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REVIEW ARTICLE

Clinical use of MRI:

Whole body MR Angiography: normal, pathologic and pitfalls

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الاستخدامات السريرية للتصوير بالرنين المغناطيسي

التصوير الوعائي الرنيني المغناطيسي لكامل الجسم: الطبيعي، المرضي والأخطاء

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الملخص: إن استخدام التصوير بالرنين المغناطيسي في السنوات القليلة الماضية أظهر تطورا تكامليا فيما يتعلق في كشف وتحليل الحالات المرضية. التصوير بالرنين المغناطيسي أصبح الأداة الفاعلة في تشخيص وكشف كافة أعضاء الجسم البشري بما في ذلك الأعضاء الجوفاء. ملخص الدراسة يصف واحدة من التقنيات الأساسية للتصوير بالرنين المغناطيسي يسمى التصوير الوعائي الرنيني المغناطيسي لكامل الجسم مع التركيز على الاستطبابات، اكتساب المعطيات، عامل المغايرة متوازي المغناطيسية المضاف داخل الأوعية الدموية، إضافة إلى النتائج والمحددات. إضافة لذلك سيتم في هذا البحث مناقشة بعض التقنيات الحديثة الأخرى المتعلقة بتحسين دقة التشخيص الشعاعي.

مفتاح الكلمات: الجهاز الوعائي ، التصلب العصيدي الشرياني، عامل المغايرة، الطاولة المتحركة، التصوير الوعائي الرنيني المغناطيسي لكامل الجسم.

ABSTRACT: In the last few years the use of Magnetic Resonance Imaging has shown a proceeding development regarding detection and quantification of pathologies. MRI has been a leading tool for the diagnosis of all organs of the human body including the hollow organs. This review article describes one of the underlying techniques of MRI namely whole body MR angiography concerning indications, data acquisition, the intravenously applied paramagnetic contrast agent, as well as results and limitations. In addition, new techniques to improve diagnostic accuracy are discussed.

Keywords: Vascular system, atherosclerosis, contrast agent, moving table, whole body MR angiography

MAGNETIC RESONANCE IMAGING

Magnetic resonance imaging (MRI) as non-invasive technique without radiation exposure has been shown to be an appropriate diagnostic tool for the detection of almost pathologies of the

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human body. The excellent contrast of MRI provides a good differentiation between the different soft tissues of the body and makes it especially useful in brain, muscles, heart, vessels and cancer compared with other medical imaging techniques based on Roentgen radiation or endoscopy. Recently, new investigation areas like functional brain MRI, cardiac MRI, virtual MR colonoscopy and whole body MR angiography have been introduced.

The aim of this review articles is to describe one of the applications of MRI namely whole MR angiography (WB-MRA) based on our 10 years experience on MRI.

VASCULAR SYSTEM AND ANGIOGRAPHY:

Atherosclerosis as a systemic disease represents a frequent health problem and is the most common disease of the vascular system. Due to their systemic nature patients with peripheral arterial disease (PAD) or vasculitis often have concomitant arterial pathologies outside the peripheral arteries. Therefore, the investigation of the whole vascular system is important for the therapeutic management in patients with PAD or vasculitis. Traditionally, the diagnostic approach to atherosclerosis using conventional digital subtraction angiography (DSA) has remained segmental for various reasons including radiation exposure, contrast dose limitations, invasiveness and economic factors. The implementation of MR angiography (MRA) as a robust and safe technique became as alternative for DSA. Initial studies of MRA were focused on spatially limited anatomic regions because of immaturity of the technique. Thus, venous overlay and contrast dose limitations had initially curtailed contrast-enhanced three dimension (3D) MRA to the display of the arterial territory contained within a single field-of-view extending over 400 - 480 mm. Therefore, the investigation of the whole vascular system carried out on many different days. However, extended coverage from the supra-aortic arteries to the distal runoff vessels appears desirable. With the implementation of faster gradient systems whole body coverage extending from the carotid arteries to the run-off vessels with 3D MRA had become possible in merely 72 seconds[1] and has named whole body MR angiography (WB-MRA).

MR scanner:

WH-MRA should be performed using a MR scanner with minimal field strength of 1.5 Tesla and multi receiver channels and high-performance gradients characterized by an amplitude of circa 40 mT/m and a slew rate of circa 200mT/m/msec. In addition, the gradient system should to be strong enough to enable switching of highest possible gradient amplitudes in the shortest possible time with the aim to deliver the shortest possible repetition times (TR) and the shortest possible echo times (TE). Furthermore, the MR scanner should have a moving table and the use of commercially available floating-table MR angiography software ensures rapid motion of the MR table from one imaging position to the next. An automatically contrast agent injector should be available.

MR examination:

Similar to virtual MR colonoscopy, MRA is based on the principle of ultra-fast, T1-weighted 3D gradient-echo acquisitions collected within the confines of a single breath-hold. After exclusion of contraindications to MRI, such as presence of pacemaker, metallic implants, or claustrophobia and after placement of a venous catheter the MRA examination could be performed in spine or prone position. However, the patients should be placed in unit feet first due to the moving MR table outside of the MR gantry. The dedicated vascular coils have to cover the patient form the skull base to the feet. Based on multiplanar scout MR image findings, the acquisitions of five overlapping 3D data sets are

planned. The slabs of the neck, chest, abdomen, pelvis, thighs, and lower parts of the legs should be strictly coronal, whereas the slabs of the feet are angulated to cover the dorsal arteries of the feet and the plantar arch arteries. At first a pre-contrast 3D T1-weighted gradient-echo sequence of the five stations with linear k-space sampling and partial Fourier are performed. MR imaging parameters should be adapted for each station to achieve the best MR image quality (table 1). The data sets of the thorax and abdomen should be performed under breath holding to avoid breathing artifacts. A test bolus of contrast agent could be used to determine the contrast material arrival time. A paramagnetic contrast material is injected automatically through the vein catheter with a rate of circa 1.5 ml/sec. and a contrast dose of 0.2 mmol per kilogram of body weight (range 20 - 40 ml contrast agent per normal weighted person). The operator manually starts the acquisition of the post-contrast 3D data sets when the contrast agent is detected in the aortic arch. So, five consecutive post-contrast data sets from the neck to the feet are performed by means of the moving table. A saline solution with a rate of 0.5 ml/sec. flushes the administrated contrast agent (range 20 - 30 ml). To enable image subtraction, each pre-contrast 3D data set is subtracted from the contrast-enhanced data set at each level using suitable software for the MRA. In addition, rotated maximum intensity projections (MIPs) could be rendered using reconstructions.

Parameters of WB-MRA	Recommended data / range
Sequence Orientation	Coronal
Repetition time TR (msec)	2.2 – 3.7
Echo time TE (msec)	0.74 – 1.37
Flip angle	20
Field of View FoV (mm x mm)	350 400
Acquired section thickness (mm)	1.5 – 3.33
Interpolated section thickness (mm)	1 - 2
Section spatial resolution (%)	60 - 66
Number of section	48 - 120
Partial Fourier transform phase	6/8 – 7/8
Acquired matrix	210 x 384 – 358 x 512
Interpolated matrix	420 x 768 – 757 x 1024
Acquired voxel size (mm^3)	0.8 x 0.8 x 1.51 – 1.7 x 1.0 x 3.3
Interpolated voxel size (mm^3)	0.4 x 0.4 x 1 – 0.8 x 0.5 x 2
Bandwidth (Hz/pixel)	390 - 770
Acquisition time per each data set (sec)	13 - 44
Time to center k-space (sec)	3.6 – 17.1
Acceleration factor	0 - 2

Table 1: The parameters of WB-MRA at a 1.5 Tesla MR scanner and using high-spatial resolution sequences are displayed with their recommended data which should be adapted for each station to achieve the best MR image quality.

WHOLE BODY MR ANGIOGRAPHY:

The whole-body MRA-concept is traditionally based on the acquisition of several slightly overlapping 3D data sets of approximately 400 - 500 mm lengths acquired in immediate succession. The patient table and the patient are moved relative to the imaging volume in between the various steps. The first data set covers the aortic arch, supra-aortic branch arteries and the thoracic aorta, while the second data set covers the abdominal aorta with its major branches including the renal arteries. The third data set displays the pelvic arteries, and the last two data sets cover the arteries of the thighs and calves,

respectively. Various coil concepts utilizing radiofrequency (RF) surface coils were implemented to overcome the limitations of the segmental MRA using whole body RF coil only.[2-4]

With the implementation of a moving table platforms such as the Angio*SURF* platform (Angio*SURF* is abbreviation for Angiographic System for Unlimited Rolling Field of view, MR-Innovation GmbH, Essen/Germany, figure 1) limited fields of view and the need to reposition the patients during the whole body MRA exam were overcome.[5-8] For the Angio*SURF*-examination all patients have been placed feet first within the bore of the magnet and examined in the supine position on the fully MR-compatible Angio*SURF* platform, which had been placed on the existing table top. The Angio*SURF* platform has been fitted on most standard MR systems manufactured by Siemens, Erlangen/Germany. 240 cm in length, the platform is placed on 7 pairs of roller bearings, which are anchored within the existing patient table. Up to six 400 mm 3D data sets can be acquired in immediate succession. Markers permit adjustment of the desired field-of-view. Signal reception is accomplished using posteriorly located spine coils and an anteriorly located torso phased array coil, which remains stationary within the bore. While the two utilized elements of the spine coil are integrated in the patient table, the standard torso phased array coil is anchored in a height-adjustable holder, which remains fixed to the stationary patient table. Thus, data for all 5 stations are collected with the same stationary coil set positioned in the isocenter of the magnet. Thus, the use of Angio*SURF* technique reduced the examination time and the image quality of whole body MRA could improve in comparison to techniques using body coils (figure 2). Many studies confirmed the feasibility and tolerance of whole body MRA using AngioSURF technique in patients with PDA.[5,7,9] Herborn et al. examined using whole-

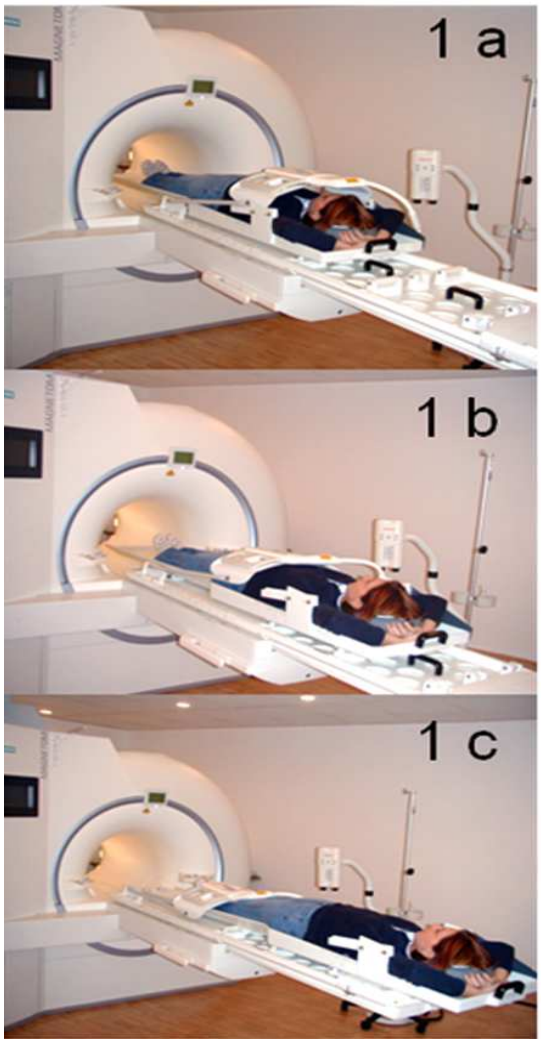


Figure 1 a-c: AngioSURF (Angiographic System for Unlimited Rolling Field-of-views, MR-Innovation GmbH, Essen/Germany) is a manually driven table platform for the acquisition of high-resolution contrast enhanced whole-body 3D MR angiography. It enables the patient to be manually moved stepwise between the spine coil embedded in the table and the surface coil resulting in significantly enhanced signal-to-noise-ratio.
a) *Volunteer on the AngioSURF table.* Shown are the table and coil positions in the first of five stations. For demonstration purposes, the station is shown outside of the magnet tunnel. The coil holder, including the circularly-polarized body array, rests over the face of the patient at this station.
b) *Volunteer on the AngioSURF table.* Shown is the third of five stations. The AngioSURF table has been manually moved two stations. The volunteer glides between the permanently-installed spine array and the body array mounted on the coil holder.
c) *Volunteer on the AngioSURF table.* Shown is the last of five stations. After an examination time of 72 seconds (five scans each lasting 12 seconds and four 3-second pauses for the manual table movement), the 3D contrast-enhanced whole-body MR angiography is available.

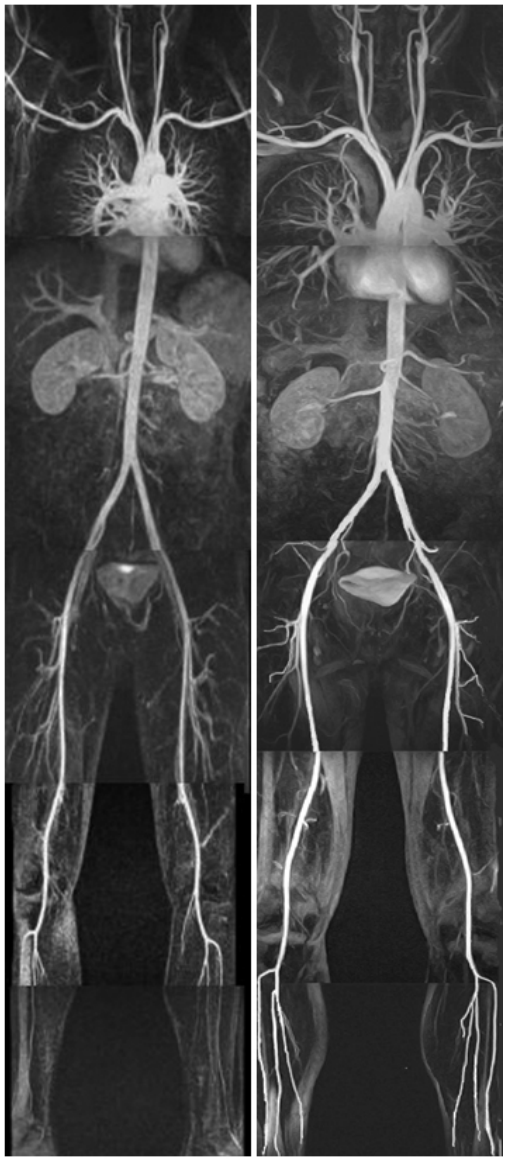


Figure 2: *Whole-body 3D MR-angiogram of a volunteer using the body coil (left) and the AngioSURF-system (right).* The exam consists of five slightly overlapping 3D data sets collected over 72 seconds. The acquisition time for each 3D data set amounts to 12 seconds. During a 3 second acquisition break the table is manually repositioned to the center of the subsequent image volume. With five successive acquisitions craniocaudal coverage thus extended over 176 cm, while the total data acquisition time amounted to 72 s. Gd-BOPTA (Multihance, BRACCO) was administered at a dose of 0.3 mmol/kg body weight at a rate of 1.3 ml/sec for the first half and 0.7 ml/sec for the second half of the contrast volume, followed by a 30 ml saline flush using an automated injector. The scan delay was determined with a 2 ml test bolus at the level of the descending aorta. The quality of the whole body MR-angiogram is sufficient to assess the arterial system from the supraaortic arteries to run-off vessels. *The AngioSURF-system leads to a better delineation of the arterial morphology, especially in the infrapopliteal vessel segments.*

body MR angiography fifty-one patients with clinically documented peripheral arterial occlusive disease which referred for DSA as a reference standard for the peripheral vasculature in all patients.[9] AngioSURF-based whole-body MRA had overall sensitivity of circa 93% and specificity of circa 90% for the detection of vascular stenoses. Additional vascular diseases were detected in 12 patients (23%) and were subsequently assessed on Doppler sonography, dedicated MR angiography, or both.[9] This explains the need to evaluate the whole vascular system in patients with atherosclerosis or vasculitis due to their systemic nature (figure 3).

The combination of multicoil and multichannel capabilities and the ability to move the table a full 205 cm range are specific advantages of the latest MR-scanners for whole body MRA. Acquisition times of approximately 10 seconds per station and voxel of approximately 0.8 x 1.2 x 1.5 mm^3 have become achievable utilizing 3D interpolated spoiled gradient echo sequences with iPAT factor 3 (interpolated **Parallel Acquisition Technique**), an imaging matrix of 512, and imaging stations of 40-45 cm. With automatic subtraction and MIPs (Maximum Intensity Projection), the entire whole body MRA protocol can be performed in less than 30 minutes (figure 4).

This has paved the road for the implementation of the move during scan (MDS) concept for whole body MRA.[10-12] With the MDS techniques data acquisition takes place continuously in the isocenter of the magnet during patient table move which leads to one large, seamless FoV (Field of View) that covers the entire patient. Utilizing the MDS approach, the entire whole body MRA data set can be acquired as one single run from head to toe (figure 5).

In a study by Nielsen et al. eleven patients with symptomatic peripheral arterial disease underwent whole body MRA at 3 Tesla scanner with body coil acquisition and using the blood

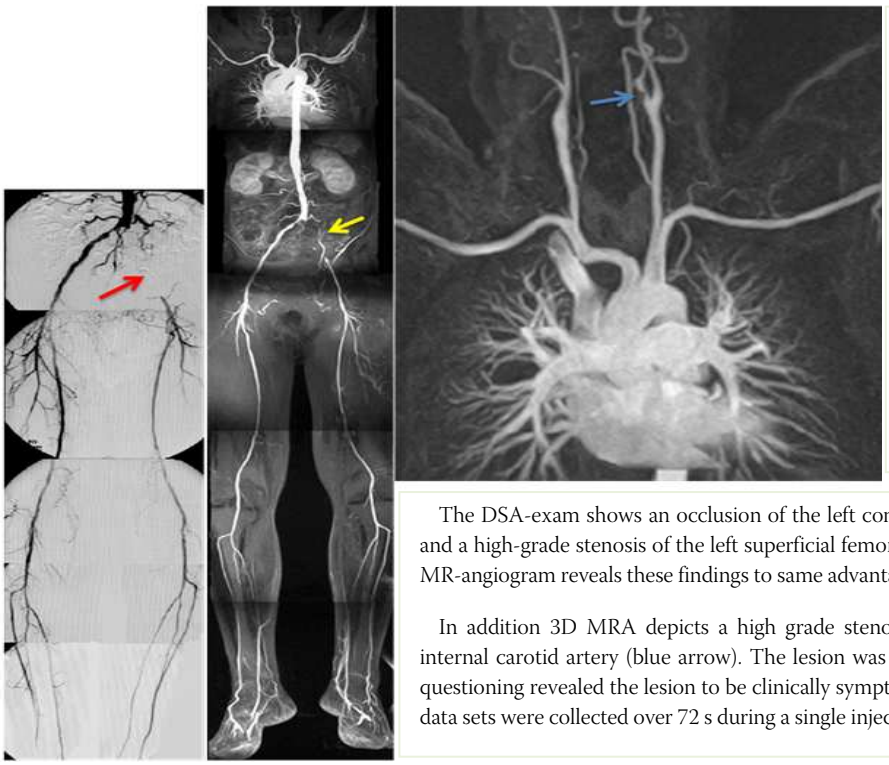


Figure 3: *Intra-arterial digital subtraction angiogram (left) and 3D-whole-body MR-angiogram using AngioSURF (middle) in a 63–year old male patient with history of peripheral vascular disease and a pain-free walking distance of < 200m.*

The DSA-exam shows an occlusion of the left common and external iliac artery and a high-grade stenosis of the left superficial femoral artery (red arrow). The 3D-MR-angiogram reveals these findings to same advantage (yellow arrow).

In addition 3D MRA depicts a high grade stenosis (bottom, right) of the left internal carotid artery (blue arrow). The lesion was initially unsuspected. Focused questioning revealed the lesion to be clinically symptomatic. The whole body MRA data sets were collected over 72 s during a single injection of paramagnetic contrast.

pool contrast agent gadofosveset trisodium.[13] As reference method DSA of the aorta and the inflow and runoff arteries was used. In this study whole body MRA showed good reproducibility but only moderate to good results in comparison with DSA. The sensitivity for the detecting of significant arterial lesions was 0.66% and the specificity was 0.82%. Therefore, further assessment and establishment of WB-MRA using 3 Tesla scanners and comparison to 1.5 Tesla scanners WB-MRA should be evaluated, especially due to the increased applications of 3 Tesla MR scanners in clinical routine.

CONTRAST AGENT:

With the implementation of surface coils covering the entire body or the application of the Angio*SURF* technique, the image quality and SNR (**Signal-to-noise ratio)** improved dramatically which was translated in reduction of the contrast agent dose to 0.2 mmol/kg body weight. Traditionally, the contrast material application has been divided in two injections in order to perform first pass scanning of the entire arterial system. The first bolus is used to display the aortic arch and the supra-aortic arteries. With the second injection a larger vascular territory ranging from the thoracic aorta to the pedal arteries is covered. Therefore, venous contamination in the most distal station may become problematic in the second part of the exam.[14] The contrast agent is diluted with 0.9% of normal saline to a total volume of 60 ml is automatically injected using a biphasic protocol: the first half is injected at a rate of 1.3 ml/s, while the second half is administered at a rate of 0.7 ml/s. The contrast is flushed with 30 ml of saline injected at 1.3 ml/s.[15] The dose of 0.2 mmol/kg body weight has shown to significantly improve the image quality as compared to 0.1 mmol/kg body weight while no significant difference were found between 0.2 mmol/kg body weight and 0.3 mmol/kg body weight.[15]

To assure maximal arterial enhancement, Gd-BOPTA (MultiHance®, Bracco, Milano, Italy) a paramagnetic contrast agent with high intravascular relaxivity owing to some degree of

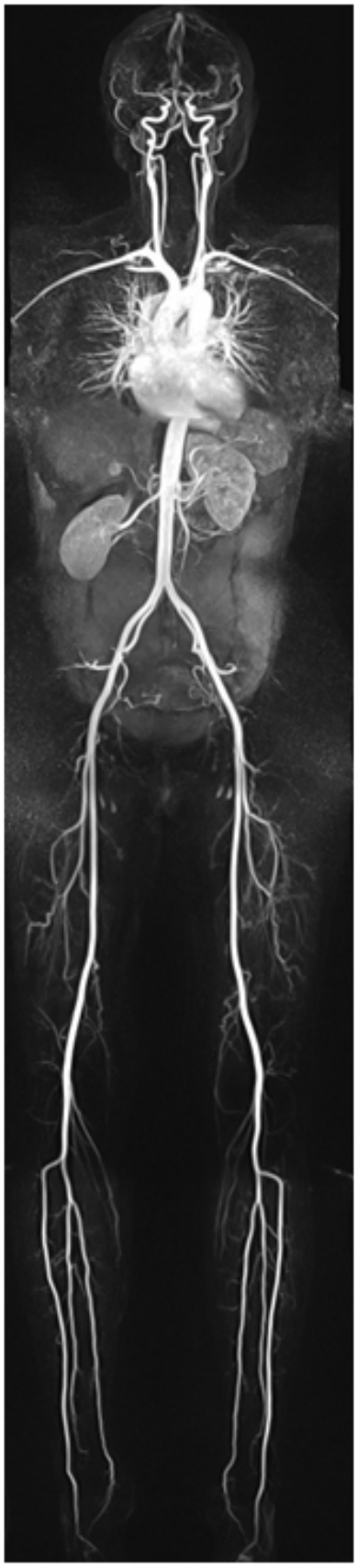
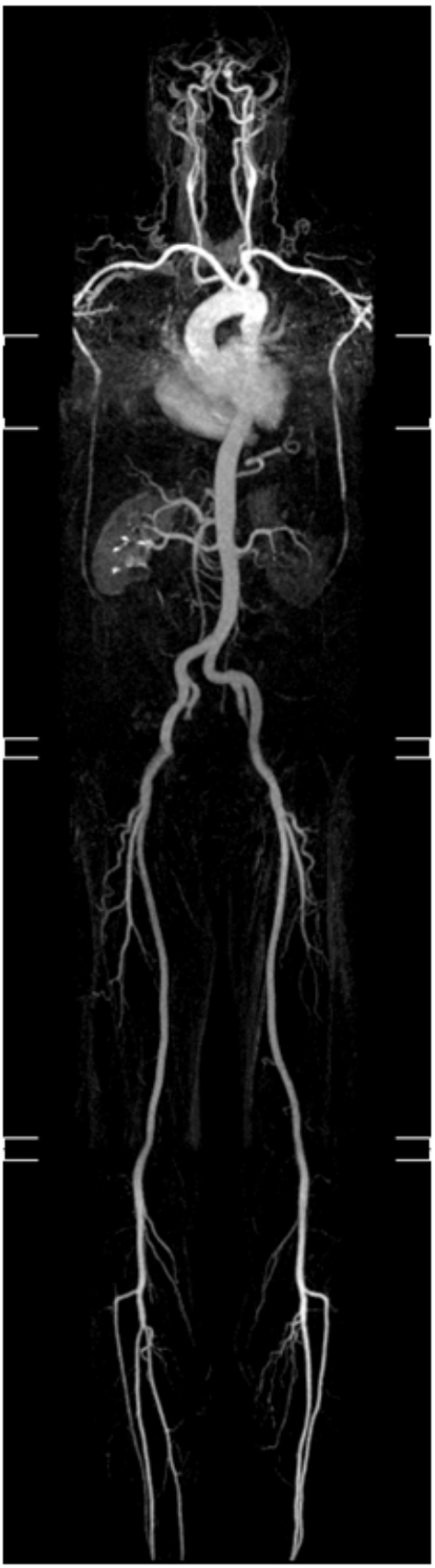


Figure 4: *Whole body MRA of a 45-year old female patient who underwent the MRA within a screening examination due to new diagnosed primary hypertension (left).*

The examination was performed using high-spatial resolution with iPAT factor 3 and matrix of 512. In this patient no pathology was found.

Figure 5: *Whole body MRA of a male patient who underwent the MRA by known arterial hypertension to exclude atherosclerosis and vessel stenosis (right).*

The examination was performed using the move during scan technique (MDS). Thus, the whole body MRA data set can be acquired as one single run from head to toe. In this patient no high-grade stenoses could be diagnosed. As norm variant two vessel run-off of the left lower leg was seen.



albumin-binding can be employed.[16] Contrast compounds with higher concentration formulations such as Gadobutrol (Gadovist® 1.0 M, Bayer Health Care, Leverkusen, Germany) might be advantageous with regard to arterial enhancement[17] as compared to 0.5 M extracellular contrast agents. Blood pool or intravascular contrast agents are large enough or bind to large enough molecules when injected that they do not leak out of the capillaries but stay within the intravascular compartment. Gadofosveset Trisodium (Vasovist®/Ablavar®, Lantheus Medical, N. Billerica, MA, USA) is the first imaging agent approved for magnetic resonance angiography in the U.S. It is the only intravascular contrast agent that is approved in Europe but today it is not available on the European market anymore.

PITFALLS OF WB-MRA AND NEW TECHNIQUES:

Although referred to as a whole-body MRA-examination – the study does not cover the intracranial or coronary arteries, that still require a dedicated diagnostic assessment. However, noninvasiveness, three-dimensionality, extended coverage and high contrast conspicuity are the characteristics of whole body MR angiography that combine to allow a quick, risk-free, and comprehensive evaluation of the arterial system in patients with system vascular diseases such as atherosclerosis, diabetes, thromboembolic diseases or vasculitis.

One potential pitfall in whole body MRA is venous overlay in the lower leg arteries. This occurs especially in patients with diabetes or ischemic ulcers. Various strategies have been implemented to overcome this shortcoming:

1) Midfemoral venous compression administered with inflated thigh cuffs to reduce venous flow and to prevent venous contamination.[18-20]

2) A hybrid technique utilizing parallel acquisition techniques with reduced acquisition time of 60 seconds and fast table movement allows a protocol setup such that the WB-MRA exam starts with the aortic arch and supra-aortic arteries as the first step (first half of the total amount of contrast agent), followed by rapid table movement that overtakes the contrast bolus down to the lower extremity for assessment of the calf vessels as the second step. Then a second contrast application (second half of the total amount of contrast agent) is started for the assessment of the thoracic and abdominal aorta, the pelvic and thigh vasculature.[14]

Due to the large volume to cover in whole body MRA the bolus can easily be missed or overtaken, depending on the speed of the table movement. As in any MRA field inhomogeneities caused by metal implants and stents can degrade image quality. Depending on the stent material, in-stent re-stenosis may not be assessable with MRA. As a matter of fact, signal loss due to stents may be misdiagnosed as arteriosclerotic lesion or occlusion.

With multiple stations acquired in whole body MRA potential misregistration may occur at the borders of various stations leading to so-called “stitching artifacts”. Too little or too much overlap can be inadvertently planned between the stations. Also, signal intensity falls off and non-linearity in the gradient system leads to geometric distortion on the margins of the FoV resulting in artifacts in the combined overview image. These problems are certainly overcome with the MDS technique that leads to a seamless whole body MRA.

As with any MRA exam patient movement between reference scan and contrast enhanced scan can cause artifacts. When covered with multiple surface coils “like a mummy” in whole body MRA patients may suffer from claustrophobia exacerbation.

Finally, with the need to cover a large vascular territory higher doses of contrast agents tend to be administered. Today we know that there is a relationship of the amount of contrast material administered and incidence of nephrogenic systemic fibrosis (NSF) in certain linear contrast agents in patients with renal insufficiency.[21]

SUMMARY:

Whole-body MR angiography as a suitable three-dimensional, nonionising modality permits a rapid, noninvasive, and accurate evaluation of the whole arterial vasculature in patients with generalized arterial diseases like arteriosclerosis or vasculitis with the exception of intracranial and coronory arteries, and it may allow identification of additional relevant vascular diseases that were previously undetected and could be very important for the therapeutic management.

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