima M, Isogawa K, Nambu M, Uetani H, Morita K, Nakaura T, Tateishi M, Yamashita YY, Yamashita YY (2019) Deep learning based noise reduction for brain MR imaging: tests on phantoms and healthy volunteers. Magn Reson Med Sci. https://doi.org/10.2463/mrms.mp.2019-0018
117. Etienne A, Botnar RM, Van Muiswinkel AMC, Boesiger P, Manning WJ, Stuber M (2002) “Soap-Bubble” visualization and quantitative analysis of 3D coronary magnetic resonance angiograms. Magn Reson Med 48:658–666
118. Soleimaniard S, Schär M, Hays RG, Weiss RG, Stuber M, Prince JL (2012) Vessel centerline tracking and boundary segmentation in coronary MRA with minimal manual interaction. In: Proc—Int symp biomed imaging, pp 1417–1420
119. Yonezawa M, Nagata M, Kitagawa K, Kato S, Yoon Y, Nakajima H, Nakamori S, Sakuma H, Hatakenaka M, Honda H (2014) Quantitative analysis of 1.5-T whole-heart coronary MR angiograms obtained with 32-channel cardiac coils: a comparison with conventional quantitative coronary angiography. Radiology 271:356–364
120. Kim SM, Choi J-H, Choe YH (2016) Coronary artery total occlusion: MR angiographic imaging findings and success rates of percutaneous coronary intervention according to intraluminal signal intensity patterns. Radiology 279:84–92
121. Kawasaki T, Koga S, Koga N, Noguchi T, Tanaka H, Koga H, Serikawa T, Orita Y, Ikeda S, Mito T, Goto Y, Shintani Y, Tanaka A, Fukuyama T (2009) Characterization of hyperintense plaque with noncontrast T(1)-weighted cardiac magnetic resonance coronary plaque imaging: comparison with multislice computed tomography and intravascular ultrasound. JACC Cardiovasc Imaging 2:720–728
122. Noguchi T, Yamada N, Higashi M, Goto Y, Naito H (2011) High-intensity signals in carotid plaques on T1-weighted magnetic resonance imaging predict coronary events in patients with coronary artery disease. J Am Coll Cardiol 58:416–422
123. Oshita A, Kawakami H, Kito K, Kono Y, Miyoshi T, Matsuoka H (2018) Clinical utility of non-contrast T1-weighted magnetic resonance imaging in percutaneous coronary intervention: a case report. J Cardiol Cases 19:9–11
124. Raman SV, Winner MW, Tran T, Velayutham M, Simonetti OP, Baker PB, Olesik J, McCarthy B, Ferketich AK, Zweier JL (2008) In Vivo Atherosclerotic plaque characterization using magnetic susceptibility distinguishes symptom-producing plaques. JACC Cardiovasc Imaging 1:49–57
125. Sharkey-Toppen TP, Tewari AK, Raman SV (2014) Iron and magnetic susceptibility distinguishes symptom-producing plaques. J Cardiovasc Transl Res 7:533–542
126. Károlyi M, Seifarth H, Liew G, Schlett CL, Maurovich-Horváth P, Stolzmann P, Dai G, Huang S, Goergen CJ, Nakano M, Otsuka F, Virmani R, Hoffmann U, Sosnovik DE (2013) Classification of coronary atherosclerotic plaques ex vivo with T1, T2, and ultrafast echo time cmr. JACC Cardiovasc Imaging 6:466–474
127. Chan CF, Keenan NG, Nielles-Vallespin S, Gatehouse P, Shepard MN, Boyle JJ, Pennell DJ, Firmin DN (2010) Ultra-short echo time cardiovascular magnetic resonance of atherosclerotic carotid plaque. J Cardiovasc Magn Reson Off J Soc Cardiovasc Magn Reson 12:17
128. Yang Q, Barnes SRS, Wu Z, Neelavalli J, Hu J, Li K, Liu J, Haacke EM (2009) Imaging the vessel wall in major peripheral arteries using susceptibility-weighted imaging. J Magn Reson Imaging 30:357–365
129. Rajendran R, Minqin R, Ronald JA, Rutt BK, Halliwell B, Watt MP,2019-0018
131. Hood WB (1968) Regional venous drainage of the human heart. Heart 30:105–109
132. Lund GK, Wendland MF, Shimakawa A, Arheden H, Stålberg F, Higgins CB, Saeed M (2000) Coronary sinus flow measurement by means of velocity-encoded cine MR imaging: validation by using flow probes in dogs. Radiology 217:487–493
133. Kato S, Saito N, Nakachi T, Fukui K, Iwasawa T, Taguri M, Kosuge M, Kimura K (2017) Stress perfusion coronary flow reserve versus cardiac magnetic resonance for known or suspected CAD. J Am Coll Cardiol 70:869–879
134. Sakuma H, Kawada N, Takeda K, Higgins CB (1999) MR measurement of coronary blood flow. J Magn Reson Imaging 10:728–733
135. Van De Hoef TP, Van Lavieren MA, Damman P, Delewi R, Pick MA, Chamuleau SAJ, Voskuil M, Henriques JPS, Koch KT, De Winter RJ, Spaan JAE, Siebes M, Tijssen JGP, Meuwissen M, Pick JJ (2014) Physiological basis and long-term clinical outcome of discordance between fractional flow reserve and coronary flow velocity reserve in coronary stenoses of intermediate severity. Circ Cardiovasc Inter 7:301–311
136. Van De Hoef TP, Siebes M, Spaan JAE, Pick JJ (2015) Fundamentals in clinical coronary physiology: Why coronary flow is more important than coronary pressure. Eur Heart J 36:3312–3319
137. Murthy VL, Naya M, Foster CR, Hainer J, Gaber M, Di Carli G, Blankstein R, Dorbala S, Sitek A, Pencina MJ, Di Carli MF (2011) Improved cardiac risk assessment with noninvasive measures of coronary flow reserve. Circulation 124:2215–2224
138. Deng Z, Fan Z, Lee S-E, Nguyen C, Xie Y, Pang J, Bi X, Yang Q, Choi B-W, Kim J-S, Berman D, Chang H-J, Li D (2017) Noninvasive measurement of pressure gradient across a coronary stenosis using phase contrast (PC)-MRI: a feasibility study. Magn Reson Med 77:529–537
139. Dyverfeldt P, Bissell M, Barker AJ, Bolger AF, Carlhäll CJ, Ebbers T, Francios CJ, Frydychowicz A, Geiger J, Giese D, Hope MD, Kilner PJ, Kozerke S, Myerson S, Neubauer S, Wieben O, Markl M (2015) 4D flow cardiovascular magnetic resonance consensus statement. J Cardiovasc Magn Reson 17:1–19
140. Shinoda K, Isogawa K, Nambu M, Yamashita Y, Uetani H, Kita-jima M, Yamashita Y (2019) Deep learning based adaptive noise reduction in multi-contrast MR images. ISMRM 2019 Abstr
141. Mugler JP, Brookeman JR (1990) Three-dimensional magnetization-prepared rapid gradient-echo imaging (3D MP RAGE). Magn Reson Med 15:152–157

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