Whole-body MRI

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Abstract
This article discusses recent developments in whole-body magnetic resonance imaging (wb-MRI) and its clinical indications. Improvements in hardware, such as extended table translation, and a high number of simultaneous receiver channels are prerequisites for wb-MRI. Generally, two different strategies can be followed: multi-station wb-MRI and data acquisition during continuous table movement, both permitting a variety of different sequences and contrasts.

Wb-MR angiography facilitates the visualisation of the entire arterial system from head to toe with the exception of the coronary arteries. Wb-MRI can replace skeletal scintigraphy in the detection of bone marrow metastases by using fluid-sensitive sequences, while fast contrast-enhanced sequences can be used as an alternative approach in the search for tumours and metastases. Such a wb-MRI approach can even be superior to a combination of positron emission tomography and computer tomography in the detection of distant metastases.

One of the challenges for which the radiologist must be prepared in wb-MR protocols is a dramatic increase in image data, which might result in an increase in false negative findings.

Further developments in wb-MRI aim at multi-contrast imaging and further improvements in coil technology for faster data acquisition (parallel imaging), with the goal of reducing total examination costs.

Recent developments
Whole-body (wb) magnetic resonance imaging (MRI) has evolved as a valuable alternative diagnostic tool to other imaging modalities. It is important to recognize that the term 'wb-MRI' was introduced as far back as 1980 and denotes the examination of body regions beyond the neuroradiological domain – i.e. thorax, abdomen or extremities.

Until a few years ago, only a single very restricted part of the body could be assessed within reasonable examination time. Today, however, wb-MRI actually means imaging the whole body in one MR examination 'from head to toe'.

The first wb-MRI technique, wb-MR angiography, depicted the arterial system from head to lower legs in one examination following the administration of only one contrast agent bolus (Figure 1). Soon afterwards, wb-MRI began to be used in the search for tumours and metastases in bones. Today the assessment of the musculoskeletal system, the parenchymal organs, the vessels and the heart, and even the colon, has become possible within a single setting. This article aims to discuss the technical requirements as well as the potential of wb-MRI and also some of its diagnostic implications.

Overview of techniques
Various pulse sequence types can be applied to create many different tissue contrasts. Other than computer tomography (CT), MRI has always needed a clear diagnostic hypothesis, as only single, restricted body regions with a cranio-caudal field-of-view of 40–50 cm could be examined within a single session. For more extended body coverage, multiple body regions each with a field of view of 40–50 cm are examined one after the other. Due to restricted maximum table translation range, the patient has to be repositioned from 'head first' to 'feet first' to bring cranial and caudal body parts into the isocentre of the magnet in succession. Due to the restricted number of signal reception channels, repositioning of the various radiofrequency coils onto the body region currently being examined in the isocentre is also required. If intravenous contrast agent injection is required, this can only be applied to one or two body regions. All these steps lead to long examination times and, consequently, to high stress for patients.

Recent technical achievements in hardware have enabled radiologists to overcome these problems, thus making wb-MRI possible.

Multi-station wb-MRI
Among the first MR techniques for imaging a larger field-of-view in a short time were a rolling platform with extended field of view, which allowed wb examinations without repositioning,[1] and 'moving-bed infusion-tracking MR angiography',[2] both of which are dependent on a rolling table platform. Today, commercially available scanners offer a table range of 200 cm and up to several dozen simultaneous receiver channels. In addition, the patient can be covered with coils from 'head to toe', so the repositioning of patient or coils is not required. The high number of simultaneous receiver channels additionally allows for 'parallel imaging' which can, for example, be used for increased spatial resolution while keeping acquisition times constant.[3]

It should be noted that the actual cranio-caudal field of view still is limited to 40–50 cm; it depends on the homogeneity of the main magnetic field B_0, and this

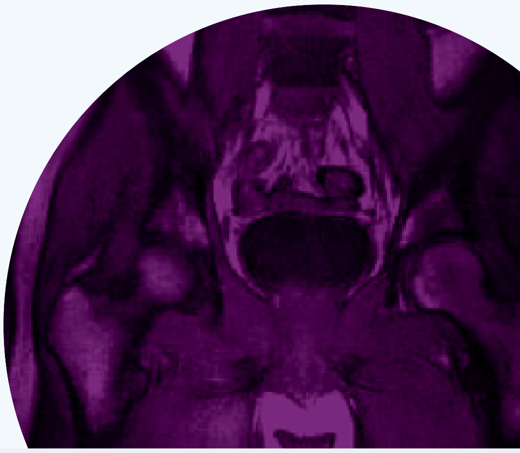

Figure 1. Multi-station MR angiography; patient without arterial stenoses. Contrast-enhanced 5 consecutive 3D datasets (spoiled gradient-echo), maximum intensity projections.

Figure 2. Whole-body MRI, acquired during continuously moving table.

has not changed (because of the length of the magnet and bore diameter required). Hence, the acquisition times and the field-of-view for the continuing blockwise acquisitions remain constant. Additionally, there is loss in efficacy due to pauses in data acquisition during table movement from one body region to the next. This has implications, especially for MR angiography, in which fast 'bolus chasing' is crucial. Due to magnetic field 'inhomogeneities', the borders of the different data blocks will not match perfectly – border artefacts will occur, even if 5 cm of overlap is allowed (Figure 1).

Continuously moving table

The field-of-view can, however, be virtually increased to 200 cm by acquiring data during continuous movement of the table (Figure 2).[4–8] Time efficiency is increased compared with multi-station MRI as no pauses occur during the examination. In addition, a single image with large field-of-view that does not suffer from border artefacts is obtained.

Adequate image reconstruction requires knowledge about the table position at every time point, which has only recently become possible. With this technique, high spatial-resolution two-[5] or three-dimensional[9] data sets of various contrasts[10] can be acquired, in analogy to CT. MR angiographies can be obtained without border artefacts (Figure 3).[4,11] An attractive application is the acquisition of images in short bore magnets; despite the small field-of-view, the scanner could be used for wb-MRI.

Further developments in continuous table movement aim at the reduction of breathing artefacts – i.e. by creating algorithms that compensate for free breathing[12] – as well as the acquisition of multi-contrast sequences during a single table translation[10] and the adaptation of table velocity with respect to the varying travel velocities of the contrast agent bolus in different body territories.[13]

Indications and clinical experience

Atherosclerosis

MRI offers a unique opportunity to assess what damage, if any, has already been inflicted by atherosclerosis on the peripheral arterial system in the single individual. MR angiography has been shown to be almost equivalent to invasive techniques in virtually all single vascular territories including the carotid,[14] the renal[15] and the peripheral arteries.[16,17]

The implementation of faster gradient systems laid the foundation for wb-MRA from the carotid arteries to the trifurcation vessels of the calves.[2,16,18,19] In wb-MR angiography, acquisition times as well as the required amount of contrast agent do not increase linearly with the field-of-view; rather, the performance of the gradient systems allows for sufficiently fast data acquisition to 'chase' the contrast agent bolus through

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Figure 3. MR angiography acquired during continuous table movement. No border artefacts occur (maximum intensity projection of 3D data set).

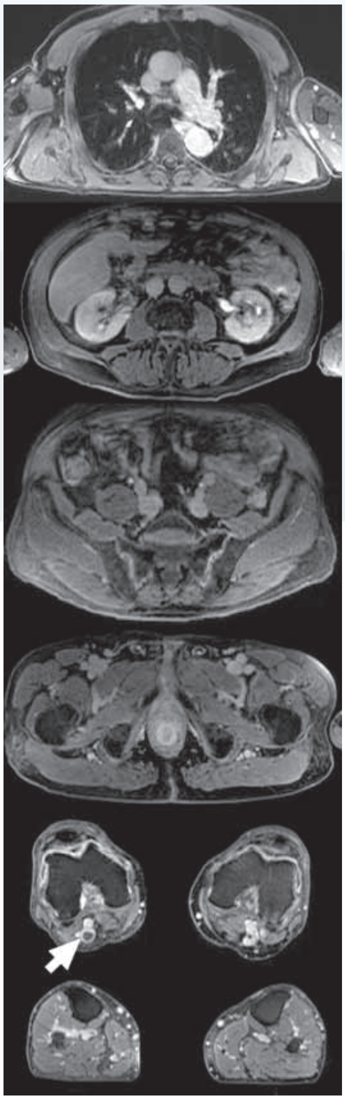


Figure 4. Six out of approximately 500 axial slices; contrast-enhanced fat-saturated 3D spoiled gradient echo data sets. A thrombus is seen as a clear filling defect in the right popliteal vein (arrow).

each of the four to six body regions or field-of-views. This is reflected in the relatively low costs for wb-MR angiography. Further improvement in image quality is expected from the use of the recently introduced continuous table movement techniques (variable table movement velocity, seamless image quality)[4,11] and automated table velocity control.[20]

Cardiovascular survey

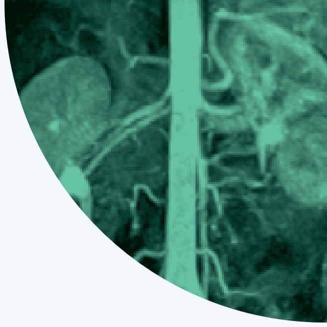
Based on a wb-MR angiography approach,[16] a fairly comprehensive combined protocol can be developed that achieves the depiction of the brain, the heart and the peripheral arteries from the carotids to the ankles.[21,22] This protocol optimises the logistics of intravenous contrast agent administration. It offers high image quality and can be performed in less than 60 minutes. Not only are macroscopic changes of the arterial system (except the coronaries) visualised but potential organ damage such as myocardial infarction, stroke or cerebral microangiopathy can also be observed.

MR venography

Venous MR angiography traditionally was performed by use of flow-sensitive pulse sequences (i.e. time-of-flight). Since the introduction of paramagnetic contrast agents in 1988, contrast-enhanced techniques are increasingly used. Many departments perform MR angiographies of the pulmonary arteries in a one-field-of-view technique; these can be complemented by MR venography of the lower extremities and abdominal-pelvic region (Figure 4) to detect potential sources for pulmonary emboli.[23,24] The high accuracy of MR venography in comparison with conventional phlebography can have a particular impact in the care of pregnant women (given due consideration of recommendations for contrast agent administration in pregnancy).[25] Another potential application for wb-MRI of vessels is the search for arterio-venous malformations.[26]

Wb tumour and metastasis search

There is broad clinical consensus about the need for screening for metastases in cancer patients, especially



as the presence of metastases might alter therapy from surgical to non-surgical alternatives.[27] Usually, screening for metastases is performed by a set of multiple diagnostic methods such as bone marrow scintigraphy, computer tomography, ultrasound, laboratory findings or more dedicated nuclear medicine techniques, depending on the tumour type. MRI in this context has traditionally been used for specific diagnostic hypotheses in restricted parts of the body (i.e. metastasis search in regional lymph nodes, liver, brain or spine) and until recently could not provide a complete survey, especially for M (metastasis) staging.

The first wb-MR studies used a rather slow fluid-sensitive sequence (short tau inversion recovery-sequence: 'STIR'), which was applied station-wise throughout the whole body. It could depict bone marrow infiltration by lymphomas and metastases but also by infection with high sensitivity.[28,29] The technique additionally allows the (rather superficial) assessment of parenchymal organs, so that MR could perhaps substitute for bone scintigraphy and CT.[30] Metastases in the vertebral bodies are better depicted by STIR MR compared with skeletal scintigraphy.[31]

Thin-slice axial three-dimensional T1 images after contrast agent application offer higher spatial resolution in all three dimensions, compared with STIR images. They potentially better characterise lesions in parenchymal organs and bone and soft tissues and can more easily be acquired in breath-hold techniques. This approach[32,33] allows for the evaluation not only of the bones but also the lung, the abdominal parenchymal organs and the lymphatic structures. MR detects almost all lung and all brain metastases seen by CT. With respect to skeletal scintigraphy, vertebral and pelvic bones in particular are better evaluated. As in-room time is under 15 minutes, this MR approach could be an alternative to skeletal scintigraphy screening for metastases.[32]

Recent studies have compared positron emission tomography combined with CT (PET-CT) with wb-MRI with respect to staging accuracy in malignant disease.[32,34] In detecting distant metastases, both modalities performed similarly well. MR performed better in the detection of bone and liver metastases,[35,36] but had the tendency to underdiagnose T (tumour) and N (node) stage. In case PET-CT is not available, or in the case of repeated examinations of children (where radiation exposure can be a risk), wb-MRI can be a valuable alternative. This might also hold true for patients with a known allergy to iodinated contrast agents.

The 'total' protocol

Not only can cardiovascular disease be assessed in one setting but also by adding MR of the lungs, contrast-enhanced cerebral MR and MR colonography, a comprehensive examination of virtually 'all' morphologically visible pathologies results (limitations will be described below).[21] MR colonography has been shown to be adequately sensitive for detection of polyps over 5 mm diameter.[37]

Post mortem MRI

Wb-MRI has been performed in human corpses, rendering valuable additional information on the cause of death. Problems with this indication include the low potential of coronary visualisation, and of differentiating between thrombi and emboli.[38] However, wb-MRI could play a role in examining cases without consent to autopsy or in case of distinct risk of infection.[39,40] In many countries, however, the legal basis for post mortem imaging remains undetermined.

Estimation of fat and muscle mass

Axial wb-MRI allows for assessment of total and compartmental adipose tissue as well as quantification of muscle mass of humans.[41,42] Fat–water separation has also been shown to be possible with continuous table movement.[43,44] In this regard, success control of physical training (i.e. body building) becomes possible.[45] In the future, wb-MRI could also play a role in the assessment of systemic diseases such as polymyositis[46] or muscular dystrophy.[47]

Wb screening

MRI is a natural candidate for screening, a term that refers to the search for occult disease – disease that has not yet become symptomatic (secondary prevention). The aim of screening is detection of disease in an early stage, which allows for more efficient therapy and may result in reduction of morbidity and mortality.

MRI fulfils many requirements for a screening technique: no ionizing radiation, no known effect on individuals with normal renal function, high diagnostic accuracy and high patient acceptance. The only drawback is the high cost involved. However, the combination of several single examinations in one combined screening protocol can reduce the relative costs.

The application of such a combined MR screening protocol in a large group of presumably healthy volunteers resulted in a very low detection rate of arterial and organ pathologies.[48] This highlights the need for adequate pre-selection for reaching an acceptable cost:benefit ratio.

Advantages and disadvantages of wb-MRI

Wb-MRI is capable of meeting a variety of needs in a single examination. However, there are some limitations to the technique. Many anatomic structures cannot be assessed: among them are the small bowel and stomach, breast, prostate, joints, and coronary arteries. Some of these structures can be assessed by dedicated MRI (for example, MR mammography screening especially in younger patients with high risk of breast cancer[49]) but they all remain unassessable in a non-specific wb-MRI, as presented above.

Another challenge is the enormous increase in image data in wb-MRI, which not only implies an increase in evaluation time for the radiologist but also increases the potential for false negative findings. Additionally, the radiologist cannot restrict him or herself to assessing

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only the target structures (i.e. myocardial morphology and function, arterial pathologies, tumours or colonic polyps). In particular, the three-dimensional nature and the large field-of-view of wb-MRI necessitate the work-up of all visible structures: bones and soft tissues, parenchymal organs, lymph nodes and the venous system. The radiologist must assume responsibility for chance findings, and the patient must consider the possibility that indistinct findings may be made and that these might have to be assessed with further, potentially invasive tests.

Future directions

MR manufacturers have acknowledged current demands and now offer scanners allowing high-speed data acquisition and data reconstruction (parallel imaging strategies), extended table movement range and a set of dedicated surface coils for the whole body. Future developments will be targeted toward high-frequency technology and pulse sequence design for ultrafast, high-quality imaging and concomitant reduction of total examination costs.

Additionally, there is a tendency towards higher field strengths. These render higher signal:noise ratios, which can be translated into higher spatial resolution but also into drastically lower acquisition times. Three Tesla systems have entered clinical practice, and the growing number of 7 Tesla systems or higher in research centres will certainly open new options, not only for brain imaging but also for wb applications.

Computer-aided diagnosis could be another keyword for future developments in wb-MRI, serving as competent second reader, as is possible in CT.[50]

The coronary arteries remain a focus of interest; they will certainly profit from future technical improvements. Depiction of the coronaries would enhance the assessment of cardiovascular disease as the major cause of death in Western countries.

Finally, the inherently higher sensitivity of MR compared with CT for many indications makes a combination of positron emission tomography with its functional information and MRI with its high soft tissue contrast (PET-MRI) a very promising dual-modality alternative to PET-CT for the work-up of tumour patients.[51]

Discussion

Wb-MR is a novel technique for examining a large portion of the body. Within a single MR setting, a variety of clinical questions can be answered which, until recently, required multiple, distinct examinations, usually on different days. Wb-MRI has already been established in some radiological departments and the potential indications for the technique are quite well refined. Wb-MRI is sufficiently accurate to be used as a side step if other wb modalities cannot be applied.

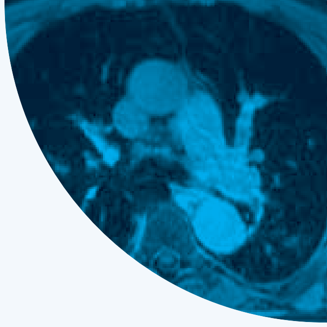
In the clinical setting, oncological wb-MR is already a valuable alternative if PET-CT is unavailable, for certain tumour types (tracer-negative tumours) or for follow-up of malignant conditions in children. Up to now, the lack of cost assumptions by health insurance companies has been a hindrance to the use of wb-MR in the clinical setting in many countries.

Today's limitations and pitfalls of wb-MRI include the lack of information on small bowel, breast, prostate, joints and coronary arteries (although organ-specific MRI may be valuable for these sites). Another drawback is the enormous increase in image data, which not only leads to an increase in reading time for the radiologist but also might increase the rate of false negative findings.

However, the continued development of MR scanner hardware will further facilitate wb-MRI. Thus, the concept of wb-MRI is likely to remain a focus of active research in the coming years.

Key Learning

- Wb-MRI became possible because of improvements in hardware, such as extended table translation, and the availability of a high number of simultaneous receiver channels
- Wb-MRI approaches will shift the spectrum of indications from dedicated characterisation of single pathologies towards assessment of systemic disease (atherosclerosis, metastatic disease, malformations)
- Wb-MRI appears to be a valuable alternative to PET-CT in children or in FDG-negative tumours
- Combined wb-MR protocols lead to a dramatic increase in image data, and might result in an increase in false negative findings
- Further developments in wb-MRI aim at multi-contrast imaging and further improvements in coil technology for faster data acquisition (parallel imaging), with the goal of reducing total examination costs



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