Clinical Application of 3D/4D MR Angiography in Cardiovascular Diseases

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Introduction

Less than a decade following its first description, contrast-enhanced MR angiography (MRA) has replaced invasive catheter angiography as the diagnostic procedure of first choice for most vascular diseases. MRA provides high-spatial resolution 3D data sets with excellent image contrast and allows visualization of almost all vascular territories. Motivated by the clinical success of MRA, the technical developments have even gained speed within the last years. Latest hardware and software developments aim to move from static imaging of a single vascular territory towards dynamic data acquisition schemes.

For a standard MRA examination 10 to 30 ml of a Gadolinium-based contrast agent followed by a saline bolus are typically injected into the antecubital vein with a flow rate of 1 to 3 ml/s. The transit time is defined using a test bolus or care bolus technique and during peak arterial enhancement in the vascular territory of interest a 3D data set is collected within 10 to 30 seconds. This technique provides a stack of 60 to more than 100 cross-sectional images of the contrast filled arteries which can be post processed using maximum intensity projection (MIP), multi-planar reformats (MPR) or volume rendering. However, compared to DSA standard MRA techniques only provide morphologic information, whereas digital subtraction angiography as the standard of reference collects several images during the first-pass of the contrast agent providing additional information on flow dynamics. The lack of functional information has been considered one of the major limitations of MRA by some clinicians familiarized with DSA examinations. The recently introduced ***syngo*** **TWIST** dynamic MRA application provides **sub-millimeter 3D data sets** with a high temporal resolution of about 1 to 5 seconds depending on the sequence parameters and the spatial resolution. Incorporating parallel acquisition techniques (iPAT) even a **subsecond temporal resolution** can be obtained while maintaining a reasonable spatial resolution. Additionally, MRA with perfect arterial enhancement can be performed **without bolus-timing**, and only **very low doses of contrast** are required for excellent arterial enhancement using TWIST.

syngo TWIST: dynamic MRA with subsecond temporal or submillimeter spatial resolution in all body regions.

Another exciting recent development is ***syngo*** **TimCT**, a technique for continuous moving table data acquisition providing seamless volume coverage for large body parts. The craniocaudal field-of-view (FoV) for a conventional single station MRA examination is limited to typically 40–50 cm. Therefore, MRA examinations of the run-off system covering the abdominal aorta down to the pedal arteries have to be performed using multi-station protocols. Following a single contrast bolus the different vascular territories are covered step by step in rapid succession using three to four 3D-data sets. This approach results in several steps which have to be performed by the technician at the right time and in the correct order, making peripheral MRA examinations difficult to perform for inexperienced staff. TimCT (Continuous Table move acquisitions using Tim – Total imaging matrix – coils) introduces a completely new approach since a single high-resolution large-FoV 3D data set covering the entire run-off system can be collected "on the move".

syngo TimCT Angiography allows MRA image acquisition „on the move".

High-quality MRA requires a 1.5 or 3 Tesla MR scanner equipped with high-performance gradients, dedicated surface coils that can cover the different regions of interest and an automatic injector for the contrast agent. The typical in-room time for an MRA examination is about 15 to 20 minutes, however additional sequences for functional information or parenchymal imaging may need some extra time. In this article we would like to give an overview of techniques, scan protocols and the impact on patient management for five of the most common indications for MRA with regard to cardiovascular diseases.

Carotid artery stenosis

Background: Arterial steno-occlusive disease of the carotid arteries can frequently be found in elderly patients with the potential risk of ischemic cerebral infarctions and fatal stroke.

MRA versus other imaging modalities: Imaging of the carotid arteries is feasible using several different imaging modalities including ultrasound (US), computed tomography angiography (CTA), digital subtraction angiography (DSA) and magnetic resonance imaging (MRI). Ultrasound can easily be performed as a bed-side test and allows reliable measurements of wall thickness and the degree of stenoses especially in the carotid bifurcation. However, the ability to provide information on vascular morphology from the aortic arch up to the small intracranial arteries combined with information on parenchymal brain lesion related to carotid artery stenoses and microvascular diseases is a unique feature of magnetic resonance imaging.

MRA is the diagnostic test of first choice for a comprehensive evaluation of the carotid arteries and the brain.

Protocol recommendation: The basic protocol should include a diffusion-weighted sequence for the detection of acute ischemic lesions, a T2*-weighted sequence for the detection of intraparenchymal hemorrhage and a FLAIR / DarkFluid sequence for the morphologic evaluation of brain lesions. The MRA should preferably be performed using the care-bolus technique for timing of the data acquisition. The voxel size should be below 1 mm^3 and the scan time should not exceed 20 seconds to avoid venous overlay (Figure 1).

Conclusion: MRA is the diagnostic test of first choice for a comprehensive evaluation of the carotid arteries and the brain.

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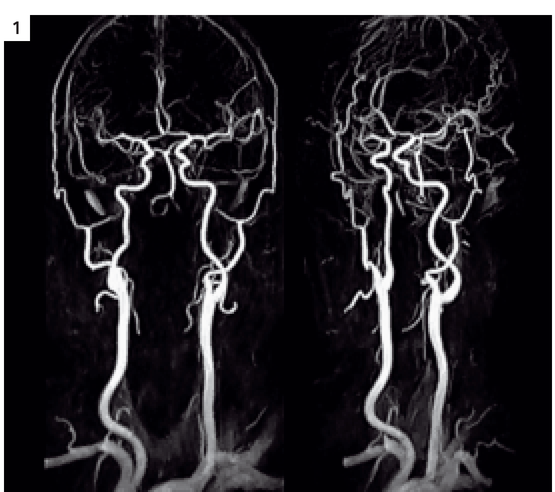


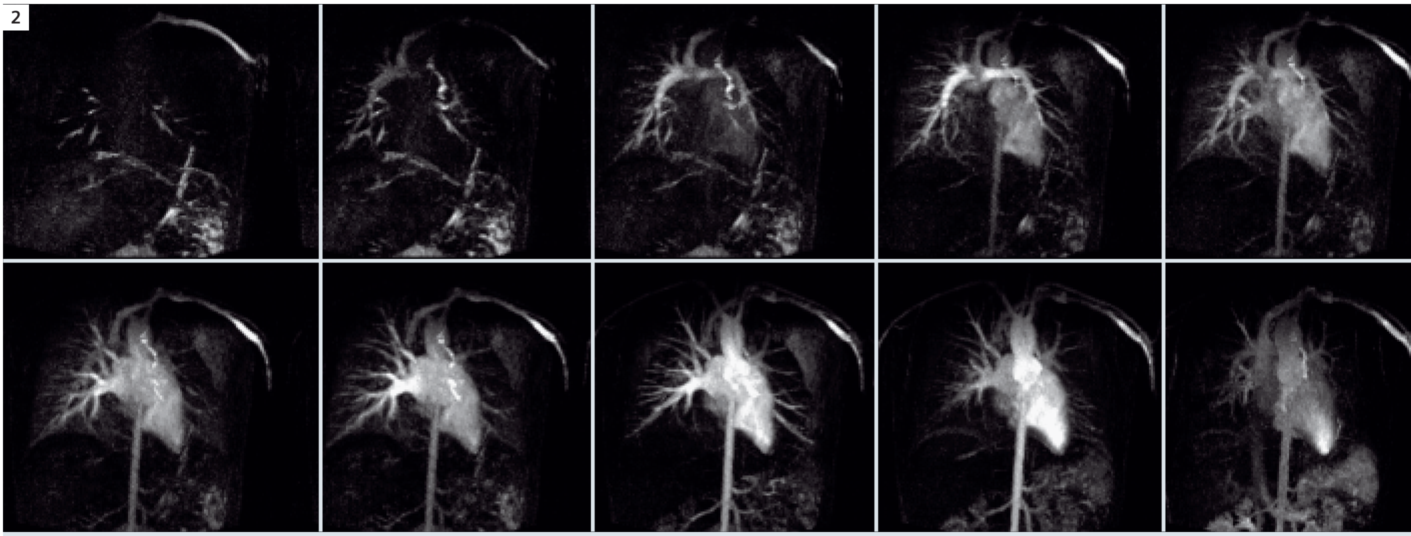
1 High-resolution MRA of the carotid arteries.

Congenital heart disease and vascular variants

Background: The most frequent congenital heart diseases (CHD) are frequently associated with vascular variants and malformations. Therefore in patients with known or suspected CHD cardiac MRI examinations including dark-blood TSE sequences, steady-state free precession sequences (e.g. TrueFISP) for the assessment of right and left ventricular function and phase velocity encoded cine MRI for flow measurements are typically combined with an MRA examination of the thoracic vessels. This comprehensive protocol provides all clinically relevant information on morphology and function that cannot be obtained with any other single imaging modality.

MRA versus other imaging modalities: Echocardiography, which is typically the first diagnostic test in CHD patients cannot visualize the entire vascular system and is of limited value for the assessment of right ventricular function. Additionally, a poor acoustic window may hamper a comprehensive cardiac exam especially in grown-up patients with CHD. ECG-triggered computed tomography (CT) provides excellent information on cardiac and vascular morphology but lacks functional information, e.g. quantification of shunt volumes and flow. Additionally, due to the need of routine follow-up examinations and the fact that mainly children and young adults are affected, radiation exposure must be considered a major limitation. Compared to all other imaging modalities catheter angiography still provides an unbeaten spatial and temporal resolution, however the lack of 3D information inherent to a projection technique and the invasiveness have to be taken into account.

Protocol recommendation: For a comprehensive assessment of cardiac and vascular abnormalities in CHD patients we perform a time-resolved 3D (= 4D) MRA with subsecond temporal resolution using *syngo* TWIST and a small amount of contrast (5–8 ml) injected at a high flow rate (≥ 3 ml/s)



2 Subsecond 4D MRA using *syngo* TWIST in a patient with cavopulmonary anastomosis and hypoperfusion of the left lung.

(Figure 2). Due to the very high temporal resolution required for the assessment of shunts, spatial resolution has to be sacrificed to some degree. Therefore, the dynamic MRA is combined with a standard high-resolution MRA. The dynamic information from the TWIST sequence can be used for bolus timing and according to our experience the injected contrast does not reduce the image quality of the high resolution scan even if performed immediately following the dynamic MRA scan.

Conclusion: The combination of time-resolved and high-resolution MRA allows a comprehensive and fast evaluation of vascular abnormalities and shunts in patients with known or suspected congenital heart disease.

Aortic diseases

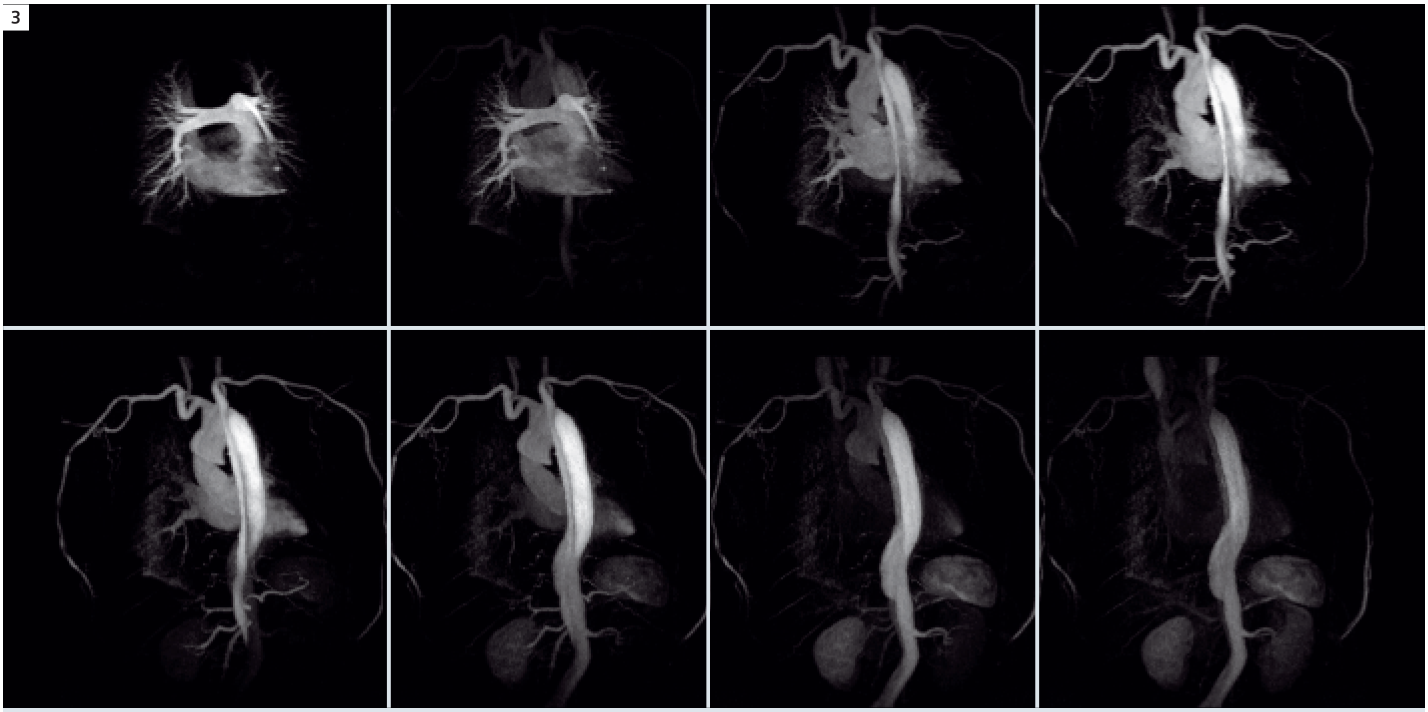
Background: Acute aortic syndromes are an important differential diagnosis in chest pain patients which are frequently missed or delayed diagnosed. Especially in Type A dissections this may have fatal consequences due to the high mortality rate if left untreated.

MRA versus other modalities: In patients with suspected acute aortic syndrome transesophageal echocardiography (TEE) is a fast and reliable bedside test that can be performed in the emergency room or the intensive care unit. However, TEE cannot display entire aorta including the side branches. Therefore, additional cross-sectional imaging is routinely performed prior to treatment. Due to the short scan time and the excellent patient access during the examination computed tomography is the imaging modality of first choice in case of an emergency. However, in stable patients, for follow-up examinations or for treatment planning MRA is an attractive alternative. Major advantages of MRA compared to CTA include the additional functional information (flow direction, tissue perfusion) that can be obtained from time-resolved MRA and the higher sensitivity of MRA for the detection of slow filling endoleaks after interventional treatment. Due to the invasive nature, the low sensitivity for the detection of small penetrating atherosclerotic ulcer, and the inability to detect intramural hemorrhage, catheter angiography can no longer be considered as a first line diagnostic test in patients with acute aortic syndromes.

Protocol recommendations: Our standard protocol comprises a timeresolved MRA in patients with suspicion of aortic syndromes. *syngo* TWIST combined with Parallel Acquisition Techniques (iPAT) provides a temporal resolution of about 2 seconds allowing the assessment of flow dynamics and organ perfusion combined with a sufficient spatial resolution for the assessment of vascular morphology (Figure 3). The time-resolved MRA allows a reliable detection and exclusion of aortic dissections and aneurysms. For the detection of intramural hemorrhage and small penetrating atherosclerotic ulcer, however, additional morphologic sequences (dark-blood turbo spin echo, steady-state free precession cine) and a high resolution stan-

syngo TWIST as a 4D MRA solution can be used either as a standalone technique or in addition to 3D MRA.

Time-resolved MRA with *syngo* TWIST allows reliable detection and exclusion of aortic dissections and aneurysms.



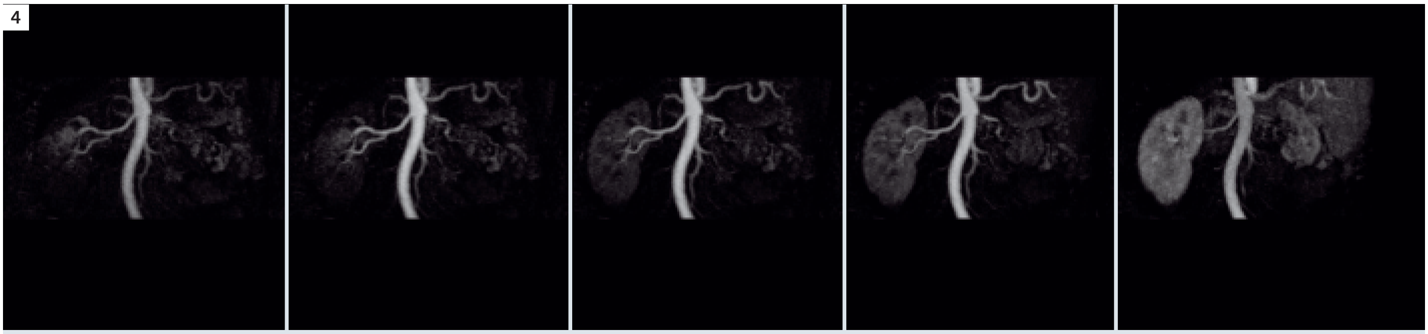
3 4D MRA using *syngo* TWIST in a patient with acute aortic dissection and delayed perfusion of the left kidney, which is supplied by the false lumen.

MRA can be combined with flow and tissue perfusion measurements providing additional functional information in renal artery stenosis.

dard MRA sequence may be added to the protocol.
Conclusion: MRA allows a complete evaluation of acute aortic syndromes in clinically stable patients and for follow-up examinations. Due to the limited patient access during the examination and the longer scan time, multi-slice CT should preferably be used in emergency patients.

Renal artery stenosis

Background: Arterial hypertension is a common clinical finding and must be considered an important risk factor for several potentially fatal events including stroke and myocardial infarction. Although arterial hypertension is only rarely caused by renal artery stenoses it has to be excluded to avoid missing of treatment options e.g. stent placement.
MRA versus other modalities: Digital subtraction angiography is still considered the standard of reference for detecting renal artery stenosis. However, DSA has several important disadvantages including risk of death, arterial dissection and renal failure. Therefore non-invasive imaging techniques such as ultrasound, CTA and MRA have been introduced for the diagnostic work-up of renal artery stenosis. Ultrasound of the renal arteries is challenging especially in obese patients and the results strongly depend on the experience of the investigator.
MRA and CTA developed rapidly within the last five years and both modalities provide a high negative predictive value in patients with suspected atherosclerotic renal artery stenosis, whereas the diagnosis of fibromuscular dysplasia is more challenging. However, MRA can be combined with flow measurements and measurements of tissue perfusion providing additional functional information (Figure 4) which must be considered an important advantage of MRA compared to CTA.
Protocol recommendation: For the visualization of the renal arteries spatial resolution is crucial. We perform a multiphase standard MRA examination using the test bolus or care bolus approach for the timing of the data acquisition. The scan duration must be adapted to breath-hold capabilities of the patients to avoid motion artifacts. Most patients can hold their breath for about 20 seconds and within that scan time a spatial resolution below 1 mm^3 can be obtained. To assess the hemodynamic significance of stenoses and to detect concomitant renoparenchymal disorders, flow measurements using the phase-contrast technique and first-pass perfusion mea-



4 MRA of the renal arteries using *syngo* TWIST. High-grade stenosis of the left renal artery with delayed contrast enhancement of the hypoplastic left kidney.

surements following contrast administration can be added to the protocol.

Conclusion: A comprehensive examination combining high-resolution MRA with flow and perfusion measurements is a unique feature of magnetic resonance imaging and allows accurate characterization of renovascular and parenchymal disease.

Peripheral arterial disease

Background: Peripheral arterial disease (PAD) affecting the limb arteries is a frequent clinical problem being mostly caused by atherosclerosis. The leading feature is arterial narrowing with subsequent reduction of blood flow to the limbs resulting in intermittent claudication, which is estimated to occur in about 5% of people over 55 years old, but PAD is frequently under-diagnosed. Visualization of the entire limb arteries is a prerequisite to make the correct diagnosis and for treatment planning.

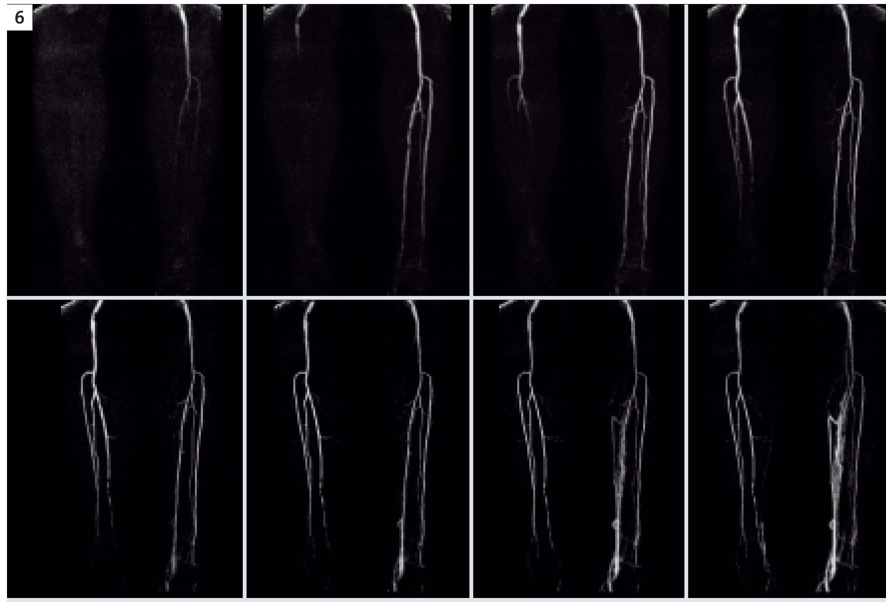
MRA versus other modalities: Duplex ultrasound providing high sensitivity and specificity for the detection of stenoses is an excellent first line test but exhibits a couple of disadvantages: it strongly depends on the experience of the physician and the acoustic window can be limited especially for the iliac arteries in obese patients. Additionally, ultrasound cannot display the entire vascular system in a single image to provide a comprehensive overview of the vascular system. The highly accurate digital subtraction angiography is still regarded as the gold standard for the diagnosis of atherosclerotic changes in peripheral vessels. However, important disadvantages including invasiveness, procedure related mortality and morbidity, costs, availability and the use of ionizing radiation as well as potentially nephrotoxic contrast agents must be taken into account.
CT angiography can be performed to visualize the peripheral arteries but radiation exposure, potentially nephrotoxic contrast agents, time-consuming postprocessing and problems evaluating severely calcified vessels must be considered as important limitations. Therefore bolus-chase MRA protocols collecting multiple high resolution data sets covering the arterial vessels from the renal arteries down to the pedal arteries can be considered as the state of the art technique and imaging modality of first choice for a fast and comprehensive evaluation of patients suffering from peripheral arterial disease.

Protocol recommendation: Although the technique has been used in clinical routine for about 10 years, MRA of the run-off vessels can be still be challenging. Optimal timing of the contrast injection is crucial because inadequate timing may result in poor arterial opacification or venous overlay. Additionally, several data sets requiring user interaction have to be collected in rapid succession, making the procedure difficult to perform for inexperienced users. To overcome these limitations several new techniques have been developed. To simplify the procedure and to improve the workflow, *syngo* TimCT (Tim Continuous Table move) has recently been introduced. Instead of collecting several overlapping 3D data sets in rapid succession, a single high resolution 3D data set covering the arterial system from the abdominal aorta down to the pedal arteries, is collected during continuous table movement. This technique is revolutionary because motion, which was considered one of the major obstacles for MR imaging is now used to extend the field-of-view in cranio-caudal direction. TimCT is a robust and easy to

MRI allows accurate characterization of renovascular and parenchymal disease.

With *syngo* TimCT, table motion is used to extend the field-of-view in z-direction.

5 MRA acquired with *syngo* TimCT in a patient with PAD.



6 Dynamic MRA of the calf arteries using *syngo* TWIST.

perform protocol for patients with PAD (Figure 5). In patients with diabetes or pedal ulcer which are prone to early venous filling, however, TimCT might not be the ideal tool. To avoid venous overlay for the infrapopliteal arteries hybrid MRA techniques combining time-resolved MRA of the lower legs using TWIST followed by bolus chase MRA for the pelvis and upper legs may be advantageous. Combining TWIST and Parallel Acquisition Techniques, a dynamic MRA can be obtained with a temporal resolution of about 2 seconds and a voxel size below 1 mm^3 which reliably avoids venous overlay and adds functional information comparable to DSA (Figure 6).

MRA provides different imaging protocols for peripheral MRA and has replaced diagnostic DSA in PAD patients.

Conclusion: MRA provides different imaging protocols for peripheral MRA and has replaced diagnostic DSA in PAD patients.

Discussion

MRA is a robust and reliable technique that can be applied to visualize all different vascular territories in daily clinical routine. The only vascular territory that remains challenging is MR angiography of the coronary arteries (MRCA). Reliable compensation of cardiac and respiratory motion cannot be achieved in all patients resulting in motion artifacts and reduced image quality. Therefore, MRCA must still be considered as a field of active research and is not ready for routine clinical application in coronary artery disease patients. However, MRA is still developing rapidly and the new techniques will definitively change our scan protocols and further improve the diagnostic impact of MRA. The various MRA techniques mentioned above cover different parts of the vascular system. Using recent hard and software developments the examination can easily be extended to wholebody MRA without increasing the dose of contrast. The investment in increased scan times, the inroom time as well as the time required for post-processing and reading of the examination are, however, justified by, for example, the high prevalence of concomitant atherosclerotic findings in the carotids and thoracic aorta in PAD patients, and may improve patient care. Additionally, this might be a completely new approach for risk assessment in atherosclerotic disease because the total plaque burden within the arterial system can easily be assessed in a single examination taking only 15 to 20 minutes.

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