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Review Article

Highlights of the society for magnetic resonance angiography 2024 conference

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ABSTRACT

The 36th Annual International Meeting of the Society for Magnetic Resonance Angiography (SMRA), held from November 12–15, 2024, in Santiago de Chile, marked a milestone as the first SMRA conference in Latin America. Themed "The Ever-Changing Landscape of MRA", the event highlighted the rapid advancements in magnetic resonance angiography (MRA), including cutting-edge developments in contrast-enhanced MRA, contrast-free techniques, dynamic, multi-parametric, and multi-contrast MRA, 4D flow, low-field solutions and artificial intelligence (AI)-driven technologies, among others. The program featured 174 attendees from 15 countries, including 43 early-career scientists and 30 industry representatives. The conference offered a rich scientific agenda, with 12 plenary talks, 24 educational talks, 98 abstract presentations, a joint SMRA-MICCAI challenge on intracranial artery lesion detection and segmentation and a joint session with the Society for Cardiovascular Magnetic Resonance (SCMR) emphasizing accessibility, low-field MRI, and AI's transformative role in cardiac imaging. The meeting's single-track format fostered engaging discussions on interdisciplinary research and highlighted innovations spanning various vascular beds. This paper summarizes the conference's key themes,

ABBREVIATIONS: AI, Artificial Intelligence; ASL, Arterial Spin Labeling; bSSFP, balanced Steady State Free Precession; BB, Black-blood; CE, Contrast-enhanced; CIED, Cardiac Implantable Electronic Device; CMR, Cardiovascular Magnetic Resonance; CTA, Computed Tomography Angiography; CTCA, Computed Tomography Coronary Angiography; DCE, Dynamic Contrast Enhanced; DSA, Digital Subtraction Angiography; DVT, Deep Venous Thrombosis; ECG, Electrocardiogram; FF, Fat Fraction; LGE, Late Gadolinium Enhancement; Non-CE, Non-Contrast Enhanced; MOLLI, Modified Look-Locker inversion recovery imaging; MRA, Magnetic Resonance Angiography; MRI, Magnetic Resonance Imaging; MRL, MR lymphangiography; PC, Phase Contrast; PS, Phase Sensitive; RCA, Right Coronary Artery; SNR, Signal to Noise Ratio; TOF, Time of Flight; VNR, Velocity-to-noise ratio; 4D, four-dimensional; 5D, five-dimensional; SMRA, Society for Magnetic Resonance Angiography; MICCAI, Medical Image Computing and Computer Assisted Intervention; SCMR, Society for Cardiovascular Magnetic Resonance; INSTED, Intracranial Aneurysm and Intracranial Artery Stenosis Detection and Segmentation; MERGE, multiple echo recombined gradient echo; SNAP, simultaneous non-contrast angiography and intra-plaque hemorrhage; MR, imaging technique; VISTA, volume isotropic turbo spin echo acquisition; SPACE, sampling perfection with application optimized contrasts using different flip angle evolution; GRE, gradient recalled echo; iNAV, image navigator; bT1RESS, balanced T1 relaxation-enhanced steady-state; iT2prepBOOST, interleaved T2 and inversion recovery prepared sequence; CG-recon, conjugate gradient deep learning reconstruction; Time-SLIP, time-spatial labeling inversion pulse

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emphasizing the collaborative efforts driving the future of MRA, while reflecting on SMRA's vision to advance research, education, and clinical practice globally.

1. INTRODUCTION

The Society for Magnetic Resonance Angiography (SMRA) was founded in 1989 as the MR Angio Club to bring together scientists, clinicians and industry with a common interest in MR Angiography (MRA). The MR Angio Club formally became the nonprofit Society for Magnetic Resonance Angiography (SMRA) in 2015. The SMRA unites an international group of scientists and clinicians devoted to the development, application and promotion of Magnetic Resonance (MR) imaging techniques to visualize the cardiovascular system and to improve patient care. Over the past three decades, the SMRA annual conference has been recognized as the premier meeting focusing on vascular MR research and clinical applications, showcasing the latest advances and collaborations in the field of MR angiography (MRA), including developments in cardiovascular MR (CMR) beyond MRA. This year marks a significant milestone as the conference was held for the first time in Latin America. The 36th Annual International Meeting of SMRA was hosted in Santiago de Chile from 12th to 15th of November 2024, led by SMRA's President Dr. Wieben and by Program Chairs Dr. Botnar and Dr. Prieto.

The theme of the SMRA 2024 conference was “The Ever-Changing Landscape of MRA”. From a scientific perspective, this theme encapsulates the dynamic evolution of MRA. Over the years, the SMRA community has been at the forefront of pioneering advancements, including multi-parametric and multi-contrast high-resolution imaging, 4D flow techniques, contrast-free MRA techniques, contrast-enhanced (CE) MRA, and artificial intelligence (AI)-driven solutions from acquisition to diagnosis. By addressing the "ever-changing" nature of MRA, the theme highlights the ongoing efforts to explore new frontiers in MRA research and integrate multidisciplinary expertise in clinical practice. The connection to Chile's landscapes adds a compelling metaphorical layer to the theme. By intertwining the SMRA's cutting-edge advancements with Chile's rich and diverse topography, "The Ever-Changing Landscape of MRA" serves as a reminder of how innovation and collaboration can shape the future of MRA.

The hosting city and country for the annual SMRA meeting changes every year to encourage international participation. It had previously taken place in North America, Europe, Asia, and Africa while the 2024 marked the first SMRA meeting in South America. The conference hosted 174 attendees, including 43 early-career scientists and trainees and 30 industry representatives, representing 15 countries. Of the 144 non-industry attendees, 24.8% (36/144) were trainees and 71.5% (103/144) identified as male, 26.3% (38/144) as female, 1.4% (2/144) as non-binary, and 0,7% (1/144) preferred not to disclose. Geographically, 55.6% (80/144) were associated with an institution in North America, 18.2% (26/144) with Europe, 15.3%(22/144) from South America, and 8.4%(12/144) from Asia (Fig. 1). Compared to the 2023 meeting in Sendai, Japan, participation increased for North America (80 vs 58), South America (22 vs 0), slightly increased for Europe (26 vs 22) and decreased for Asia (12 vs 88). The lower participation from Asia is attributed to very long travel times and associated high travel costs as well as the extraordinary high participation of trainees from Asia at the Sendai meeting. The program consisted of 2 named lectures, 12 plenary talks, 24 educational talks, 37 oral abstract presentations, 61 power-pitch presentations, and 1 grand challenge, showcasing the latest developments in the field.

The plenary sessions discussed the current opportunities, challenges, and future directions in MRA research; the path toward more accessible and affordable MRA and CMR; the potential and current role of AI in these advancements; the value and promises of interventional MRI; as well as new horizons and the future of MRA and CMR. These plenaries also included talks by industry representatives to highlight the value of scientific-industry collaboration and showcase widespread translation in patient care. Two of the plenary sessions were jointly organized with sister societies, the Society for Cardiovascular Magnetic Resonance (SCMR) and the Medical Imaging Computing and Computer Assisted Intervention Society (MICCAI). The joint session with SCMR focused on more accessible and affordable CMR and discussed how to balance the cost and performance in cardiac MR imaging, as well as the potential of low-field (< 1T) MRI to bridge the gaps in healthcare accessibility. The Latin America case was also discussed, by the upcoming SCMR President Dr. Carlos Rochitte, to exemplify the challenges of MRA and CMR. The joint session with MICCAI discussed the role of AI for the imaging pipeline from referral to reporting as well as its potential for AI-based prediction of disease progression and outcome. This session also included the 4th joint SMRA-MICCAI Challenge, this year focused on Intracranial Aneurysm and Intracranial Artery Stenosis Detection and Segmentation (INSTED2024). The SMRA community provided curated clinical MRA data sets from healthy volunteers and patients, now available as an open-accessible database with well-labeled bounding boxes and segmentation masks of intracranial aneurysm and intracranial artery stenosis to facilitate the development and validation of reliable automatic intracranial lesion detection and segmentation algorithms, thereby filling a previously unmet need. The SMRA

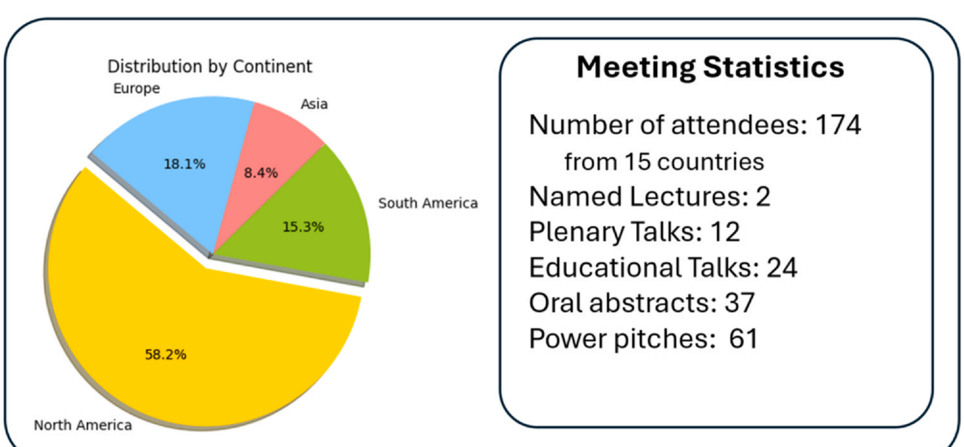

Fig. 1. Statistics of the SMRA 2024 annual scientific meeting in Santiago de Chile. The pie chart shows the distribution of participants (industry representatives excluded) across the continents. *SMRA* society for magnetic resonance angiography

challenged imaging scientists to automatically detect, segment, and measure lesion geometry on the provided 3D time-of-flight (TOF)-MRA images, thereby bringing together the latest and most advanced algorithms from the MICCAI community and meaningful, real-world tasks in the SMRA community. The winning teams were MIC from the German Cancer Research Center, HNPH from CTS Philips, and BriBra from Anke High-tech Co. More information can be found in the official website of the challenge https://www.codabench.org/competitions/2139/.

The program also featured two named lectures, the Martin Prince and Kazuhiko Sadamoto Lectures. The lectures were given by Dr. Mitsue Miyazaki from University San Diego and Dr. Debiao Li from Cedars Sinai Medical Center, and highlighted strategies for breaking barriers to enhance access to MR angiography and explored the future of MRA and CMR, respectively. Training of the next generation of physicians and imaging scientists is an important mission of the SMRA. The early career development plenary session, organized jointly with the SMRA Early Career Committee, featured plenary talks highlighting the value of interdisciplinary research and training, as well as the importance of team management, scientific innovation, and clinical practice in medical education. SMRA junior fellowships were awarded for the first time and the recipients had an opportunity to share their scientific journey and the importance of mentorship in the early career development session. The Early Career Committee also organized a dedicated "Meet the Faculty" coffee break to provide the trainees with additional opportunities to connect with MRA experts. The series of educational talks covered a wide range of clinical applications, from head and neck to cardiac, abdominal, thoracic, and peripheral regions. These sessions also highlighted cutting-edge technologies in MRA and CMR, including quantitative imaging, AI, flow imaging, modeling and processing, as well as CE and non-CE MRA techniques.

This year SMRA established the newly formed Junior Fellowship Awards, honoring outstanding contributions to the SMRA from early career researchers in both basic science and clinical categories. The inaugural SMRA Junior Fellowships were awarded to Anastasia Fotaki from the Royal Brompton Hospital and Guy's and St Thomas's London, Judit Csőre from Semmelweis University, and Lexiaozi Fan from Northwestern University.

The conference had strong participation from early career scientists and trainees, with 98 abstract presentations as oral talks or power-pitch presentations. The top scored abstracts were finalists for the SMRA Potchen and Passariello Awards. This year the awardees of the Potchen Award were Tabita Catalan (1st place) from Pontificia Universidad Católica de Chile, Thara Nallamothu (2nd place) from Northwestern University, USA, and Pia Callmer (3rd place) from the Karolinska Institute, Sweden, for their work on "Accelerated cardiac cine MRI using Implicit Neural Representations Unsupervised Reconstruction," "5D Flow MRI captures respiration-driven alterations in flow energetics in congenital heart disease" and "Deep learning for temporal super-resolution and denoising of 4D Flow MRI," respectively. The awardees of the Passariello Awards were Judit Csőre (1st place) from Semmelweis University, Hungary, Simon Littlewood (2nd place) from King's College London, UK, and Andrew Phair (3rd place) from King's College London, UK, for their works on "Transforming Chronic Limb-Threatening Ischemia Care with Pre-procedural Magnetic Resonance Histology in Peripheral Vascular Interventions," "High-Resolution Non-Contrast Magnetic Resonance Coronary Angiography for Coronary Artery Assessment" and "Data-consistent super resolution for 3D whole-heart MRI using a motion-corrected deep learning reconstruction framework," respectively.

The single-track format of SMRA fosters a shared experience with plentiful opportunities for engaging discussions about MRA. This paper delves into the key themes and highlights from the meeting emphasizing the innovations and collaborations guiding the future of MRA. Topics are organized by vascular beds and notable innovations. Highlights from the early-career activities are also discussed, as well as a vision for the future of SMRA. The following delimitation of scope is considered in this paper for MRA and CMR. MRA focuses on imaging vascular diseases, evaluating vessel anatomy, blood flow, and hemodynamics, and providing insights into vessel wall composition, pathology, and molecular markers using advanced MRI techniques. CMR is a broader field that encompasses imaging the heart's structure, function, and blood flow, including myocardial tissue characterization and cardiac functional assessment. While MRA emphasizes vascular imaging, CMR integrates cardiac and vascular evaluations for a comprehensive understanding of cardiovascular health.

2. Clinical and technical highlights

2.1. Head and neck MRA

MRA enables the non-invasively characterizing of the pathology of neurovascular diseases, such as atherosclerosis, aneurysm, vasculitis, dissection, venous thrombus, etc. This year's dedicated Head and Neck SMRA session has been expanded to include both, neurovascular lumen and vessel wall MR imaging techniques. There are still unsettled debates on the use of angiography vs vessel wall imaging as well as CE vs non-contrast enhanced (non-CE) angiography in clinical settings. The major advances in MRA include small vessel angiography at ultrahigh field such as 7T platforms and Ferumoxytol enhanced MRA [1,2]. In recent years, joint head and neck vessel wall imaging techniques, such as MERGE, SNAP, and VISTA/SPACE/CUBE [3,4], have been developed to provide large longitudinal coverage and isotropic high spatial resolution with short scan time. These imaging techniques facilitate the assessment of co-existing intracranial and extracranial atherosclerotic disease [5–7]. In addition, for better quantification of vulnerable plaque compositional features, a series of quantitative multi-parametric imaging techniques have been introduced [8–10].

At SMRA 2024, several abstracts reported on the advances in technical development and clinical applications of head and neck MRA and vessel wall imaging. For MRA, investigators proposed a highly time-efficient dual-contrast arterial-spin labeling (ASL) technique for hybrid 4D MRA and perfusion imaging, which is a potentially useful tool to comprehensively characterize cerebrovascular disease. Researchers performed TOF MRA and phase-contrast (PC) MRI at 7T to evaluate the morphology and pulsatile hemodynamics of lenticulostriate arteries [11] and demonstrated significant association with cerebral small vessel diseases including white matter hyperintensity and enlarged perivascular space.

Ferumoxytol is a superparamagnetic iron-oxide agent that is increasingly used off-label for CE MRI and MRA [1]. Ferumoxytol's favorable pharmacokinetic properties offer distinct advantages over extracellular contrast agents and enable prolonged steady-state acquisitions where gains in signal to noise ratio (SNR) could be used to significantly improve spatial resolution. Investigators found that Ferumoxytol enhanced MRI/MRA identified almost all brain arteriovenous malformations seen on digital subtraction angiography.

For MR vessel wall imaging, a high resolution (0.2 mm × 0.3 mm) imaging protocol using Gadolinium-based contrast agents has been utilized in a study to diagnose giant cell arteritis. The frontal branches of the superficial temporal artery and the occipital artery usually exhibit circumferential mural thickening and contrast enhancement on vessel wall imaging in patients with giant cell arteritis [12]. The contrast enhancement in the aneurysm wall may represents inflammatory process. Researchers performed a randomized controlled trial of statins to reduce the inflammation in vertebrobasilar dissecting aneurysm and found that statin may slow down the haemotoma progression [13].

In recent years, low field (< 1T) MR systems garnered attention in cardiovascular imaging, primarily motivated by the potential to improve cost-effectiveness. Investigators developed a simultaneous contrast-free 3D vascular lumen and wall imaging with efficient iT2prep-BOOST technique at low field of 0.55T [14]. Carotid vessel wall quantitative imaging is challenging due to B1 inhomogeneity and motion. Investigators implemented a free-running gradient echo (GRE) dual flip angle (2FA) technique for B1+ correction combined with a respiratory-resolved reconstruction. In the proposed technique, the T1 value overestimation in the carotid artery wall was successfully avoided by applying the 2FA technique and the measured values showed better repeatability.

2.2. Coronaries

Coronary MRA (CMRA) offers a promising radiation-free and contrast-free alternative to computed tomography coronary angiography (CTCA). However, it still suffers from long scan times and limited spatial resolution [15,16]. Over the past few years, several advances have been proposed to address these challenges, including self-navigated free-running methods [17–19] and image-based (iNAV) navigator approaches [20–22].

An extension of the iNAV-based technique to improve resolution from 0.9 mm^3 to 0.7 mm^3 was demonstrated in a cohort of patients with suspected coronary artery disease. This approach showed good agreement with CTCA for assessing coronary anatomy and stenosis, albeit with a relatively long scan time of 14 min. CMRA techniques typically employ diastolic ECG-triggering to reduce cardiac motion, with the timing and duration of triggering determined from the minimal motion of the proximal right coronary artery (RCA) as observed in a previously acquired cine image. However, determination of the timing and duration of triggering requires manual input and expertise. Recently an automatic approach based on deep learning has been developed to simplify planning and trigger delay setting and has been incorporated in the iNAV-based 3D whole-heart CMRA approach [23]. Furthermore, with the development of free-running 5D techniques [19], it was shown that the optimal cardiac phase for achieving the best image quality can be determined for each coronary segment, potentially improving diagnostic performance.

CMRA is usually performed without contrast agents, using T2 preparation pulses to enhance the contrast between blood and myocardium [24]. More recently Ferumoxytol enhanced CMRA has been investigated to improve coronary visualization by enhancing myocardium and fat signal suppression [25,26]. This approach was extended to Dixon encoding and evaluated in patients with chronic kidney disease, who are contraindicated for iodine contrast agents in CTCA. Promising results at 3T demonstrated excellent blood-pool/myocardium contrast. Another study demonstrated the feasibility of combining Ferumoxytol enhanced CMRA in T1 mapping for vasoreactivity testing in woman. However, Ferumoxytol is not currently suitable for evaluating first-pass perfusion or late gadolinium enhancement (LGE), potentially impacting the workflow and one-stop-shop potential of cardiac MRI exams.

A boost (bT1RESS) has been recently proposed for brain imaging to impart T1 weighting and suppress background signals [27,28]. Here bT1RESS was extended to obtain equilibrium phase CMRA with standard gadolinium-based contrast agents, prolonging the duration of blood pool contrast enhancement and showing excellent depiction of venous, arterial and cardiac anatomy.

The advancements presented at SMRA 2024 underscore the growing sophistication of CMRA and highlight the potential of both non-CE and CE approaches to continue moving forward toward high-resolution simplified CMRA in short and predictable scan times.

2.3. Cardiac beyond MRA

Cardiac imaging beyond MRA was an important focus of SMRA 2024, including a joint plenary session with SCMR and a hybrid educational and abstract session on cardiac and quantitative imaging. The plenary session focused on developments and pathways to move toward affordable and accessible CMR. The need for efficiency and value, balancing the cost and performance in CMR, was an important theme in this topic. The importance of not only optimizing workflows and shortening scan times, but most importantly reducing the total exam time to answer the clinical questions, was discussed. The importance of CMR for precision medicine and the need for awareness of the cofounders for quantification along the imaging pipeline were also highlighted. The potential of low-field MRI as a transformative tool for bridging gaps in healthcare accessibility was discussed, enabling broader adoption of cardiac MR imaging in resource-limited settings. Additionally, the theme of "Navigating Challenges: Maximizing Impact of MRA and CMR in Latin America" was included to reflect unique constraints and opportunities in the region. The need of having access to state of the art technology, protocols suited for most clinical scenarios, well-trained personnel as well as bringing international conferences to Latin America was highlighted.

Low-field MRI offers reduced cost, lower energy consumption, and compatibility with wider populations, thus making it ideal for increasing the global reach of cardiac MRI [29]. The ability of low-field cardiac MRI to provide good image quality with similar diagnostic value than 1.5T and 3T, has been demonstrated by several previous studies [30,31]. Most of these studies focus on conventional 2D sequences including cardiac cine, perfusion, and mapping. At SMRA 2024 several scientific abstracts highlighted advancements in low-field MRI, particularly for comprehensive quantitative mapping at 0.55T. This included the demonstration of T1, T2 and fat fraction (FF) cardiac MRF at 0.55T, showing good agreement with reference values in phantom and healthy subjects, despite the reduced signal to noise ratio and longer TRs required at low-field. Furthermore, a 3D whole-heart joint T1/T2/FF sequence and a T1/T1rho/T2 sequence for comprehensive myocardial tissue characterization were demonstrated at 0.55T by extending an image-navigator (iNAV) based approach [32] with dictionary matching.

Several studies have reported the clinical utility of MR myocardial perfusion for the evaluation of patients with known or suspected coronary artery disease [33,34]. Advances in myocardial perfusion include further development of quantitative myocardial perfusion MRI [35], via quantification of myocardial blood flow, to improve diagnosis accuracy; acquisition speed up to shorter scan time and/or improve resolution, as well as non-CE perfusion approaches, among many others. A temporal structured low-rank (tSLR) reconstruction technique for first-pass perfusion imaging was presented at SMRA 2024 that significantly enhanced image fidelity and myocardial blood flow quantification. This approach leverages average linear time- invariant dependencies during image reconstruction, thus implicitly incorporating pharmacokinetic modeling, outperforming current state of the art reconstruction.

Displacement encoding (DENSE) MRI encodes the displacement of the heart during cardiac motion and enables quantitative assessment of the myocardial contractile function [36,37]. Several studies have demonstrated high reproducibility of global and regional strain measurements using cine DENSE. At SMRA 2024 a study on cine DENSE MRI validated its reproducibility for strain measurements before and after gadolinium administration, supporting its integration into streamlined clinical workflows during the waiting period after contrast injection for late enhancement imaging.

MRI in patients with cardiac implantable electronic devices (CIED) is safe with appropriate protocols, however it has several challenges, including the presence of image artifacts due to off-resonance [38]. At SMRA 2024, a study using wideband MOLLI T1 applied two thresholding techniques in a wideband MOLLI dataset with a CIED present and evaluated fibrosis volumetric accuracy with respect to conventional phase-sensitive (PS) LGE without a CIED. The study showed good agreement in dense scar and overall enhanced tissue location and volume, but poor agreement in gray zone location and volume. Another study proposed a free-breathing wideband black-blood (BB) LGE method to improve myocardial scar detection in patients with CIED unable to hold their breath, successfully reducing CIED artifacts in all patients and allowing better scar detection with improved scar-blood contrast compared to wideband inversion recovery.

Together, these contributions reflect a concerted effort to make cardiac MR imaging more efficient, accessible, and accurate, and they are highlighting the joint efforts from both SMRA and SCMR communities.

2.4. Thoracic MRA

Non cardiac MRA in the chest is traditionally accomplished by high resolution CE MRA or alternatively by non-CE MRA, depending on the clinical situation [39,40]. Common clinical applications are the assessment of aortic aneurysms and dissections [41], congenital disease [42], vasculitis, central venous disease, and pulmonary embolisms [43,44].

One standard approach for assessing vessel lumens is the acquisition of a T1-weighted, first pass, high resolution CE MRA during a breath-hold. Such an acquisition can be ECG gated to minimize artifacts from cardiac motion and pulsatility, e.g. when imaging ascending aorta disease. In cases where dynamic information on vascular filling is of interest, e.g. in aortic dissections, time-resolved CE-MRA can provide supplemental diagnostic information. Meanwhile, imaging of vasculitis, the central veins, and pulmonary emboli is accomplished with a similar T1-weighted sequence but delayed after the first pass of the bolus.

Lowering of total gadolinium dose [45] can been achieved by newer gadolinium chelates [46], imaging at higher field strengths, and the use of deep learning reconstructions [47]. However, imaging beyond 3T becomes extraordinarily challenging in the chest. Alternatively, Ferumoxytol enhanced CMRA can be used, e.g. in pediatric patients [48], and for pulmonary embolism screening in pregnant women [49] as well as for imaging of central venous disease. A feasibility study for comprehensive vascular mapping with successive neck, chest, abdomen, and pelvis scans using Ferumoxytol for preoperative assessment of multi visceral transplantation was presented.

Non-CE MRA has applications in patients with contra indications to contrast agents, frequent follow ups, or when looking for additional information beyond vessel lumen [40,50,51]. 3D bSSFP sequences acquires images during free breathing and with ECG gating to provide bright blood signal from the T2/T1 weighting with high SNR, and whole chest coverage or targeted volumes with high spatial resolution for applications such as aortic, pulmonary artery, and congenital heart disease [39,51]. Strategies such as fat suppression and T2 preparation are used to increase the contrast between blood and surrounding tissues. Novel works on free breathing combined 3D bright and black-blood bSSFP imaging for combined lumen and vessel wall imaging across multiple respiratory phases at standard and low fields of 0.55T with an approach called iT2prep-BOOST imaging were introduced. Deep learning approaches were presented to improve 3D bright blood chest imaging by (1) deep learning supported compressed sensing reconstruction algorithms for better image quality and (2) automated segmentation of aortic lumens.

4D flow MRI has emerged as a powerful method to comprehensively capture vascular anatomy and hemodynamic function throughout the cardiac cycle over a large vascular region. Acquisition protocols and post-processing packages approved for clinical use are now commercially available and have facilitated clinical adaptation [52]. 4D flow is a very active research area with high interest in the chest, including congenital heart and aortic disease and exciting developments were presented in a dedicated session. Novel works were presented in dedicated sessions, including advances in 5D flow imaging (respiratory and cardiac resolved 3-directional flow imaging) which has evolved from feasibility demonstrations to intriguing studies of physiological patterns and the analyzing of flow energetics in congenital heart disease and arrhythmia resolved 5D flow MRI patterns in the left atrium in patients with atrial fibrillation. 4D and 5D flow analysis has been hampered by long acquisition and post-processing times and several AI works were presented that promise significant improvements in these regards. A deep learning approach to enable highly accelerated data sampling by k-pace subsampling and a reduction from 4 to 2 velocity direction encodings for each k-space line showed promising results with accelerations factors of up to 32. It was also shown in silico and in a small volunteer cohort that a previously introduced approach for deep learning to denoise and increase spatial resolution of 4D Flow MRI can be adopted to denoise and improve the temporal resolution. Several groups reported on the use of deep learning for streamlined workflows, including (1) fully automated analysis of aortic hemodynamics including vessel segmentation and plane placements for more rapid, robust, and reproducible quantitation, (2) the application of such methods for multi-site studies, (3) time resolved segmentation throughout the cardiac cycle from the 4D flow images, (4) automated velocity anti-aliasing by applying neural networks that enforce divergence free conditions, and (5) Physics-Informed Neural networks to non-invasively predict pressure gradients in aortic coarctations from the 4D flow data. A new concept was introduced where AI trained on 4D flow MRI data derives key hemodynamic parameters from CE MRA anatomical data alone.

2.5. Abdominal and pelvic MRA

Another important area of development is abdominopelvic MRA applications and value, including vessel wall MRA. Vessel wall MRA is most commonly employed for assessing inflammatory vasculopathy, followed by the evaluation of atherosclerosis, as highlighted in a recent survey study [53]. This is also applicable to abdominopelvic vessel wall MRA for the evaluation of large artery vasculitis, specifically Takayasu arteritis and other aortitis processes [54]. The applications and potential pitfalls of MRA and vessel wall MRA of the body were highlighted during the conference, providing examples of large artery vasculitis and the technique's ability to show non-stenotic abnormalities not otherwise seen on computed tomography angiography (CTA) or catheter angiography.

Dynamic-contrast enhanced (DCE) perfusion imaging using Ferumoxytol was another area of focus, particularly for characterizing placental perfusion at the maternal fetal interface [55]. One study investigated Ferumoxytol DCE perfusion in rhesus macaque placentas with thrombosis in the intervillous space, correlating imaging findings with histology. Regions of hypoperfusion on imaging matched histological thrombosis, illustrating that pathological changes can be detected noninvasively on placental Ferumoxytol DCE [56]. Ferumoxytol DCE perfusion also showed longitudinal perfusion alterations in Zika-infected placentas, corresponding to the degree of injury determined histologically [57].

4D flow imaging in the portal venous system was a key topic. Setting appropriate velocity-encoding (Venc) parameters remains a challenge, as incorrect settings can result in inaccurate velocity assessments or reduced velocity-to-noise ratio (VNR) [58]. A study comparing low, medium, and high Venc settings concluded that medium Venc provided the best correlation with high Venc acquisitions while preserving VNR. Alterations in 4D flow metrics, such as the helicity index, were also observed in post-Fontan patients compared to controls. Another study highlighted AI-based auto-segmentation of balanced steady-state free precession (bSSFP) images, which significantly reduced analysis time while improving reproducibility and agreement.

Low-field MRI applications are also emerging for abdominopelvic imaging. Quantitative liver mapping using 3D water, T1, T2 and proton-density fat fraction mapping using 0.55T MRI was presented, showing good image quality and quantitative value agreement with published values at 0.55T [59].

Full-body Ferumoxytol-enhanced steady-state MRA demonstrated good image quality and excellent inter-reader agreement, providing a feasible approach for preoperative workup.

This technique enables simultaneous arterial and venous phase assessment in a single 11-minute acquisition, highlighting its efficiency and potential clinical utility.

Innovative quantitative non-CE renal imaging techniques using Time-SLIP (spatial labeling inversion pulse) MRA were also discussed. Advances such as motion-robust radial stack-of-stars sequences and conjugate gradient deep learning reconstruction (CG-Recon) for ultrashort TE Time-SLIP renal MRA showed promise. CG-Recon improved image quality and branch artery visualization compared to raw datasets while achieving 33% acceleration in scan time without compromising image quality. This technique fosters a pathway for reduced scan time while maintaining renal MRA image quality, potentially improving technique clinical penetrance.

2.6. Peripheral MRA

CE and non-CE peripheral MRA techniques are widely used in clinical practice [60], providing comparable image quality and clinical evaluation to CTA techniques. Advancements in the field to reduce scan times, improve spatial resolution and reduce the reliance on gadolinium-based contrast agents for extremity MRA, were discussed during the conference.

One innovative approach combined velocity-selective arterial-spin labeling with spatially-selective inversion and T2 preparation pulses to suppress venous and muscle signal. This method demonstrated improved artifact removal and enhanced background tissue suppression compared to velocity-selective techniques alone, along with significantly higher quantitative arterial signal-to-noise ratio (SNR). Another study introduced non-subtraction fresh-blood and fast-field echo techniques, achieving suppression of venous, background, and fat signals while maintaining excellent image quality.

Peripheral MRA was also discussed as a crucial tool for preoperative evaluation in autologous perforator flap reconstruction. This technique provides high-resolution imaging of vascular anatomy, including perforator branches, and has been shown to improve post-surgical outcomes, reduce operative times, and minimize surgical complications [61].

Current diagnostic algorithms for assessing the likelihood of successful revascularization in peripheral atherosclerotic ischemia remain limited, with a 15–30% technical failure rate for revascularization in chronic limb-threatening ischemia [62,63]. Presentations at the SMRA 2024 showed ultrashort TE MRI, bSSFP, and multi-contrast 9.4T MRI protocols could differentiate between calcified or collagen-rich “hard” plaque and “soft” plaque. “Hard” plaque was associated with significantly higher long-term recanalization rates and was the only factor to predict immediate technical failure compared to conventional clinical scoring systems. Multi-contrast 9.4T MR imaging features of peripheral artery atherosclerosis was used to develop a variational autoencoder that showed good agreement with histological differentiation between “hard” and “soft” plaque composition, and significant association between AI-based and histology-based determination of plaque interventional crossability.

MRA/MRI techniques can provide additional value in assessment of deep venous thrombosis (DVT) composition. An ex vivo study evaluated quantitative T1, T2, and T2* mapping of DVTs in relation to histological findings, providing valuable insights into thrombus characterization.

2.7. CE MRA

A strong focus on designing, optimizing, and validating cardiovascular MRA and MRI methods that exploit and maximize endogenous contrast dominated much of SMRA 2024. This reflects a trend that has gained momentum over the past decade. The motivation driving this focus is clear: the growing demand for safe, accessible, and affordable diagnostic imaging solutions.

Despite this emphasis on endogenous contrast, research into exogenous CE-MRA and CE-MRI continues to yield significant innovations across several domains, including improvements in sequence design for CE-MRA utilizing existing contrast agents, characterization of novel gadolinium-based contrast agents, and the use of non-gadolinium-based contrast agents.

The SMRA 2024 conference showcased several key developments in these areas. A notable innovation involved gadopiclenol [64], a Gadolinium-based contrast agent recently approved for clinical use. A study reporting relaxivity properties of gadopiclenol in human blood and plasma was presented at SMRA 2024. Gadopiclenol is characterized by higher relaxivities than any other currently available gadolinium-based contrast agent. However, optimizing contrast administration and image acquisition protocols for CE-MRA with gadopiclenol will require more detailed analysis of pronounced R2* effects on water exchange.

As mentioned in the previous sessions for different applications, the use of Ferumoxytol continues to attract much interest and generates promising results, particularly in pediatric applications and in patients with contraindications to gadolinium-based contrast agents, such as patients with compromised kidney function [65,66]. An interesting novel application that combines Ferumoxytol enhanced MRA and MRI presented at SMRA 2024 involved the assessment of myocardial vascular reactivity by measuring the difference between Ferumoxytol-shortening of myocardial T1 at rest and at peak regadenoson-induced vasodilator stress [67], following the acquisition of 3D Ferumoxytol-enhanced 3D coronary MRA.

Across the board, CE-MRA and CE-MRI continue to benefit from recent developments in the design of ultrafast, free running, multi-contrast sequences and AI enhanced acquisition and reconstruction methods, with improved delineation of vascular anatomy, including ultra-high-resolution CE-MRA for the imaging and characterization of vascular walls and plaques.

Furthermore, exogenous contrast administration allows comprehensive quantitative multi-parametric tissue characterization, (i.e. extracellular volume fraction, microvascular perfusion, vessel permeability, fractional blood volume). Measurement of macroscopic parameters such as blood flow and tissue strain can also be improved by a targeted and optimized administration of exogenous contrast agents. When combined with high-quality CE-MRA, multi-parametric quantitative CE-MRI could provide a comprehensive morphological and functional assessment of the cardiovascular system, unparalleled by any other imaging modality.

SMRA 2024 demonstrated that the creative tension between endogenous and exogenous contrast acts as a catalyst for development of cutting-edge research solutions in both camps. A pragmatic design of efficient diagnostic protocols will continue to rely on the availability of optimized and validated batteries of both CE and endogenous contrast methods.

2.8. New technologies and AI in MRA

SMRA 2024 featured cutting-edge advancements in MRA, emphasizing the role of AI and technological innovations in improving imaging [68]. This included an educational overview of non-CE MRA techniques that eliminate the need for contrast agents and an overview with insights on how AI is transforming MRA and CMR, highlighting applications in image reconstruction, workflow automation, and diagnostic reporting. These developments not only increase efficiency but also ensure reliable imaging quality, addressing bottlenecks in traditional practice. The integration of ultra-high-field scanners with AI for intracranial imaging was also discussed, showing how this combination improves resolution and sensitivity, enabling the detection of complex brain abnormalities.

Several scientific proffered abstracts introduced advances in new technologies and AI-base solutions for MRA and CMR. A study introduced a motion-corrected deep learning framework for super-resolution 3D whole-heart MRI, achieving isotropic high-resolution imaging with faster acquisition times and greater computational efficiency. A predoctoral Potchen-Passariello award-winning talk was presented on unsupervised cardiac cine reconstruction using implicit neural representations to eliminate the need for large training datasets. Furthermore, a deep learning framework for single-heartbeat cine imaging, delivering rapid and accurate cardiac images in just 40 s was proposed, paving the way for single-breath-hold acquisitions that improve patient experience and diagnostic reliability. Regarding flow, a pipeline for automatic labeling of intracranial arteries in 4D flow MRI, streamlining post-processing workflows and reducing the time and effort required for cerebrovascular analysis was presented. In the field of CMR fingerprinting, a sequence for low-field imaging at 0.55T was proposed, achieving reproducible mapping of T1, T2, and fat fraction, which holds significant potential for affordable quantitative imaging. Rapid-fire power pitches also showcased a wide array of innovative contributions. Advances in image reconstruction included meta-learning for real-time cine-MRI reconstruction, motion-compensated techniques for pediatric congenital heart imaging, and segmentation methods for joint T1/T2 mapping. AI applications, such as neural networks for cardiac strain estimation and super-resolution for cerebrovascular imaging, emphasized improved accuracy, reproducibility, and efficiency. Methodological innovations included new MRA techniques for better vascular imaging and the use of extracellular volume maps to assess extravascular lung water, with promising implications for pulmonary diagnostics. Collectively, these contributions highlighted significant advancements in imaging speed, capability, and accessibility.

2.9. Accessible and affordable MRA and CMRA

SMRA 2024 highlighted efforts to make MRA and CMR more accessible globally by addressing cost and technological barriers with innovative approaches, including a joint plenary session between SMRA and SCMR. In the Martin Prince Lecture, Dr. Miyazaki presented strategies to expand access to MR angiography, emphasizing non-CE coronary MRA. Her groundbreaking work with zigzag fan-shaped centric k-space trajectories and deep learning reconstruction enables high-quality imaging in under five minutes [69], significantly reducing scan times and improving feasibility for resource-constrained settings. The critical balance between cost and performance in cardiac MR imaging was discussed in one of the plenary talks, showing how AI can reduce costs by automating workflows, improving image reconstruction, and enhancing operational efficiency. These advancements pave the way for wider adoption without sacrificing diagnostic quality. Another plenary talk focused on the transformative potential of low-field MRI [29], demonstrating its affordability and adaptability for underserved rural areas. These systems, which are cheaper and simpler to operate than traditional high-field systems, can provide high-quality imaging in low-resource settings, bridging critical gaps in healthcare access. Finally, a third plenary talk explored challenges specific to Latin America, including disparities in infrastructure, limited access to advanced equipment, and the shortage of trained professionals. Together, the speakers emphasized a collective push for affordable, innovative MR technologies to ensure equitable imaging access and improve outcomes for diverse populations worldwide.

2.10. Interventional MRI meets MRA

Interventional MRI applications were reviewed in a joint session combining MR physics and advances in imaging with cardiology and neurointerventional translational applications. Innovations in MRA to guide interventional applications were presented, followed by advances in real-time MR imaging enabling catheter tracking and intraprocedural guidance. Applications of interventional MRA and cardiac MRI in risk-stratifying congenital heart diseases and guiding intervention were reviewed, highlighting how interventional MR is currently used in clinical practice. The role of pre-procedural and post-procedural MRA with 4D flow MRI in a busy neurointerventional practice was detailed, including the need for outcomes data to support broader use in clinical practice. From the discussion that ensued, it is clear that more centers are utilizing both pre- and post-procedural MR and MRA to assess treatment effects and risk-stratify patients. Another area of clinical application is MR lymphangiography (MRL) [70]. Although both non-contrast and CE methods have been used, intranodal MRL has significantly improved diagnosis of complex veno-lymphatic abnormalities, enabling treatment planning while offering an attractive, efficient technique to risk-stratify congenital heart disease patients for definitive therapy [71].

Several abstracts were presented highlighting the role of pre-interventional MRI imaging to guide a subsequent intervention. Venous thrombus characterization using a T1-weighted BB technique [72] was predictive of the risk of acute pulmonary embolism in a cohort of 62 patients. Additionally, plaque composition determined by an MRI-histology approach leveraging ultrashort echo time imaging and steady-state free precession contrasts demonstrated superior prediction for successful catheter-directed revascularization compared to common angiographic scoring systems [73]. Early work from ex-vivo MR imaging of deep vein thrombus with histologic correlation demonstrated promising results towards in-vivo characterization for fibrin content, which may drive patient selection for thrombolysis vs primary stenting.

2.11. Early career highlights

The early career committee organized a range of activities during SMRA 2024, providing ample opportunities to network and foster growth and collaboration among early career researchers and seasoned experts in magnetic resonance angiography.

The inaugural class of SMRA junior fellows featured Anastasia Fotaki, MD, PhD, (King's College London), Judit Csőre, MD, PhD, (Semmelweis University), and Lexiaozi Fan, PhD (Northwestern University). Dr. Fotaki and Dr. Csőre attended the conference and delivered talks reflecting on their training journeys, importance of mentoring and support throughout their career, as well as their current research areas. Dr. Fotaki's current research focuses on clinical validation of advanced cardiac and coronary imaging in congenital heart disease patients [74]. Dr. Csőre currently researches AI-guided MRI analysis of peripheral arterial disease lesions, aimed at assessing crossability and informing device selection [75]. Although Dr. Fan was not present, her current research on developing advanced pulse sequence and deep learning-based image reconstruction techniques for cardiac imaging [76] was highlighted as an innovative contribution to the field.

Career development talks were delivered by Prof. Roderick Pettigrew from Texas A&M University and Prof. Yingkun Guo from West China Second Hospital. Dr Pettigrew highlighted his efforts in integrating engineering and medicine into a novel single "physicianeer" training program at Texas A&M, which required collaboration between medicine and engineering departments. The intent of this program is to blur the lines between engineering and medicine schools of thought to cultivate holistic problem-solving approaches. Dr. Guo discussed his experience in organizing a successful training program for junior and senior researchers in a collaborative lab environment. He further emphasized how innovative research projects led by junior trainees lead to future publications and grant proposals that propel many scientific careers.

The early career activities also included a lively fireside chat with seasoned experts in the area. The panelists answered questions about their initial interactions with cardiovascular MRI and the SMRA and described their backgrounds in academia and industry. In this session, audience members asked questions about fostering collaboration between scientists and clinicians, key skill sets for trainees to develop, and motivation for trainees to be involved in MRA research.

Overall, the early career activities at SMRA provided a platform to celebrate outstanding achievements, share career guidance, and inspire the next generation of scientists in the field of magnetic resonance angiography.

2.12. Vision for the future

Cardiovascular MR has long been a driver for advances in MR hardware as well as data acquisition and image reconstruction to meet its unique demands such as rapid dynamic 3D imaging in the presence of cardiac and respiratory motion, which have ultimately benefitted the MRI field as a whole. Cutting-edge cardiovascular MR techniques including CE and non-CE MRA methods, dynamic and time-resolved 3D imaging, and quantitative cardiac MR methods including 4D flow MRI are now available from all vendors and supported by a wide array of advanced post-processing solutions for use in clinical practice across the globe. The SMRA is committed to continue to advance the techniques, clinical applications, and value of cardiovascular MR imaging to improve patient care.

Despite the technical maturity of these methods, the growth rate of MRA has slowed relative to CTA across body regions. This is seen in US Medicare trends for peripheral arterial disease specifically [84,85] and across subspecialties [86]. This may be partially explained because MRA is slower and considered more difficult to acquire and analyze than CTA. Additionally, CTA may be more readily available than MRA and referring specialties may be less comfortable relying on MRA as a primary diagnostic modality. Furthermore, the inclusion of MRA as an attractive diagnostic imaging technique in patients with calcified lesions indicates its current clinical value and is a call to the society to close gaps in training for technologists and clinicians to ensure that patients have access to this modality around the world.

The development of significantly faster, motion-robust imaging sequences, AI-driven image reconstruction, and standardized acquisition protocols are key advancements that can further enhance MRA's clinical adoption by streamlining workflows and reducing exam times. MRA can strengthen its role as the first-line imaging modality in vascular diagnostics. Continued collaboration among researchers, clinicians, and industry partners is essential to refine MRA's capabilities, ensuring that its unique benefits—such as superior vessel wall imaging and quantitative hemodynamic assessments—translate into broader clinical impact. The SMRA will continue its efforts to bridge the training gap through targeted educational efforts such as state-of-the-art reviews [40,77–81], statement papers [82], webinars, and inclusion of trainees and early-career scientists and clinicians to shape the society and annual meeting contents. This is a call to action for MR physicists, MR technologists, radiologists, and cardiologists involved in cardiovascular MR to advocate for its use where it offers advantages over other modalities and to streamline imaging protocols to offer high value and robust ease of use in order to ensure that patients have access to this essential technology in clinical scenarios.

The field of MRA continues to evolve. The exploration and integration of AI into all aspects of medicine, including cardiovascular imaging and workflows [83] has been an is continuing to advance at an unprecedented pace. The drive for truly quantitative cardiovascular MR that is reproducible across scanners and sites is a cornerstone for the concept of personalized medicine and remains an important yet challenging goal. 4D flow MRI has matured but has not reached its full potential in clinical practice yet and would benefit from multi-site, prospective studies and demonstrating clinical benefits. Other venues currently explored include a focus on value-based MRA with accelerated scans, more targeted exams, and the use of low field scanners for cost reductions and other benefits such as interventional imaging.

CE approaches also present exciting opportunities. In particular, Ferumoxytol may significantly expand the role of MRA in vascular diagnostics. Its unique properties enable high-resolution, steady-state imaging, opening avenues for more comprehensive vascular assessments. Research efforts are increasingly focused on optimizing imaging protocols, exploring novel applications in inflammation and macrophage imaging, and integrating it into emerging quantitative techniques. Further studies, including multi-center trials and regulatory advancements in those countries where is yet not available, will be key to establishing standardized protocols and broadening its clinical adoption, ensuring that patients benefit from its full potential in both routine and advanced MRA applications.

We are looking forward to the 37th SMRA meeting in Budapest, Hungary (August 21–24, 2025; Theme: *MRA innovations flowing through time*) to again provide a stimulating forum for trainees, basic and clinician scientists, clinicians, clinical staff, and industry interested in MR angiography techniques. The common goal is to exchange scientific ideas, share the latest developments in research and clinical findings relate to MRA, to build connections, pool knowledge, and educate each other in order to accelerate the refinement of MRA technology and to apply it in clinical practice.

Author contributions

Xihai Zhao: Writing – review & editing, Writing – original draft. **Jeremy D. Collins:** Writing – review & editing, Writing – original draft. **Yin Guo:** Writing – review & editing, Writing – original draft. **Aleksandra Radjenovic:** Writing – review & editing, Writing – original draft. **René M. Botnar:** Writing – review & editing, Writing – original draft, Conceptualization. **Oliver Wieben:** Writing – review & editing, Writing – original draft. **Anthony Christodoulou:** Writing – review & editing, Writing – original draft. **Calder D. Sheagren:** Writing – review & editing, Writing – original draft. **Claudia Prieto:** Writing – review & editing, Writing – original draft, Conceptualization. **Mahmud Mossa-Basha:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Finn JP, Nguyen KL, Hu P. Ferumoxytol vs. gadolinium agents for contrast-enhanced MRI: thoughts on evolving indications, risks, and benefits. J Magn Reson Imaging 2017;46(3):919–23.
[2] Si G, Du Y, Tang P, Ma G, Jia Z, Zhou X, et al. Unveiling the next generation of MRI contrast agents: current insights and perspectives on ferumoxytol-enhanced MRI. Natl Sci Rev 2024;11(5):nwae057.
[3] Zhou Z, Li R, Zhao X, He L, Wang X, Wang J, et al. Evaluation of 3D multi-contrast joint intra- and extracranial vessel wall cardiovascular magnetic resonance. J Cardiovasc Magn Reson 2015;17(1):41.
[4] Jia S, Zhang L, Ren L, Qi Y, Ly J, Zhang N, et al. Joint intracranial and carotid vessel wall imaging in 5 min using compressed sensing accelerated DANTE-SPACE. Eur Radiol 2020;30(1):119–27.
[5] Xu Y, Yuan C, Zhou Z, He L, Mi D, Li R, et al. Co-existing intracranial and extracranial carotid artery atherosclerotic plaques and recurrent stroke risk: a three-dimensional multicontrast cardiovascular magnetic resonance study. J Cardiovasc Magn Reson 2016;18(1):90.
[6] Li J, Li D, Yang D, Huo R, Chen X, Xu Y, et al. Co-existing cerebrovascular atherosclerosis predicts subsequent vascular event: a multi-contrast cardiovascular magnetic resonance imaging study. J Cardiovasc Magn Reson 2020;22(1):4.
[7] Wu G, Zhu C, Wang H, Fu D, Lu X, Cao C, et al. Co-existing intracranial and extracranial carotid atherosclerosis predicts large-artery atherosclerosis stroke recurrence: a single-center prospective study utilizing combined head-and-neck vessel wall imaging. Eur Radiol 2023;33(10):6970–80.
[8] Wang Y, Liu X, Wang J, Wang Y, Qi H, Kong X, et al. Simultaneous T1, T2, and T2* mapping of carotid plaque: the SIMPLE* technique. Radiology 2023;307(3):e222061.
[9] Qiao H, Yang Q, Huo R, Han H, Ning Z, Shen R, et al. Reliability and value of 3D sequential quantitative T(1) -T(2) -T(2) * MAppings (SQUMA) MR multi-parametric imaging in characterizing carotid artery atherosclerosis. J Magn Reson Imaging 2023;57(5):1376–89.
[10] Qi H, Sun J, Qiao H, Zhao X, Guo R, Balu N, et al. Simultaneous T(1) and T(2) mapping of the carotid plaque (SIMPLE) with T(2) and inversion recovery prepared 3D radial imaging. Magn Reson Med 2018;80(6):2598–608.
[11] Tang J, Heidari Pahlavian S, Joe E, Gamez MT, Zhao T, Ma SJ, et al. Assessment of arterial pulsatility of cerebral perforating arteries using 7T high-resolution dual-VENC phase-contrast MRI. Magn Reson Med 2024;92(2):605–17.
[12] Froehlich M, Guggenberger KV, Vogt M, Mihatsch PW, Dalla Torre G, Werner RA, et al. MRVAS-introducing a standardized magnetic resonance scoring system for

assessing the extent of inflammatory burden in giant cell arteritis. Rheumatology 2024;63(10):2781–90.
[13] Turhon M, Kang H, Huang J, Li M, Liu J, Zhang Y, et al. Atorvastatin for unruptured intracranial vertebrobasilar dissecting aneurysm (ATREAT-VBD): protocol for a randomised, double-blind, blank-controlled trial. BMJ Open 2022;12(4):e059616.
[14] Munoz C, Fotaki A, Hua A, Hajhosseiny R, Kunze KP, Ismail TF, et al. Simultaneous highly efficient contrast-free lumen and vessel wall MR imaging for anatomical assessment of aortic disease. J Magn Reson Imaging 2023;58(4):1110–22.
[15] Kato S, Azuma M, Nakayama N, Fukui K, Ito M, Saito N, et al. Diagnostic accuracy of whole heart coronary magnetic resonance angiography: a systematic review and meta-analysis. J Cardiovasc Magn Reson 2023;25(1):36.
[16] Hajhosseiny R, Bustin A, Munoz C, Rashid I, Cruz G, Manning WJ, et al. Coronary magnetic resonance angiography. Tech Innov Lead Us Promised Land? JACC Cardiovasc Imaging 2020;13(12):2653–72.
[17] Holtackers RJ, Stuber M. Free-running cardiac and respiratory motion-resolved imaging: a paradigm shift for managing motion in cardiac MRI? Diagnostics (Basel). 2024;14(17):1946.
[18] Stehning C, Bornert P, Nehrke K, Eggers H, Stuber M. Free-breathing whole-heart coronary MRA with 3D radial SSFP and self-navigated image reconstruction. Magn Reson Med 2005;54(2):476–80.
[19] Di Sopra L, Piccini D, Coppo S, Stuber M, Yerly J. An automated approach to fully self-gated free-running cardiac and respiratory motion-resolved 5D whole-heart MRI. Magn Reson Med 2019;82(6):2118–32.
[20] Henningsson M, Koken P, Stehning C, Razavi R, Prieto C, Botnar RM. Whole-heart coronary MR angiography with 2D self-navigated image reconstruction. Magn Reson Med 2012;67(2):437–45.
[21] Cruz G, Atkinson D, Henningsson M, Botnar RM, Prieto C. Highly efficient nonrigid motion-corrected 3D whole-heart coronary vessel wall imaging. Magn Reson Med 2017;77(5):1894–908.
[22] Hajhosseiny R, Rashid I, Bustin A, Munoz C, Cruz G, Nazir MS, et al. Clinical comparison of sub-mm high-resolution non-contrast coronary CMR angiography against coronary CT angiography in patients with low-intermediate risk of coronary artery disease: a single center trial. J Cardiovasc Magn Reson 2021;23(1):57.
[23] Wood G, Pedersen AU, Kunze KP, Neji R, Hajhosseiny R, Wetzl J, et al. Automated detection of cardiac rest period for trigger delay calculation for image-based navigator coronary magnetic resonance angiography. J Cardiovasc Magn Reson 2023;25(1):52.
[24] Botnar RM, Stuber M, Danias PG, Kissinger KV, Manning WJ. Improved coronary artery definition with T2-weighted, free-breathing, three-dimensional coronary MRA. Circulation 1999;99(24):3139–48.
[25] Dong Z, Si G, Zhu X, Li C, Hua R, Teng J, et al. Diagnostic performance and safety of a novel ferumoxytol-enhanced coronary magnetic resonance angiography. Circ Cardiovasc Imaging 2023;16(7):580–90.
[26] Roy CW, Di Sopra L, Whitehead KK, Piccini D, Yerly J, Heerfordt J, et al. Free-running cardiac and respiratory motion-resolved 5D whole-heart coronary cardiovascular magnetic resonance angiography in pediatric cardiac patients using ferumoxytol. J Cardiovasc Magn Reson 2022;24(1):39.
[27] Edelman RR, Ozturk O, Pursnani A, Balasubramanian S, Leloudas N, Koktzoglou I. Equilibrium phase contrast-enhanced magnetic resonance angiography of the thoracic aorta and heart using balanced T1 relaxation-enhanced steady-state. J Cardiovasc Magn Reson 2024;26(2):101046.
[28] Edelman R, Leloudas N, Pang J, Bailes J, Merrell R, Koktzoglou I. Twofold improved tumor-to-brain contrast using a novel T1 relaxation-enhanced steady-state (T(1) RESS) MRI technique. Sci Adv 2020;6(44).
[29] Campbell-Washburn AE, Varghese J, Nayak KS, Ramasawmy R, Simonetti OP. Cardiac MRI at low field strengths. J Magn Reson Imaging 2024;59(2):412–30.
[30] Bandettini WP, Shanbhag SM, Mancini C, McGuirt DR, Kellman P, Xue H, et al. A comparison of cine CMR imaging at 0.55 T and 1.5 T. J Cardiovasc Magn Reson 2020;22(1):37.
[31] Varghese J, Jin N, Giese D, Chen C, Liu Y, Pan Y, et al. Building a comprehensive cardiovascular magnetic resonance exam on a commercial 0.55 T system: a pictorial essay on potential applications. Front Cardiovasc Med 2023;10:1120982.
[32] Milotta G, Bustin A, Jaubert O, Neji R, Prieto C, Botnar RM. 3D whole-heart isotropic-resolution motion-compensated joint T(1) /T(2) mapping and water/fat imaging. Magn Reson Med 2020;84(6):3009–26.
[33] Nagel E, Greenwood JP, McCann GP, Bettencourt N, Shah AM, Hussain ST, et al. Magnetic Resonance Perfusion or Fractional Flow Reserve in Coronary Disease. N Engl J Med 2019;380(25):2418–28.
[34] Greenwood JP, Maredia N, Younger JF, Brown JM, Nixon J, Everett CC, et al. Cardiovascular magnetic resonance and single-photon emission computed tomography for diagnosis of coronary heart disease (CE-MARC): a prospective trial. Lancet 2012;379(9814):453–60.
[35] Knott KD, Camaioni C, Ramasamy A, Augusto JA, Bhuva AN, Xue H, et al. Quantitative myocardial perfusion in coronary artery disease: a perfusion mapping study. J Magn Reson Imaging 2019;50(3):756–62.
[36] Mangion K, Carrick D, Clerfond G, Rush C, McComb C, Oldroyd KG, et al. Predictors of segmental myocardial functional recovery in patients after an acute ST-Elevation myocardial infarction. Eur J Radio 2019;112:121–9.
[37] Auger DA, Bilchick KC, Gonzalez JA, Cui SX, Holmes JW, Kramer CM, et al. Imaging left-ventricular mechanical activation in heart failure patients using cine DENSE MRI: validation and implications for cardiac resynchronization therapy. J Magn Reson Imaging 2017;46(3):887–96.
[38] Lanz H, Strauss K, Hopler J, Kraft M, Hoffmann S, Binzenhofer L, et al. Safety of magnetic resonance imaging in patients with cardiac implantable electronic devices. J Cardiovasc Dev Dis 2024;11(10):313.
[39] Kocaoglu M, Pednekar A, Fleck RJ, Dillman JR. Cardiothoracic magnetic resonance angiography. Curr Probl Diagn Radio 2024;53(1):154–65.
[40] Francois CJ, Hecht EM, Roditi G, Finn JP. MR angiography series: noncardiac chest MR angiography. Radiographics 2022;42(2):E48–9. E48-E9.
[41] Expert Panels on Vascular I, Interventional R, Bonci G, Steigner ML, Hanley M, Braun AR, et al. ACR appropriateness criteria((R)) thoracic aorta interventional planning and follow-up. J Am Coll Radio 2017;14(11S):S570–83. S570-S83.
[42] Baumgartner H, De Backer J, Babu-Narayan SV, Budts W, Chessa M, Diller GP, et al. 2020 ESC Guidelines for the management of adult congenital heart disease. Eur Heart J 2021;42(6):563–645.
[43] Garg I, Grist TM, Nagpal P. MR angiography for aortic diseases. Magn Reson Imaging Clin N Am 2023;31(3):373–94.
[44] Bergmann LL, Ackman JB, Starekova J, Moeller A, Reeder S, Nagle SK, et al. MR angiography of pulmonary vasculature. Magn Reson Imaging Clin N Am 2023;31(3):475–91.
[45] Nael K, Moriarty JM, Finn JP. Low dose CE-MRA. Eur J Radio 2011;80(1):2–8.
[46] Iyad N, Alkhatib MSA, Hjouj SG. M. Gadolinium contrast agents- challenges and opportunities of a multidisciplinary approach: literature review. Eur J Radio Open 2023;11:100503.
[47] Montalt-Tordera J, Quail M, Steeden JA, Muthurangu V. Reducing contrast agent dose in cardiovascular MR angiography with deep learning. J Magn Reson Imaging 2021;54(3):795–805.
[48] Nguyen KL, Ghosh RM, Griffin LM, Yoshida T, Bedayat A, Rigsby CK, et al. Four-dimensional multiphase steady-state MRI with ferumoxytol enhancement: early multicenter feasibility in pediatric congenital heart disease. Radiology 2021;300(1):162–73.
[49] Starekova J, Nagle SK, Schiebler ML, Reeder SB, Meduri VN. Pulmonary MRA during pregnancy: early experience with ferumoxytol. J Magn Reson Imaging 2023;57(6):1815–8.
[50] Panda A, Francois CJ, Bookwalter CA, Chaturvedi A, Collins JD, Leiner T, et al. Non-contrast magnetic resonance angiography: techniques, principles, and applications. Magn Reson Imaging Clin N Am 2023;31(3):337–60.
[51] Gumus KZ, Virarkar M, Miyazaki M, Francois CJ, Kee-Sampson J, Gopireddy DR. Non-contrast MR angiography: physical principles and clinical applications in chest, abdomen and pelvis imaging. Abdom Radiol 2024;50(1):453–66.
[52] Bissell MM, Raimondi F, Ait Ali L, Allen BD, Barker AJ, Bolger A, et al. 4D Flow cardiovascular magnetic resonance consensus statement: 2023 update. J Cardiovasc Magn Reson 2023;25(1):40.
[53] Mossa-Basha M, Yuan C, Wasserman BA, Mikulis DJ, Hatsukami TS, Balu N, et al. Survey of the American society of neuroradiology membership on the use and value of extracranial carotid vessel wall MRI. AJNR Am J Neuroradiol 2022;43(12):1756–61.
[54] Romero-Sanchez G, Dabiri M, Mossa-Basha M. Primary large vessel vasculitis: takayasu arteritis and giant cell arteritis. Neuroimaging Clin N Am 2024;34(1):53–65.
[55] Badachhape AA, Devkota L, Stupin IV, Sarkar P, Srivastava M, Tanifum EA, et al. Nanoparticle contrast-enhanced T1-mapping enables estimation of placental fractional blood volume in a pregnant mouse model. Sci Rep 2019;9(1):18707.
[56] Chen R, Seiter D, Keding LT, Vazquez J, Antony KM, Simmons HA, et al. Cotyledon-specific flow evaluation of rhesus macaque placental injury using ferumoxytol dynamic contrast-enhanced MRI. J Magn Reson Imaging 2024;60(5):2196–204.
[57] Seiter DP, Nguyen SM, Morgan TK, Mao L, Dudley DM, O'Connor DH, et al. Ferumoxytol dynamic contrast enhanced magnetic resonance imaging identifies altered placental cotyledon perfusion in rhesus macaques. Dagger Biol Reprod 2022;107(6):1517–27.
[58] Motosugi U, Roldan-Alzate A, Bannas P, Said A, Kelly S, Zea R, et al. Four-dimensional Flow MRI as a marker for risk stratification of gastroesophageal varices in patients with liver cirrhosis. Radiology 2019;290(1):101–7.
[59] Tripp DP, Kunze KP, Crabb MG, Prieto C, Neji R, Botnar RM. Simultaneous 3D T1, T2, and fat-signal-fraction mapping with respiratory-motion correction for comprehensive liver tissue characterization at 0.55. T Magn Reson Med 2024;92(6):2433–46.
[60] Leiner T, Carr JC. Noninvasive angiography of peripheral arteries. In: Hodler J, Kubik-Huch RA, von Schulthess GK, editors. Diseases of the Chest, Breast, Heart and Vessels 2019-2022: Diagnostic and Interventional Imaging. Cham (CH): IDKD Springer Series; 2019. p. 223–38.
[61] Thimmappa ND. MRA for preoperative planning and postoperative management of perforator flap surgeries: a review. J Magn Reson Imaging 2024;59(3):797–811.
[62] Bradbury AW, Moakes CA, Popplewell M, Meecham L, Bate GR, Kelly L, et al. A vein bypass first versus a best endovascular treatment first revascularisation strategy for patients with chronic limb threatening ischaemia who required an infra-popliteal, with or without an additional more proximal infra-inguinal revascularisation procedure to restore limb perfusion (BASIL-2): an open-label, randomised, multicentre, phase 3 trial. Lancet 2023;401(10390):1798–809.
[63] Farber A, Menard MT, Conte MS, Kaufman JA, Powell RJ, Choudhry NK, et al. Surgery or endovascular therapy for chronic limb-threatening ischemia. N Engl J Med 2022;387(25):2305–16.
[64] Robic C, Port M, Rousseaux O, Louguet S, Fretellier N, Catoen S, et al. Physicochemical and pharmacokinetic profiles of gadopiclenol: a new macrocyclic gadolinium chelate with high T1 relaxivity. Invest Radio 2019;54(8):475–84.
[65] Hope MD, Hope TA, Zhu C, Faraji F, Haraldsson H, Ordovas KG, et al. Vascular imaging with ferumoxytol as a contrast agent. AJR Am J Roentgenol 2015;205(3):W366–73.
[66] Nguyen KL, Yoshida T, Kathuria-Prakash N, Zaki IH, Varallyay CG, Semple SI, et al. Multicenter safety and practice for off-label diagnostic use of ferumoxytol in MRI. Radiology 2019;293(3):554–64.
[67] Colbert CM, Le AH, Shao J, Currier JW, Ajijola OA, Hu P, et al. Ferumoxytol-enhanced magnetic resonance T1 reactivity for depiction of myocardial

hypoperfusion. NMR Biomed 2021;34(7):e4518.
[68] Leiner T, Rueckert D, Suinesiaputra A, Baessler B, Nezafat R, Isgum I, et al. Machine learning in cardiovascular magnetic resonance: basic concepts and applications. J Cardiovasc Magn Reson 2019;21(1):61.
[69] Ota H, Morita Y, Vucevic D, Higuchi S, Takagi H, Kutsuna H, et al. Motion robust coronary MR angiography using zigzag centric ky-kz trajectory and high-resolution deep learning reconstruction. MAGMA 2024;37(6):1105–17.
[70] Negm AS, Collins JD, Bendel EC, Takahashi E, Knavel Koepsel EM, Gehling KJ, et al. MR lymphangiography in lymphatic disorders: clinical applications, institutional experience, and practice development. Radiographics 2024;44(2):e230075.
[71] Kelly B, Mohanakumar S, Ford B, Smith CL, Pinto E, Biko DM, et al. Sequential MRI evaluation of lymphatic abnormalities over the course of fontan completion. Radiol Cardiothorac Imaging 2024;6(3):e230315.
[72] Huang C, He X, Xie Y, Chen H, Ye Y, Sun Y, et al. Thrombus signal on T1-weighted black-blood MR predicts outcomes of catheter-directed thrombolysis in acute deep vein thrombosis. Thromb Haemost 2023;123(4):453–63.
[73] Roy TL, Chen HJ, Dueck AD, Wright GA. Magnetic resonance imaging characteristics of lesions relate to the difficulty of peripheral arterial endovascular procedures. J Vasc Surg 2018;67(6):1844–1854.e2. e2.
[74] Fotaki A, Pushparajah K, Rush C, Munoz C, Velasco C, Neji R, et al. Highly efficient free-breathing 3D whole-heart imaging in 3-min: single center study in adults with congenital heart disease. J Cardiovasc Magn Reson 2024;26(1):100008.
[75] Csore J, Karmonik C, Wilhoit K, Buckner L, Roy TL. Automatic classification of magnetic resonance histology of peripheral arterial chronic total occlusions using a variational autoencoder: a feasibility study. Diagnostic (Basel) 2023;13(11):1925.
[76] Fan L, Hong K, Allen BD, Paul R, Carr JC, Zhang S, et al. Ultra-rapid, free-breathing, real-time cardiac cine MRI using GRASP amplified with view sharing and KWIC filtering. Radio Cardiothorac Imaging 2024;6(1):e230107.
[77] Primrose CW, Hecht EM, Roditi G, Francois CJ, Maki JH, Dumoulin CL, et al. MR angiography series: fundamentals of contrast-enhanced MR angiography. Radiographics 2021;41(4):E138–9. E138-E9.
[78] Navot B, Hecht EM, Lim RP, Edelman RR, Koktzoglou I. MR angiography series: fundamentals of non-contrast-enhanced MR angiography. Radiographics 2021;41(5):E157–8. E157-E8.
[79] Costello J, Alexander MD, McNally JS, Hecht EM, Porambo ME, Lau VC, et al. MR angiography series: neurovascular MR angiography. Radiographics 2021;41(7):E204–5. E204-E5.
[80] Roditi G, Wieben O, Prince MR, Hecht EM. MR angiography series: abdominal and pelvic MR angiography. Radiographics 2022;42(3):E94–5. E94-E5.
[81] Dhaliwal J, Hecht EM, Roditi G, Douglas P. MR angiography series: MR angiography of the extremities. Radiographics 2022;42(4):E132–3. E132-E3.
[82] Sui B, Sannananja B, Zhu C, Balu N, Eisenmenger L, Baradaran H, et al. Report from the society of magnetic resonance angiography: clinical applications of 7T neurovascular MR in the assessment of intracranial vascular disease. J Neurointerv Surg 2024;16(8):846–51.
[83] Haq IU, Haq I, Xu B. Artificial intelligence in personalized cardiovascular medicine and cardiovascular imaging. Cardiovasc Diagn Ther 2021;11(3):911–23.
[84] Goldfarb JW, Weber J. Trends in cardiovascular MRI and CT in the U.S. medicare population from 2012 to 2017. Radio Cardiothorac Imaging 2021;3(1):e200112.
[85] Guichet PL, Duszak Jr. R, Chaves Cerdas L, Hughes DR, Hindman N, Rosenkrantz AB. Changing national medicare utilization of catheter, computed tomography, and magnetic resonance extremity angiography: a specialty-focused 16-year analysis. Curr Probl Diagn Radio 2021;50(3):308–14.
[86] Tsiouplis NJ, Reeves RA. Trends in utilization of common tests and procedures in treating peripheral arterial disease in the medicare population from 2011 to 2021. J Vasc Inter Radio 2024.