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THE ROLE OF IMAGING IN SCREENING SPECIAL FEATURE: REVIEW ARTICLE

Whole Body MRI and oncology: recent major advances

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ABSTRACT

MRI is a very attractive approach for tumour detection and oncological staging with its absence of ionizing radiation, high soft tissue contrast and spatial resolution. Less than 10 years ago the use of Whole Body MRI (WB-MRI) protocols was uncommon due to many limitations, such as the forbidding acquisition times and limited availability. This decade has marked substantial progress in WB-MRI protocols. This very promising technique is rapidly arising from the research world and is becoming a commonly used examination for tumour detection due to recent technological developments and validation of WB-MRI by multiple studies and consensus papers. As a result, WB-MRI is progressively proposed by radiologists as an efficient examination for an expanding range of indications. As the spectrum of its uses becomes wider, radiologists will soon be confronted with the challenges of this technique and be urged to be trained in order to accurately read and report these examinations. The aim of this review is to summarize the validated indications of WB-MRI and present an overview of its most recent advances. This paper will briefly discuss how this examination is performed and which are the recommended sequences along with the future perspectives in the field.

INTRODUCTION

For oncological patients, the accurate staging and precise evaluation of the metastatic burden are essential in order to plan an effective treatment. Following treatment, assessment of the change or not in tumour burden is equally essential in order to make decisions related to the continuation or modification of the treatment strategy. Ideally, oncological imaging techniques should be rapid, image a wide part of the body, provide high quality images and clinically significant information. All these requirements bring whole body magnetic resonance Imaging (WB-MRI) to the forefront, as a very attractive technique for tumour detection and response assessment with its lack of ionizing radiation and excellent ability to image both bone marrow and soft tissues. WB-MRI is increasingly used for a wide range of applications thanks to the improved accessibility and technological advances of the last decades.^{1,2} The use of diffusion weighted imaging (DWI), transforms WB-MRI to a “hybrid” technique as it provides functional information, enables an “at-a-glance” assessment of the whole body, reduces interpretation time and improves reader’s performance.^{3–5}

Rationale for the use of WB-MRI in oncology *Detection and staging:*

In oncology, lesion detection and precise staging are crucial in order to plan an effective treatment and assess prognosis. Many studies have shown that WB-MRI meets these demands thanks to its high performance for tumour detection, its ability to detect bone, node and distant metastasis (Figure 1), as well as the big field of view allowing to image the patient from head-to-toe. Working protocols with set-up in 1.5 and 3 Tesla MRI magnets are summarized in Table 1. In most of the studies, WB-MRI is compared to other staging techniques, such as bone scintigraphy (BS) and positron emission tomography (PET).

Solid tumours

Many studies have underlined the high sensitivity of WB-MRI for the detection of organ metastases, especially for tumours frequently metastasizing to the bone, lymph nodes and liver such as prostate,^{6–8} breast^{9,10} and colorectal cancers.¹¹ There have been reports that WB-MRI can modify a patient’s treatment¹² from radical to systemic and vice versa by correctly characterizing a patient as M0 or M1 (Figure 2).

Figure 1. Whole-body MR images in a 75-year-old male with castration-resistant prostate cancer. Coronal T_1 weighted MR images (a) and inverted scale DWI images (b -value: 1000 s mm^{-2}) (b) showing a diffuse low signal of the bone marrow on T_1 images and a high signal intensity in high b -values DWI (*) indicating diffuse metastatic bone disease, a metastatic lesion of the left lung (arrow) and an abnormal pelvic lymph node (arrow head). Note the discrepancy between T_1 and DWI. Homogenous diffuse low signal of the bone marrow on T_1 images due to the sclerotic nature of the disease with focal hyper signal lesions on DWI. DWI, diffusion weighted imaging.

Schmidt et al compared the accuracy of WB-MRI and PET-CT for the staging of various malignant tumours.¹³ For tumour assessment WB-MRI demonstrated a sensitivity of 86%, for lymph node involvement a sensitivity of 80% and a specificity of 75% and for metastatic disease a sensitivity of 96% and of specificity 82%. In another study by the same team, the diagnostic accuracy of WB-MRI and PET-CT was compared for the detection of tumour recurrence in patients with breast cancer.¹⁴ WB-MRI demonstrated an overall diagnostic accuracy of 91% with a sensitivity of 93% and specificity of 86%. PET-CT demonstrated comparable diagnostic accuracy, lower sensitivity (91%) and higher specificity (90%).

A study by Ohno et al showed that in patients with lung cancer, WB-MRI can be used for the M-stage assessment and may be considered at least as effective as fluorine-18 deoxyglucose (^{18}F FDG) PET-CT.¹⁵ For assessment of head and neck metastases, sensitivity (84.6%), and accuracy (95%) of WB-MRI were significantly higher than those of PET-CT (15.4 and 89.1%, respectively) on a per-site basis. When bone metastases were assessed, specificity (96.1%) and accuracy (94.8%) of WB-MRI were significantly higher than those of PET-CT (88.3 and 88.2%, respectively) on a per-site basis. Interobserver agreements for WB-MRI and PET-CT were similar. The same team recently

demonstrated that WB-MRI with DWI is more specific and accurate than ^{18}F FDG PET-CT and routine radiological examinations for assessment of recurrence in NSCLC patients.¹⁶ WB-MRI with and without DWI demonstrated slightly lower sensitivity.

During the last few years, major developments have been observed in the field of prostate cancer. It has been demonstrated that WB-MRI with DWI is superior to BS with or without targeted X-rays for the detection of bone metastasis.⁶ In 2014 Shen et al, effectuated a meta-analysis in order to compare the diagnostic performance of Choline PET-CT, MRI, Bone Single Photon Emission CT (SPECT), and BS in detecting bone metastases in patients with prostate cancer.¹⁷ Among these modalities, BS demonstrated the lowest sensitivity and specificity when WB-MRI was better than choline PET-CT and BS on a per-patient basis. The pooled specificities for detection of bone metastases using Choline PET-CT, WB-MRI, and BS, were 0.99 [95% CI (0.93–1.00)], 0.95 [95% CI (0.90–0.97)], and 0.82 [95% CI (0.78–0.85)], respectively. In 2016, Conde-Moreno et al compared ^{18}F -Fluorocholine PET-CT and WB-MRI with DWI for the detection of bone and/or lymph node metastases in oligo-metastatic prostate cancer patients.¹⁸ The authors concluded that WB-MRI and Choline PET-CT are complementary techniques. 35 patients were analysed and when comparing the standard work-up (BS, CT and pelvic MRI) with the combination of WB-MRI and Choline PET-CT, 16 patients went from being non-metastatic to metastatic (45.7%), five from being oligometastatic to polymetastatic (14.2%) and finally two went from being considered metastatic to M0 (5.7%). Only 12 remained at the same staging (34.3%). On the contrary, a recent study compared ^{11}C -Choline PET-CT and WB-MRI including DWI for patients with recurrent prostate cancer and found that PET-CT is superior for the detection of local recurrence and bone metastasis on a regional basis when WB-MRI showed similar diagnostic accuracy only for detecting LN metastases.¹⁹ The authors concluded that WB-MRI cannot serve as an alternative imaging modality for restaging prostate cancer.

A relatively new technique for prostate cancer detection is the Prostate Specific Membrane Antigen (PSMA) PET-CT. PSMA is a cell surface protein overexpressed by prostate cancer cells. Ligands of PSMA are labeled with ^{68}Ga , $^{99\text{m}}\text{Tc}$ and $^{123/124/131}\text{I}$ for the detection of Prostate cancer metastases or relapse^{20–22} (Figure 3). Gupta et al compared the diagnostic accuracy of ^{68}Ga PSMA PET-CT and MRI of the pelvis for the detection of LN metastasis in patients with high risk prostate cancer.²³ PET-CT was superior for the detection of pathological lymph nodes with diagnostic sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and accuracy 100, 80, 87.5, 100, 91.67%, vs 57.14, 80, 80, 57.4, 66.67%, respectively for the MRI. In 2015, Afshar-Oromieh et al studied the diagnostic value of PET-CT imaging with the new ^{68}Ga -labelled PSMA ligand HBED-CC (^{68}Ga -DKFZ-PSMA-11) for the diagnosis of prostate cancer.²⁴ The authors showed that PET-CT can detect prostate cancer in a high percentage of patients with suspected cancer (82.8%) and the tracer is highly specific for this tumour. The lesion-based analysis of sensitivity, specificity, NPV and PPV revealed values of 76.6, 100, 91.4 and 100%. Obek et al

Table 1. Proposed working protocols with set-up in 1.5 and 3 Tesla magnets

1.5 TESLA				
Sequence	WB 3D T1 WI	SPINE STIR	T2(*)	Whole body DWI
Number of stations × Acquisition time (minutes)	3 × 3:49	3 × 3:32	3 × 0:25	6 × 2:40
Sequence type	FSE	FSE	SSH	Diffusion
Plane	Coronal	Sagittal	Axial	Axial
Slices (mm), Thickness (mm), Gap(mm)	192, 1.4, 0	19, 3.5, 0.4	44, 4, 0	33, 5, 0
FOV (mm), Acquisition Matrix (mm)	440 × 440, 320 × 320	280 × 280, 320 × 256	420 × 336, 320 × 224	440 × 440, 96 × 128
Phase encoding	Right/Left	Feet-Head	Anterior-Posterior	Anterior-Posterior
TR (ms), TE (ms)	400, 12	4714, 5	562, 8	8400, 66
TI (ms)	/	140	/	/
NSA	1	2	3	1
Flip angle	varies	160°	varies	varies
Bandwidth (kHz)	62.5	31.25	83.33	250
<i>b</i> -values (s mm ⁻²)	/	/	/	50, 800 or 0, 1000
Target gam	Bone, Nodes	Bone (spine)	Liver, Nodes	Bone Nodes, Liver
3 TESLA				
Sequence	WB 3D T1 WI	SPINE STIR	T2(*)	Whole body DWI
Number of stations × Acquisition time (minutes)	4 × 3:59	3 × 2:17	3 × 0:43	4 × 3:36
Sequence type	3D TSE	STIR	SSH	Diffusion
Plane	Coronal	Sagittal	Axial	Axial
Slices (mm), Thickness (mm), Gap (mm)	210, 1.2, 0	13, 3.5, 0, 35	70, 4, 0	50, 6, 0.1
FOV (mm), Acquisition matrix (mm)	500 × 300, 440 × 230	260 × 260, 260 × 206	400 × 300, 308 × 186	400 × 352, 100 × 74
Phase encoding	Feet-Head	Feet-Head	Anterior-Posterior	Anterior-Posterior
TR (ms), TE (ms)	260, 21	3707, 45	609, 8	6000, 66
TI	/	210	/	/
NSA	2	1	1	1
Flip angle	90°	130°	90°	/
Bandwidth (Hz/pixel)	1052.2	565.6	629.2×	107.9
<i>b</i> -values (s mm ⁻²)	/	/	/	0, 50, 150, 1000
Target organ	Bone, Nodes	Bone (spine)	Liver, Nodes	Bone, Nodes, Liver

*optional sequence, not routinely used.

demonstrated that ⁶⁸Ga PSMA PET-CT is superior to morphological imaging for the detection of metastatic LN in patients with primary prostate cancer, even though surgical dissection remains the gold standard for precise lymphatic staging.²⁵

Even though there is evidence that choline PET-CT and WB-MRI are superior than BS for the detection of metastatic bone disease in PCa, the clinical benefit of detecting bone disease at an earlier time point remains to be studied further. Therefore, according to the European Association of Urology (EAU) guidelines, for high risk PCa patients, the metastatic staging should include at least a cross sectional abdomino-pelvic imaging and BS.²⁶

In the field of testicular cancer WB-MRI is very promising due to the usually young age of the patients and the surveillance protocol

which in some cases demands frequent imaging by CT^{27,28} (Figure 4). Mosavi et al evaluated the feasibility of WB-MRI with DWI for the follow up of these patients.²⁹ The authors demonstrated that WB-MRI is feasible and DWI offers functional information concerning the residual masses. Sohaib et al investigated the sensitivity of WB-MRI for the detection of retroperitoneal lymph nodes in patients with germ cells tumours.³⁰ The authors compared the retroperitoneal node detection of WB-MRI to CT and concluded that MRI has comparable sensitivity and is not inferior to CT which is the standard imaging technique at the time being. It has to be noted that DWI was not used in the WB-MRI protocol.

Neuroendocrine tumours (NET) are a heterogeneous family of slow-growing malignancies arising from the neuroendocrine

Figure 2. Whole-body MR images in a 68-year-old female with breast cancer. Bone scintigraphy anterior and posterior views (a), coronal T_1 weighted images (b) and inverted scale DWI images (b -value: 1000 s mm^{-2}) (c). The bone scintigraphy is normal, no abnormal foci are observed. WB-MRI study performed 2 days later showing minimum two bone lesions (arrows). Note the last station shading in DWI. DWI, diffusion weighted imaging.

cells. Most NET cells express somatostatin receptors (SSR), which can be targeted by labelled somatostatin analogues. There are many studies demonstrating that PET-CT in combination with ^{68}Ga -labelled SSA is very useful for the diagnosis of NETs.^{31–33} Carlbom et al compared the use of WB-MRI with DWI and liver-specific contrast agent-enhanced imaging to (^{11}C)-5-Hydroxytryptophan PET-CT (5-HTP PET-CT) for the detection of NETs.³⁴ 17 of 28 patients (61%) showed complete concordance between WB-MRI and the PET-CT examinations. There were three patients with lesions that were detected by PET-CT but not by MRI, four patients with liver lesions that were detected by MRI but not by PET-CT, and three patients with MRI-only detected lesions in other locations (1 or 2 lesions per patient). The authors concluded WB-MRI with contrast enhanced liver sequences is superior for the detection of liver metastases but did not detect all NET lesions spotted with 5-HTP PET-CT. In a prospective study Etchebehere et al compared $^{99\text{m}}\text{Tc}$ -hydrazinonicotinamide (HYNIC)-octreotide SPECT-CT, ^{68}Ga -DOTATATE PET-CT, and WB-MRI with DWI for the detection of NET lesions.³⁵ The authors demonstrated that ^{68}Ga PET-CT appears to be more sensitive for detection of well-differentiated NET lesions, especially for bone and unknown primary lesions. Moryoussef et al showed that the addition of DWI in the WB-MRI protocol revealed additional findings in 71.4% of the patients compared to WB-MRI alone, with 72.4% more lesions, mainly infracentimetric.³⁶ These observations lead to the modification of the therapeutic management for 19% of the patients.

Melanoma

In a prospective study, Muller-Horvat et al compared the efficacy of WB-MRI with conventional Whole Body CT (WB-CT) in 43 patients with advanced malignant melanoma and demonstrated that WB-MRI was more sensitive than the standard imaging for the detection of solid metastases.³⁷ WB-CT was more sensitive for the detection of lung nodules, even though WB-MRI correctly identified all lung nodules larger than 5 mm. One year later, Pfannenbergl et al compared the overall and site-based

accuracy of ^{18}F FDG PET-CT and WB-MRI. The overall accuracy in the lesion-based evaluation was 86.7% for PET-CT, 78.8% for WB-MRI, 75.0% for CT and 74.3% for PET alone.³⁸ The differences between PET-CT and WB-MRI, as well as between PET-CT and PET alone were significant. In 2010, Laurent et al compared WB-MRI with a multicontrast protocol and DWI to ^{18}F FDG PET-CT.³⁹ For the overall accuracy evaluation, the sensitivity was 88.6% for WB-MRI and 72.9% for PET-CT and the specificity was 97.6% for WB-MRI and 92.7% for PET-CT. MRI was the best modality for staging liver metastases, as PET-CT failed to identify two metastases. Regarding bone and skeletal metastases, MRI was also superior. Petralia et al studied 19 patients in order to investigate whether WB-DWI alone is adequate for detecting metastases in melanoma patients or if WB contrast-enhanced MRI is required.⁴⁰ They concluded that WB-DWI is promising for the detection of extracranial metastases (lung metastases greater than 5 mm and even smaller metastases in the abdomen, pelvis, bones, and subcutaneous tissues) but contrast enhanced MRI is required for the evaluation of the metastatic brain disease. The German evidence based guideline for cutaneous melanoma recommend the use of PET-CT for detection of extra-cranial metastatic disease even though it is specified that whole body MRI may also be used as alternative.⁴¹ The Swiss guidelines recommend the use of CT, MRI, PET or PET-CT every 1–5 years for the follow up of patients with Stage IIC, III et IV tumours.⁴²

Haematological cancers

WB-MRI is a very useful tool for the imaging of patients with monoclonal plasma cell disease (Figure 5). MRI has the highest sensitivity for detecting bone marrow involvement.^{43,44} The recent consensus statement from the International Myeloma Working Group (IMWG) has recommended WB-MRI for the work-up of solitary bone plasmacytoma and all patients suspected of having asymptomatic or smoldering multiple myeloma (MM).⁴⁵ According to the authors, MRI provides significant prognostic information in patients with symptomatic disease and may be

Figure 3. ^{68}Ga -PSMA PET CT (a) and WB-MRI (b, c, d) in a 82-year-old patient with high risk for metastasis prostate cancer (a): Clearly visible pathological accumulation of the radiotracer at the level of the spine (arrows) indicating metastatic bone disease and at the level of the pelvis (arrow head) demonstrating the presence of an abnormal lymph node (b-d): Coronal T_1 weighted MR images (b, c) and inverted scale DWI images (d, b -value: 1000 s mm^{-2}) (c) with the same findings. Multiple bone marrow metastasis at the level of the spine (arrows) and an abnormal pelvic lymph node (arrow head). Note the splenomegaly as the patient suffers from mild liver failure. DWI, diffusion weighted imaging; PET, positron emission tomography.

found useful in the better definition of complete remission. Furthermore the National Institute for Health and Care Excellence (NICE) guidelines for myeloma state that WB-MRI should be used as first line examination before WB-CT and X-rays.⁴⁶ Chantry et al also recommend the use of WB-MRI in patients with MM pointing out that this technique has prognostic value and should be used in the assessment of treatment response.⁴⁷ Bäuerle et al demonstrated that WB-MRI should be preferred over spine MRI for patients with a MM or monoclonal gammopathy of undetermined significance (MGUS).⁴⁸ In their study the authors showed that the lesions were confined to the spine or sacral bone in only 11 out of 48 patients with bone involvement.

In nine patients, the lesions were located only outside the spine, and in 28 patients the lesions were found both axially and extra-axially. The authors concluded that the detection of nearly 50% of the patients with monoclonal plasma cell would have been missed by spine MR imaging.

In a recent study Rasche et al investigated newly diagnosed MM patients using simultaneous FDG-PET and WB-DWI, in order to describe the proportion of PET false-negative patients and to identify tumour-intrinsic features associated with PET false-negativity.⁴⁹ In 11% of patients, WB-DWI was positive (DWI+) for disease when no apparent disease involvement was detected using

Figure 4. Whole-body MR images in a 25-year-old male with testicular seminoma. Coronal T_1 weighted MR images (a) and inverted scale DWI images (b -value: 1000 s mm^{-2}) (b) show a pathologic retroperitoneal lymph node (arrow). DWI, diffusion weighted imaging.

PET-CT (PET-). In order to shed light on this “PET false-negativity” phenomenon, the authors compared the gene expression profiling data derived from the DWI + /PET + and DWI + /PET - cases. The results showed a strong association between low hexokinase-2 expression and false negative FDG-PET examination results. In respect to these results, WB-DWI is arising as a very efficient alternative examination in these patients.

Dixon imaging is an approach for fat suppression using simple spectroscopic imaging, published by Dixon in 1984.⁵⁰ With this technique two different images are obtained: a conventional image with water and fat signals in phase (IP) and a second one so that fat and water signals are 180° out of phase (OP). From

these two images a water only (WO) and a fat only (FO) images are acquired. The water only sequence is very useful thanks to the fat suppression. Bray et al studied the diagnostic utility of WB Dixon MRI in MM.⁵¹ 30 patients with clinically-suspected MM underwent WB-MRI and unenhanced Dixon IP, OP, WO and FO images were obtained and analysed. The authors demonstrated that FO images were superior to the other concerning lesion counts, true positives, sensitivity and confidence. Additionally, the contrast to noise ratio was higher for FO than IP images. Also, the FO sequence offered the greatest advantage for patients with focal lesions, but also provided superior sensitivity in patients with diffuse disease. The authors conclude that in order to improve diagnostic efficacy and reporting, the radiologists should preferably review FO images.

The diagnosis of bone marrow involvement in lymphoma is of great importance because its presence indicates the highest Ann Arbor stage (Stage IV) and may have therapeutic and prognostic implications.^{52,53} Blind bone marrow biopsy (BMB), usually of the posterior iliac crest-even though it is an invasive and painful procedure prone to sampling errors and false-negatives remains the standard diagnostic test for the assessment of the bone marrow in lymphoma.⁵⁴⁻⁵⁷

WB-MRI has emerged as a very promising technique for nodal and extranodal staging of lymphoma.⁵⁸⁻⁶⁰ Recently Albano et al compared WB-MRI with DWI, ^{18}F FDG PET-CT and BMB, for the evaluation of bone marrow involvement in patients with newly diagnosed lymphoma.⁶⁰ According to the authors, both WB-MRI and PET-CT showed very high reliability in the detection of bone marrow involvement. The two techniques were concordant in all cases of diffuse large B-cell and follicular lymphomas but had low sensitivity for the detection of low volume bone marrow involvement in mantle cell and marginal zone lymphomas. A more recent study by Adams et al assessed the prognostic implications of WB-MRI findings in diffuse large B-cell lymphoma patients with a negative blind BMB and demonstrated that WB-MRI has prognostic implications in these

Figure 5. Whole-body MR images in a 68-year-old male with multiple myeloma. Coronal STIR (Short tau inversion recovery) (a) and T_1 weighted (b) MR images and inverted scale DWI images (b -value: 1000 s mm^{-2}) (c). The bone marrow shows diffuse hyperintense signal in STIR (a,*), hypointense signal in T_1 (b, *) and high signal intensity in high b -value DWI (c,*) indicating diffuse tumoral infiltration (spine, pelvis, femora, humeri and ribs). Two dorsal vertebral fractures are observed (arrows). X-ray of the skull (d) demonstrating multiple lytic lesions (arrows).

patients as it can modify their Ann Harbor score.⁵⁹ The authors concluded that disease relapse or progression and death occur more frequently in WB-MRI positive patients than in WB-MRI negative patients. An older study by Tsunoda et al demonstrated that abnormal MRI signal of the patients' femoral bone marrow, is associated with a significantly poorer survival, regardless of histologic findings of the BMB.⁶¹

Whole body MRI can play an important role in the imaging of lymphomas with poor ¹⁸F-FDG avidity as low grade lymphomas. Although most lymphoma subtypes have been shown to be highly avid to ¹⁸F-FDG, there are some subtypes with lower avidity such as small cell lymphocytic lymphoma,^{62,63} peripheral T-cell lymphoma⁶⁴ and extranodal marginal zone lymphomas, including the mucosa-associated lymphoid tissue (MALT) marginal zone lymphoma.⁶⁵ Last but not least, utility of whole-body MRI as a radiation-free alternative to FDG-PET-CT for staging of pregnant patients with malignant lymphoma has to be highlighted. It has to be underlined that the use of gadolinium should be limited only in cases which the benefits clearly outweigh the possible risks for the fetus.⁶⁵

WB-MRI as screening tool

WB-MRI can be used as a tool for cancer screening in patients with genetic predisposition to develop tumours.^{66–68} It is common knowledge that the outcome of the oncological patients improves when the tumour is identified at earlier stages. Some of the syndromes that are mentioned in the literature are multiple endocrine neoplasias I and II (such as endocrine tumours), Von Hippel-Lindau syndrome (such as renal carcinomas), familial adenomatous polyposis (such as colorectal tumours), and Li-Fraumeni syndrome (various types of tumours including sarcomas).

Quite recently Anupindi et al proposed the use of a WB-MRI protocol for the screening of children with cancer-predisposing conditions.⁶⁹ The WB-MRI protocol consisted of multiple anatomic sequences, without the use of intravenous contrast. WB-DWI was not consistently used in this study.

A recent meta-analysis by Ballinger et al investigated whether WB-MRI can detect asymptomatic cancers in a curable stage in patients with Li-Fraumeni syndrome, carriers of TP53 gene.⁷⁰ Baseline WB-MRI identified a new and treatable malignant neoplasm in 7% of the patients. The authors concluded that WB-MRI is a useful tool for early detection of neoplasms in this cancer-prone population and its use could be proposed for the routine baseline assessment of TP53 mutation carriers.

WB-MRI can be used in multiple tumours disease such as Langerhans cell histiocytosis and hereditary multiple exostoses syndrome in order to evaluate the disease.⁷¹ Hardes et al suggested the use of WB-MRI in cases of multifocal vascular tumours as angiosarcoma.⁷² Jaspersen et al evaluated the value of WB-MRI as a screening method in families with succinate dehydrogenase (SDH)-associated hereditary paragangliomas and recommended the use of this modality combined with traditional biochemical testing.⁷³

WHOLE BODY MRI: HOW TO DO IT?

General considerations

There are several technical challenges to overcome, in order to perform WB-MRI. First, the acquisition of good quality images necessitates the main magnetic field to be strong enough in order to provide a high signal to noise ratio (SNR); as a result, using a minimum of a 1.5 Tesla magnet is a prerequisite.⁷⁴ 3.0 Tesla magnets provide higher SNR for anatomic sequences. On the other hand DWI sequences are less robust when acquired with 3.0 Tesla than 1.5 Tesla magnets because the sequence is more prone to artefacts.⁷⁴

Second, WB-MRI coverage requires the development of multi-station techniques in which the different body regions are scanned step by step and the individual data are combined and composed in order to acquire a WB image. In recent years, the development and use of a high-performance gradient and radiofrequency systems provide rapid image acquisition and homogeneous excitation of large volumes retrospectively. Thanks to these technological advances, the acquisition time can be reduced without significantly sacrificing the quality of the images.^{50,51} Moreover, three dimensional (3D) acquisition images can be acquired as well as anatomical imaging with different weighting (water, fat).^{50,51}

Thirdly, the inclusion of a WB-DWI into a WB-MRI protocol increases the diagnostic performance of the protocol in various cancers.^{1,75} WB-DWI does not require breath-holding or respiratory triggering and as a result the scanning time is no longer a limiting factor. Thin slices are acquired with the possibility of 3D reconstructions as maximum intensity projections (MIPs), volume rendering, and multiplanar reformatting (MPR). Images with different diffusion weighting (*i.e.* with different *b*-values) can be acquired with the additional possibility to calculate an intra-lesional Apparent Diffusion Coefficient (ADC), or to reconstruct an ADC map of the region of interest; these latest approaches improve the detection of lesions and allow quantitative characterization.

Fourth, advanced image post-processing is required for the quantitative analysis of response to treatment. Accurate co-registration (*i.e.* accurate spatial alignment) of different examinations or of different imaging modalities have to be achieved first.

Which sequence and which plane?

A review of the literature reveals that depending on the team and acquisition time, WB-MRI protocols consist of only anatomic or anatomic and functional (DWI) sequences.⁷⁵ While the interest of WB-DWI within a WB protocol is not contested (even if further work is needed to understand how to implement it optimally), an important heterogeneity is observed between different countries, centres and teams regarding the anatomic sequences and acquisition planes.

Some teams use *T*₁ and STIR sequences of the whole body in coronal^{76–79} or axial plane, others only one of these anatomic sequences.^{7,9,80–83}

Recent studies have demonstrated the utility of WB Dixon imaging.^{51,84–88} Thus, Dixon sequences are increasing in popularity for the detection of bone lesions in oncological patients, as they offer high quality images in shorter acquisition time than classic spin echo images. Bone marrow fat fraction maps have to be generated, when Dixon images are obtained.^{89–91} In order to calculate fat fractions from gradient-echo Dixon scans, the acquired images should be proton density weighted. Depending on the sequence parameters (flip angle, repetition time), some residual T_1 weighting may result. In this case, the estimated fat fractions become inaccurate, but can be corrected by using literature values for the T_1 of fat and the tissue of interest.

Furthermore, Dixon sequences offer good fat suppression images in obese patients.⁹² The conspicuity of bone metastasis with each of the Dixon sequences was studied by Costello et al in 2013.⁸⁸ The authors concluded that in fast Dixon WB-MRI protocols, FS T_1 with contrast sagittal, FO T_1 with contrast sagittal, T_1 with Contrast sagittal, and FS T_1 with contrast axial sequences had significantly higher conspicuity for bone metastases compared to other sequences.

Regarding the acquisition plane, the coronal is widely used because it enables fast coverage of larger parts of the body, even though there are some limitations concerning the visualization of the long bones, skull, sternum, scapula and ribs. A dedicated plane can be added in order to better visualize certain structures, as a whole spine sagittal plane or an axial plane for the visualization of the ribcage and the sternum.^{6,7,81,93,94}

A new 3D T_1 WB-MRI (WB 3D T_1) anatomic sequence has been developed that could potentially replace the different anatomic components of WB-MRI protocols for the bone and node staging of cancer patients.⁹⁵ This new sequence can be reconstructed

in any plane, is of millimetric resolution and demonstrates enhanced image quality, compared to the two-dimensional (2D) sequences utilized until now (Figure 6).

Currently there is an urgent need for standardization and better evaluation of the clinical benefit of WB-MRI protocols. There are no clear recommendations stating which sequences should be used and in which plane, apart from prostate cancer. Padhani et al in METastasis Reporting and Data System for prostate cancer (MET-RADS), recommend the use of WB-DWI in axial plane (minimum 2 b -values), and for the anatomic counterpart T_1 and STIR sagittal sequences of the spine, a WB T_1 gradient echo (GRE) Dixon sequence in axial or coronal plane (or both) and optionally a WB T_2 W TSE without fat-suppression in axial plane.⁹⁶

However, according to Ohlmann-Knafo et al WB-MRI protocols for bone metastases detection could safely be limited to the T_1 sequence especially at 3 Tesla magnets.⁹⁷ According to the authors the STIR sequence can be omitted as it does not offer better performance nor modifies the diagnosis made by T_1 sequences alone.

Latest developments of whole body MRI in oncology

Treatment monitoring and prognosis

Even though WB-MRI protocols have been shown to be promising in the evaluation of treatment^{2,90,96,98–100} the radiological community is still busy searching for pertinent and robust (*i.e.* clinically validated) imaging biomarkers for the follow up of oncological patients (Figures 7 and 8). WB protocols with DWI sequences along with anatomical imaging can potentially generate these markers. The pertinence of parameters such as the (total) tumour volume, the ADC (or measurements derived

Figure 6. Whole-body 3D MR images in a 70-year-old male with prostate cancer (a) Coronal reconstructed image showing bone marrow metastasis of right iliac bone (arrows) and an abnormal iliac lymph node (arrow head) (b) Sagittal reconstructed image showing multiple bone marrow metastasis of the spine (arrows) (c1 and c2). Axial reconstructed images showing bone marrow metastasis of a left rib (arrows in c1) and an abnormal para-aortic lymph node (arrow in c2).

Figure 7. Progressive disease in a patient on androgen deprivation therapy whole body MRI images in a 69-year-old patient with prostate cancer. (a-d): Baseline examination and (e-h): 6 months follow up (a-c, e-g): Coronal T_1 weighted MR images (d, h): Reconstructed maximal intensity projection image from inverted scale DWI images (b -value: 1000 s mm^{-2}) (a-d): Sternal (arrows) and dorsal spine (arrow heads) bone marrow metastasis and a normal sized left iliac lymph node (dotted arrow) (e-h): increase in size (e-g) and in high b -value signal intensity (h) of sternal (arrows) and dorsal spine (arrow heads) bone marrow lesions and increase in size of the abnormal lymph node.

from the ADC such as the total diffusion volume, the functional response map or the ADC histograms), or the signal fat fraction are currently under investigation.

In patients with MM, Horger et al observed that DWI measurements accurately correlated with the course of the disease, according to clinical and laboratory criteria.⁹⁸ Messiou et al demonstrated that marrow ADC values (derived from MRI of the spine and pelvis) in patients with active myeloma are significantly higher than in patients in remission.⁹⁰ ADC increased

at 4–6 weeks and decreased at 20 weeks in responders. In progressing and stable patients, ADC did not change significantly between time points. In 2012 Mertz et al studied the prognostic significance of longitudinally performed WB-MRI in patients with smoldering myeloma.¹⁰¹ WB-MRI contributed to the risk stratification in these patients and defined a group that had high risk of progression to MM. The authors analysed 63 patients with smoldering myeloma which had at least two WB-MRIs for follow-up. Progressive disease in the second WB-MRI was of prognostic significance.

Figure 8. Response to treatment in a patient on androgen deprivation therapy. Whole body MRI images in 50-year-old patient with prostate cancer. (a-c): Baseline examination, (d-f): 6 months follow up, (h, i): 1 year follow-up (a, b, d, e, h, i): Coronal T_1 weighted MR images (f): dorsal region of (e), magnified (b, g, j): Reconstructed maximal intensity projection image from inverted scale DWI images (b -value: 1000 s mm^{-2}) (a-c): Multiple bone marrow metastasis (arrows) and abnormal pelvic lymph nodes (arrow heads) (d-i): Decrease in size and in signal intensity in T_1 sequence (d, e, h, i) of the spine (arrows) and left femoral (dotted arrows). Emergence of peritumoral hyperintense fat around the dorsal lesions (f-arrow) and decrease in signal intensity in T_1 sequences (d, e, h, i). Decrease in signal intensity in high b -values DWI for the dorsal lesions (g- arrows) and disappearance of the left femoral lesion (g-dotted arrow). Decrease in size (d, e, h) of the pelvic lymph nodes (arrow heads). DWI, diffusion weighted imaging.

Bannas et al compared the diagnostic performance of WB-MRI with haematological parameters (monoclonal protein concentration, serum protein electrophoresis, monoclonal immunoglobulin, immunofixation electrophoresis) for detecting persistent or relapsing disease in patients with MM after stem cell transplantation.¹⁰² The authors concluded that even though WB-MRI is very convenient and well suited for the localization of intra- and extramedullary disease, it demonstrated only moderate agreement between with serum analyses when assessing response to therapy.

In 2015, Takasu et al demonstrated that fat signal fraction derived from Dixon sequence can be used as a biomarker in order to discriminate symptomatic from asymptomatic myeloma.⁹¹ The authors proved that fat signal fraction offers superior sensitivity and specificity to bone marrow plasma cell percent of biopsy specimens.

Latifoltojar et al proved that patients with MM who demonstrate response to treatment, show a significant increase in signal fat fraction, compared to no significant change in non-responders.⁸⁹ At 8 weeks, a reduction in estimated tumour volume (eTV) was observed, as well as an increase in signal fat fraction and ADC in the group as a whole. Patients with complete/very good partial response had a significantly greater increase in signal fat fraction compared to those achieving partial response. The same team studied 21 patients with MM who underwent WB-MRI with DWI sequences at diagnosis and after two cycles of chemotherapy. ADC increased significantly following treatment in 7/14 responders.⁸⁴ After treatment in the non-responders group, ADC did not change significantly in 4/6 patients, and increased in 2/6. The authors concluded that the ADC significantly increased in responders but not in the non-responders.

Mayerhoefer et al studied whether interim ^{18}F FDG PET-CT or WB-DWI can predict the end of treatment outcome after immunotherapy in patients with MALT.¹⁰³ Patients with untreated MALT lymphoma prospectively underwent ^{18}F FDG PET-CT and WB-DWI before treatment and after three cycles of rituximab-based immunotherapy. Maximum and mean standardized uptake values (SUVmax and SUVmean respectively), and minimum and mean apparent diffusion coefficients (ADCmin and ADCmean respectively), were measured for up to three target lesions per patient. The authors also measured the rates of change between baseline and interim examinations (ΔSUVmax , $\Delta\text{SUVmean}$, ΔADCmin , and $\Delta\text{ADCmean}$). The authors found significant differences between complete remission and partial remission for parameters ΔSUVmax , $\Delta\text{SUVmean}$, and ΔADCmin and between complete remission and stable disease for parameters ΔSUVmax , $\Delta\text{SUVmean}$, ΔADCmin and $\Delta\text{ADCmean}$.

WB-DWI can be used as an indicator of response to treatment, since the data from the sequence can be quantified and used in order to construct parametric maps. In a pilot study, Blackledge et al performed a small cohort of patients with bone metastases who were classified as non-responders to treatment. They observed a significantly larger percentage increase in their total Diffusion Volume (tDV) after treatment, compared to responders.¹⁰⁴

Among the responders, there was a significant decrease in tDV, an increase in the median global Apparent Diffusion Coefficient (gADC) and gADC variance.

Perez-Lopez et al proved that WB-DWI can be used for the assessment of metastatic bone disease in patients with prostate cancer.¹⁰⁵ The authors demonstrated that there is a strong correlation between tDV and overall survival of these patients. A year later, the same team indicated that patients which show response to olaparib present a decrease in tDV and an increase in median ADC of bone metastases.¹⁰⁶

Concerning metastatic bone disease in patients with prostate cancer, Messiou et al studied 26 patients with bone metastases who underwent DWI MRI of the lumbar spine and pelvis at baseline and 12 weeks following chemotherapy.¹⁰⁷ The authors indicated that ADC and true diffusion ADC without contribution of perfusion, increase significantly in lesions of both responders and progressors and concluded that mean ADC is not an appropriate biomarker for disease response. In contrast to these results, Reischauer et al demonstrated that DWI MRI allows monitoring of hormone therapy in patients with prostate cancer and bone metastases.¹⁰⁸ Mean tumour ADC increased in response to hormone therapy and corresponded well with a decrease in PSA.

Padhani et al proposed the MET-RADS imaging recommendations for tumour detection and treatment evaluation in patients with advanced prostate cancer.⁹⁶ The main aims of this reporting system are to develop complete and detailed response criteria for bone, soft tissue and local disease assessment, in order to establish the minimum acceptable technical requirements for WB-MRI and to educate the radiologists with an aim to reduce the variability in interpretations.

Recently Kosmin et al investigated whether there is any additional benefit in using WB-MRI alongside restaging thoraco-abdominal CT scans in patients with metastatic breast cancer.¹² The authors showed that WB-MRI detected additional sites of disease not reported by the CT, mostly in bone. Moreover, in 46 cases (28%) there were differences concerning the response to treatment between WB-MRI and CT. From these cases 89.1% showed evidence of either disease progression or partial response that was reported as stable disease on CT. The systemic anti-cancer therapy was significantly modified following the additional information provided by that WB-MRI, but it is unclear whether this improved the patient outcome.

WB-MRI and oligometastatic patients

Solid tumours that have given distant metastasis are considered incurable with few exceptions such as germ cell tumours and colon cancer. Lately, the subject of oligometastatic patients is receiving more and more attention by the scientific community. In 1995, Hellman and Weichselbaum introduced the term of "oligometastases".¹⁰⁹ The authors suggested that there are intermediate tumour states between purely localized cancer and metastatic and that the oligometastatic patients could be good candidates for curative treatment. For patients with breast cancer, the existing guidelines recommend surgery, radiation,

and regional chemotherapy as possible therapeutic options in patients with localized metastatic disease.¹¹⁰ According to the consensus recommendations of The European School of Oncology–Metastatic Breast Cancer (ESO–MBC) "A *small but very important subset of metastatic breast cancer patients, for example those with a solitary metastatic lesion, can achieve complete remission and a long survival. A more aggressive and multidisciplinary approach should be considered for these selected patients*".¹¹¹

Even though according to St. Gallen Advanced Prostate Cancer Consensus Conference (APCCC) 2015, prostate cancer patients with 3 or less synchronous metastases (bone and/or lymph nodes) were considered to be oligometastatic,¹¹² the new APCCC 2017 panel did not reach a consensus.¹¹³ 10% of the panelists did not believe that "oligometastatic prostate cancer" is a clinically meaningful entity. From the panelists that believed in the definition of "oligometastatic" patients, 14% voted for ≤ 2 metastases, 66% for ≤ 3 metastases, and 20% voted for ≤ 5 metastases as a cut-off for the number of metastases to consider a patient as "oligometastatic".

There is now a significant amount of studies suggesting that there is a survival benefit if these males have radical treatment of their primary tumour alongside "metastasis-directed therapy".¹¹⁴ A recent meta-analysis concluded that metastasis-directed therapy with surgery and/or radiotherapy instead of a systematic approach, is very promising although the low level of evidence does not allow its recommendation as standard of care.¹¹⁴ Undoubtedly for these treatment options to be successful, the accurate and proper characterization of a patient as "oligometastatic" and the correct identification of all the metastatic sites are crucial.

The important role of new imaging techniques that are capable of accurately detecting metastatic lesions as WB-MRI with DWI and PET-CT is highlighted by various recent studies.^{112,115} New robust techniques such as PET-CT and WB-MRI with DWI have the greatest versatility in terms of metastasis detection even though current guidelines and recommendations remain based on conventional imaging modalities.^{112,115} In a recent study, Larbi et al demonstrated that the proportion of prostate cancer patients with oligometastatic disease can be accurately determined by WB-MRI + DWI.¹¹⁶ This study also provided a "map" demonstrating the distribution of lymph node metastases.

"All in one" WB-MRI protocols

The multimodality algorithms that are used for the TNM staging of cancer patients necessitate multiple hospital visits and appointments in different departments (Radiology and Nuclear Medicine departments), leading inevitably to additional waiting times and discomfort for this fragile group of patients (elderly with multiple comorbidities). In order to save time, single modality protocols have been developed and are used in clinical practice.

In 2003 Antoch et al emphasized on the potential of single examinations for the staging of oncological patients.¹¹⁷ The team studied the performance of WB-MRI and FDG PET-CT for the overall TNM classification of 98 patients with various malignant

Figure 9. "All in one" WB-MRI protocol for the TNM staging of a high risk for metastasis in a 74-year-old prostate cancer patient. One single step protocol combining a multiparametric MRI of the prostate (a, b) for the T and a WB-MRI protocol (c-f) for the N and M staging. T_2 axial images (a) and ADC map (b) of the prostate demonstrating a low signal intensity mass with low ADC values (arrows). No capsular invasion. Coronal T_1 weighted WB-MRI images (c, d) and inverted scale DWI images (b -value: 1000 s mm^{-2}) (e, f) showing a metastatic bone marrow lesion of the right ischio-pubic ramous (arrows) and abnormal retro-peritoneal and pelvic lymph nodes (arrow heads). The TNM staging of this patient is T2N1M1.

tumours and concluded that PET-CT was significantly superior to WB MRI.

The use of WB-MRI protocols can allow the complete disease assessment in one single examination including detection of metastasis sites which reduces the number of hospital visits for the patients.^{7,118} In 2013, anatomic and functional WB-MRI sequences were combined with a multiparametric MRI (mpMRI) of the prostate, in order to obtain the complete TNM staging of prostate patients in a single step MRI protocol⁷ (Figure 9). This new "one step" protocol outperforms the current techniques (thoraco-abdominal CT for N staging and Bone Scintigraphy with X-rays when necessary for M staging) for the staging of newly diagnosed patients. In accordance with these results, the team of Robertson et al confirmed these results and demonstrated that WB-MRI with a dedicated prostate MRI is feasible in clinical routine and provides clinically important information in patients with suspected recurrent prostate cancer.¹¹⁹ The MET-RADS imaging recommendations were also formulated in order to study all manifestations of advanced prostate cancer in one WB-MRI examination.⁹⁶

Problems to be solved and future perspectives

Cost and examination time

The two major obstacles in making the use of WB-MRI more widespread are elevated cost and longer scan times. While the MR examination time is a general concern, it becomes of paramount importance for oncologic patients who may be frail and/or in pain. WB-MRI protocols have to be constructed to include only the necessary, but sufficient sequences to answer the clinical question.

There have been many innovations in order to overcome the limit of time during the last years¹²⁰⁻¹²² but there is still a lot of work in progress. Possible strategies for the acceleration of data acquisition are the use of standard techniques (minimizing the number of signal averages, reduced scan percentage), half scan (half Fourier imaging), rectangular FOV), parallel imaging techniques (SENSE, GRAPPA etc) and the use of sparse MRI (compressed sensing). In order to reduce the acquisition time, for the anatomic sequences the plane that is usually implemented is the coronal and for the DWI, only two b -values can be used in staging. Furthermore, scan time of "All in one" WB-MRI will most probably decrease in the future as new studies support that for prostate MRI, abbreviated biparametric protocols demonstrate equivalent performance to multiparametric ones.^{123,124} A decrease in acquisition time will mean a reduction in cost and an increase in MRI machine availability, as both of these factors are dictated by scan duration. Less time spent on the machine will also mean higher level of patient comfort and reduction of movement artefacts.

Standardization of WB-MRI protocols

It is widely acceptable that there is an immediate need for standardization and uniformity of WB-MRI protocols before the literature becomes as frustrating and puzzling as a "tower of Babel", as it was suggested by Turkbey and Choyke.¹²⁵ The uniformity and standardization of WB-MRI protocols will promote a better communication between imaging specialists and clinicians and will encourage the quality assurance.

A big step forward towards this direction was recently made by Padhani et al.⁹⁶ The team described the recommendations to standardize the WB-MRI protocols for the imaging of patients with advanced prostate cancer.⁹⁶ The authors stated the minimum acceptable technical requirements and proposed a complete WB-MRI protocol including functional and anatomical sequences. For every examination, the radiologist should complete a structured clinical and radiological template. This report should contain the indication, details of the technique, the findings with description and measurements of the lesions and finally a clear and brief conclusion summing up the overall assessment of the disease status.

Of course, in order to make WB-MRI an effective examination for cancer detection and staging, radiologists have to be educated and given the skills to implement and interpret WB-MRI images. Insufficiently educated radiologists will not be able to keep up with the rising demands of clinicians and this creates a vicious cycle. They have to be coached on the right indications, what the

clinician needs to know and expects from them, how to interpret the images and draw conclusions concerning response or not to treatment. Detailed practice guideline statements and properly updated training courses are necessary steps to reach this objective.

Post-processing of WB-MRI data

To date, there is a critical lack of imaging tools to ease the analysis of WB-MRI data. Very few options exist to help in lesion detection, track the same lesion in consecutive follow-ups, and finally demonstrate automatically the evolution of functional parameters (like the ADC) during the disease.

Intensity standardization between stations and then co-registration algorithms are needed to spatially re-align the multiple stations acquired and to obtain an exact anatomical match between anatomical and functional data.

New technologies are being developed to accurately compare successive examinations with each other. Various strategies are currently investigated for research purposes^{126–128} and the development of tools for segmentation and lesion detection remains a focus of ongoing research.

For image processing and disease segmentation, Blackledge et al proposed an approach based on manual thresholding completed by a GrowCut algorithm (with the inclusion of a Markov random field to limit the number of false positive voxels) and a final reviewing by an expert radiologist in order to segment bone metastases below the C4 vertebra.¹⁰⁴ Other approaches based on machine learning are also investigated.¹²⁹

These developments are still in their infancy. Further work is therefore required in order to develop mature imaging tools which will allow an accurate and automated extraction of morphological and functional markers. Furthermore lesion detection and segmentation problems have to be resolved. These problems are complex and they may require the combination of different segmentation algorithms (thresholding, region growing, clustering).

There are some concerns regarding the reproducibility of quantitative measurements derived from MRI protocols, in particular from the ADC coefficient. Chenevert et al observed excellent agreement in ADC values obtained from different MRI magnets (from different vendors) on water phantoms (ADC variability of 5 to 6%).¹³⁰ Messiou et al demonstrated that in normal healthy volunteers, the coefficient of reproducibility of ADC was 14.8%.¹³¹ In patients with lung tumours, Weller et al evaluated the ADC variability between 4 to 10% depending on the institution/MRI vendor.¹³² According to the authors, ADC offers a robust measurement which is not critically affected by the post-processing softwares and shows a satisfactory reproducibility. Blackledge et al evaluated the inter-observer variability of two readers in quantifying WB-DWI parameters.¹³³ The authors showed that there was an excellent inter- and intra-observer repeatability for estimates of global mean/median apparent diffusion coefficient.

According to the aforementioned studies, ADC measurements from different MRI magnets are comparable when a similar acquisition protocol is implemented. However, ADC reproducibility strongly depends on the quality of the MR examination post-processing. Centralizing the quantitative analysis in a single centre may help towards this target, while allowing the realization the MR examinations of the patient in different machines and institutions.

Imaging of lung parenchyma

MRI imaging of the lung parenchyma and as a result lung tumours and metastasis, have been limited and relatively complicated because of respiratory motion, low SNR due to low tissue proton density and rapid signal decay due to susceptibility artefacts at air-tissue interfaces.^{134–137} The use of signal averaging increases SNR but also acquisition times. Furthermore, SNR could be increased by using larger voxel sizes but this would compromise the detection of smaller lung lesions because of partial volume effects.

In 2003 Biederer et al evaluated the diagnostic accuracy of different MR sequences for the detection of small artificial pulmonary nodules inside porcine lungs.¹³⁸ 3D and 2D GRE sequences demonstrated a sensitivity of 88% for 4 mm nodules. T_2 weighted FSE and T_2 weighted half Fourier single-shot sequences (T_2 -HASTE) were slightly inferior. For lesions larger than 5 mm, the sensitivity, specificity and positive and negative predictive values of all sequences except T_2 weighted HASTE were close to 100%. The authors concluded that common MR imaging sequences have a high diagnostic accuracy in detecting small pulmonary nodules when cardiac and respiratory artefacts do not occur.

Parallel imaging and better respiratory gating techniques ameliorated significantly the MRI in lung imaging.¹³⁶ Ultra-short echo time sequence for the imaging of lung parenchyma acquires signal at microseconds and reduces susceptibility artefacts.^{134,139} This sequence allows to collect data almost immediately after excitation and thus only a limited amount of T_2 and T_2^* signal decay occurs.¹³⁹

CONCLUSION

WB-MRI has proven to be an effective tool for imaging of oncological patients. This non-irradiating technique is emerging from the research field and becoming a commonly used imaging tool thanks to the increasing availability of MRI. Recent studies have convincingly demonstrated that WB-MRI can be used for treatment monitoring and prognosis and can spare patients a battery of cumbersome examinations. New or old sequences that are revisited, as the Dixon imaging, improve tumoral lesion conspicuity and demonstrate encouraging results for shortened acquisition times. There is, however, an urgent need for standardization of WB-MRI protocols. New steps towards the homogenization of WB-MRI acquisitions, interpretation and reporting have been made in order to achieve the—urgently—required uniformity. Of course, all these technological advances moved the field forward in tremendous leaps and bounds and radiologists have to follow by acquiring skills in order to implement and interpret WB-MRI examinations. This very ambitious technique stands

firm under the spotlight of evolving research, driving continuous

improvements in the technique and guiding the way towards future directions and applications.

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