Evaluation of Diffusion-Weighted Magnetic Resonance Imaging for Follow-up and Treatment Response Assessment of Lymphoma: Results of an 18F-FDG-PET/CT-Controlled Prospective Study in 64 Patients

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Abstract

Purpose: To determine the value of diffusion-weighted MRI (DWI-MRI) for treatment response assessment in 2-[18F]fluoro-2-deoxy-D-glucose (FDG)-avid lymphoma.

Experimental Design: Patients with FDG-avid Hodgkin (HL) or non-Hodgkin lymphoma (NHL) at pretherapeutic 18F-FDG-PET/CT, who had also undergone pretherapeutic whole-body DWI-MRI, were included in this prospective study. Depending on the histologic lymphoma subtype, patients received different systemic treatment regimens, and follow-up DWI-MRI and 18F-FDG-PET/CT were performed at one or more time points, depending on the clinical course. For each follow-up DWI-MRI, region-based rates of agreement, and rates of agreement in terms of treatment response (complete remission, partial remission, stable disease, or progressive disease), relative to the corresponding 18F-FDG-PET/CT, were calculated.

Results: Sixty-four patients were included: 10 with HL, 22 with aggressive NHL, and 32 with indolent NHL. The overall region-based agreement of DWI-MRI with 18F-FDG-PET/CT was 99.4%. For the 51 interim examinations (performed after 1–3 therapy cycles), region-based agreement of DWI-MRI with 18F-FDG-PET/CT was 99.2%, and for the 48 end-of-treatment examinations, agreement was 99.8%. No significant differences, in terms of region-based agreement between DWI-MRI and 18F-FDG-PET/CT, were observed between the three lymphoma groups (HL, aggressive NHL, indolent NHL; P = 0.25), or between interim and end-of-treatment examinations (P = 0.21). With regard to treatment response assessment, DWI-MRI agreed with 18F-FDG-PET/CT in 99 of 102 follow-up examinations (97.1%), with a κ value of 0.94 (P < 0.0001).

Conclusions: In patients with FDG-avid lymphoma, DWI-MRI may be a feasible alternative to 18F-FDG-PET/CT for follow-up and treatment response assessment. Clin Cancer Res; 21(11); 2506–13.

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In lymphoma, treatment response assessment by DWI has so far only been investigated in a small number of studies that were either limited by a small sample size (between 8 and 27 patients, with a mean of 15 patients/study; refs. 13–19), or a retrospective design (20). In addition, these studies included almost exclusively patients with diffuse large B-cell lymphoma (DLBCL) and Hodgkin lymphoma—there are practically no data for indolent non-Hodgkin lymphomas (NHL). Finally, almost all previous studies focused on treatment-induced changes of apparent diffusion coefficients (ADC) in target lesions (14–19); only a single study in 15 DLBCL patients directly compared DWI with 18F-FDG-PET/CT for both interim- and end-of-treatment response assessment. In addition, DWI is also attractive from an economic point of view, and in terms of general availability, in particular in comparison with PET/CT.

Translational Relevance

In patients with 2-[18F]fluoro-2-deoxy-D-glucose (FDG)—avid lymphoma, diffusion-weighted imaging (DWI), a functional MRI technique that enables an indirect assessment of cellular density, provides results that are almost equal to those of 18F-FDG-PET/CT, in terms of restaging and treatment response evaluation. This performance of DWI-MRI appears to be independent of the lymphoma subtype (i.e., Hodgkin, aggressive or indolent Non-Hodgkin lymphoma), and also independent of the duration of treatment (i.e., the number of therapy cycles). Our findings thus provide further evidence that DWI-MRI—although, unlike 18F-FDG-PET, it cannot directly assess treatment-induced functional and metabolic changes at a cellular level—may be a useful alternative to 18F-FDG-PET/CT for both interim- and end-of-treatment response assessment. In addition, DWI is also attractive from an economic point of view, and in terms of general availability, in particular in comparison with PET/CT.

Patients and Methods

Patients and design

The present study was part of a prospective, Institutional Review Board-approved trial that included lymphoma patients who were referred to the Department of Radiology and Nuclear Medicine of the local tertiary care center for staging and follow-up by means of DWI-MRI and 18F-FDG-PET/CT between August 2011 and January 2014. Lymphoma subtypes were diagnosed based on tissue samples obtained by biopsy or surgery, according to the criteria of the current WHO classification of hematologic and lymphoid malignancies, by a reference pathologist. Patients who gave written informed consent underwent baseline DWI-MRI and 18F-FDG-PET/CT, with a maximum of 7 days between the examinations. Pregnancy, general contraindications to MRI, and therapeutic interventions between corresponding DWI-MRI and 18F-FDG-PET/CT examinations were used as exclusion criteria.

For the present follow-up/treatment response assessment study, additional inclusion criteria were availability of one or more follow-up DWI-MRI and 18F-FDG-PET/CT examinations, again with a maximum of 7 days between the corresponding examinations; and a time interval of at least 2 weeks between the last day of a chemotherapy cycle and the imaging tests. A lack of FDG avidity of the lymphoma on pretherapeutic 18F-FDG-PET/CT, according to the original reports from routine clinical practice, was used as the single additional exclusion criterion.

Imaging

MRI was performed, from the vertex to the upper thigh, on a 3-Tesla system (Trios TIM; Siemens), equipped with a phased-array 16-channel body coil. A single-shot, echo-planar imaging-based, spectral adiabatic inversion recovery DWI sequence was obtained with b-values of 50 and 1,000, a repetition time (TR)/echo time (TE) of 5,100/73 ms, 5 averages, a 192 × 115 matrix, and a 5-mm slice thickness with no gap. Images were obtained during free breathing; only for the neck and chest, respiratory triggering was used. ADC maps were calculated, and a T1-weighted turbo spin-echo or, in case of breathing difficulties, a fast gradient-echo sequence was obtained for better anatomical/morphologic correlation, and to generate fused color-coded DWI-MRI images.

18F-FDG-PET/CT was performed, from the vertex to the upper thigh, using a 64-row multidetector PET/CT system (Biograph TruePoint 64; Siemens), with a transaxial field-of-view (FOV) of 605 mm (axial FOV, 216 mm), a PET sensitivity of 7.6 cps/kBq, and a transaxial PET resolution of 4 to 5 mm (full width at half maximum). Patients fasted for 5 hours before imaging; the glucose cut-off level was 150 mg/dL. PET was performed 50 to 60 minutes after a weight-dependent, intravenous administration of 18F-FDG (target dose, 300 MBq; individual dose, 270–340 MBq), with 3 minutes/bed position, four iterations per 21 subsets, a 5-mm slice thickness, and a 168 × 168 matrix, using the TrueX reconstruction algorithm. Venous-phase CE-CT was obtained after the intravenous injection of 100 mL of a tri-iodinated, nonionic contrast medium at a rate of 2 mL/second; a tube voltage of 120 kV, a tube current of 230 mA, a collimation of 64 × 0.6 mm, a 3-mm slice thickness with 2-mm increment, and a 512 × 512 matrix, were used. PET attenuation correction was based on CE-CT because previous studies have shown that the use of CE-CT instead of unenhanced CT does not negatively influence clinical diagnostic PET image interpretation (21–23).

Image interpretation

The 14 nodal regions defined at the Rye symposium (24), and the following twelve extranodal regions were evaluated on pre- and posttherapeutic images: Waldeyer ring; lungs; liver; spleen; stomach; small intestine; large intestine; right kidney; left kidney; bones; soft tissues (skin/fat/muscle); and other organs/tissues (e.g., salivary glands).

DWI-MRI was evaluated independently by two board-certified radiologists that were blinded to the corresponding 18F-FDG-PET/CT. On pre- and posttherapeutic images, regions were rated as positive for lymphoma when at least one lymph node or lesion showed a restricted diffusion on DWI, defined as a high signal on the b50 images (relative to the surrounding tissues), and a persistence or increase of the signal on the b1000 images (relative...
to the b50 images); or a high signal on the b50 images and low signal on the ADC map (relative to the surrounding tissues; ref. 25). Because the normal spleen frequently shows a higher signal on DWI than other abdominal/retroperitoneal organs (26, 27), signal inhomogeneity or well-circumscribed lesions with restricted diffusion were rated as positive in this organ. The bone marrow was rated as positive when, in addition to diffusion restriction, it showed a lower signal than the adjacent skeletal muscle on the T1-weighted images. Other regions or structures with known high signal on DWI, such as ovaries, testes of younger patients, and bowel contents (28, 29), were not regarded as pathologic. Where appropriate, lesion diameters were measured on the T1-weighted images. Following the raters’ independent regional assessment and (re-)staging, a consensus reading (i.e., a reevaluation according to the above defined criteria for MRI-DWI positivity) was performed for all examinations where discrepancies between the two readers were noted in the findings. For the evaluation of posttherapeutic DWI-MRI, raters had access to all previous DWI-MRI images.

18F-FDG-PET/CT was evaluated independently by two board-certified nuclear medicine physicians that were blinded to the corresponding DWI-MRI. Nodal and extranodal regions were rated as positive for viable lymphoma when there was at least one focal (or, for bone marrow, diffuse) area of increased tracer accumulation, relative to the surrounding tissue or mediastinal blood pool activity (30). As previously recommended, the spleen was rated as positive when the tracer uptake was higher than in the liver (5). In addition, for interim restaging of patients with Hodgkin lymphoma and DLBCL, all nodal and extranodal lesions were also only rated as positive on PET if their uptake exceeded that in the liver, as previously reported (31, 32)—this is in accordance with the consensus of the “Second International Workshop on Interim Positron Emission Tomography in Lymphoma”, where a Deauville score ≥4 was recommended for this purpose (33). The CE-CT component of 18F-FDG-PET/CT was used primarily for anatomical correlation and lesion confirmation, and, where appropriate, to measure lesion diameters. Similar to DWI-MRI, a consensus rating was performed for all examinations where discrepancies between the two readers were noted, following the raters’ independent regional assessment and (re-)staging. For the evaluation of posttherapeutic 18F-FDG-PET/CT, raters had access to all previous 18F-FDG-PET/CT images.

**Assessment of treatment response status**

Pretherapeutic staging has been previously performed and reported by our group in a larger population that also included patients eligible for the present study (34). In the present study, the performance of DWI-MRI for treatment response evaluation was determined, based on the pre- and posttherapeutic regional assessments, according to the IHP criteria of the IWG for 18F-FDG-PET/CT (30), and their application to DWI-MRI (Table 1).

**Statistical analysis**

Region-based rates of agreement between DWI-MRI and 18F-FDG-PET/CT (consensus ratings) were calculated, separately for nodal, extranodal, and all regions combined. These calculations were also performed independently for interim (i.e., after 1–3 therapy cycles) and end-of-treatment examinations, as well as the three larger lymphoma subgroups (Hodgkin lymphoma, aggressive, and indolent NHL). General estimation equations were used for group comparisons (interim vs. end-of-treatment restaging; nodal vs. extranodal involvement; Hodgkin lymphoma vs. aggressive NHL vs. indolent NHL), and Bonferroni correction was applied, as appropriate. k coefficients were used to determine the agreement of DWI-MRI with 18F-FDG-PET/CT, based on regions and IHP response status, first for all examinations combined, and then independently for interim DWI-MRI (i.e., after 1–3 therapy cycles) and end-of-treatment DWI-MRI. k coefficients were also used to assess interobserver agreement. The specified level of significance was P < 0.05 for all tests. The software package SPSS 21.0 (SPSS Inc.) was used for all statistical calculations.

**Results**

**Patient characteristics**

Of 140 lymphoma patients that received pretherapeutic staging by means of 18F-FDG-PET/CT and DWI-MRI (34), 73 patients matched the inclusion criteria for participation in our prospective follow-up/response assessment study. Of these, 9 patients [8 with extranodal marginal zone B-cell lymphoma of the mucosa-associated lymphoid tissue (MALT) lymphoma, and one with small lymphocytic lymphoma/chronic lymphocytic leukemia (SLL/CLL)] were excluded due to a lack of FDG avidity of the lymphoma. None of the remaining 64 patients showed elevated glucose levels (i.e., >150 mg/dL).

Of the 64 patients (35 females and 29 males; mean age, 56.0 ± 16.7 years; age range, 19–84 years), 17 were diagnosed with MALT lymphoma, 15 with DLBCL, 13 with follicular lymphoma, 10 with Hodgkin lymphoma, 5 with mantle cell lymphoma, and one patient each with nodal marginal zone lymphoma, anaplastic large cell lymphoma, peripheral T-cell lymphoma, and SLL/CLL. Thus, the patient population comprised 10 patients with Hodgkin lymphoma, 22 patients with aggressive NHL, and 32 patients with indolent NHL. Eighteen patients received immunotherapy (including 2 patients who received brentuximab-vedotin); 34 patients received chemo- and immunotherapy; and 11 patients received chemotherapy (Supplementary Table S1). One patient received no treatment at all, but instead, a “wait-and-see” strategy was used.

Thirty patients underwent one, 30 underwent two, and 4 patients underwent three DWI-MRI and 18F-FDG-PET/CT
follow-ups. Thus, a total of 102 follow-up scans (i.e., 1,428 nodal and 1,224 extranodal regions) were evaluated, of which 51 were categorized as “interim” (i.e., performed after 1–3 therapy cycles), and 48 as “end-of-treatment”; the remaining three examinations were performed after a “wait-and-see” interval.

Follow-up: sensitivities and specificities
At baseline, nodal and extranodal involvements were observed in 184 of 896 and 53 of 768 regions of the 64 patients, respectively, according to the reference standard (Supplementary Table S2). At follow-up (i.e., for all 102 examinations combined), nodal and extranodal (residual or newly developed) involvements were observed in 46 of 1,428 and 38 of 1,224 regions (Supplementary Table S2), according to 18F-FDG-PET/CT. The overall region-based agreement of DWI-MRI with 18F-FDG-PET/CT for detection of lymphoma at follow-up was 99.4% (Table 2). Individual agreement results for the three lymphoma subgroups (i.e., Hodgkin lymphoma, aggressive NHL, and indolent NHL) are provided in Table 3. No significant differences, in terms of region-based agreement between DWI-MRI and 18F-FDG-PET/CT, were observed between the three lymphoma groups ($P = 0.25$).

Of the 12 nodal regions that were false positive on follow-up DWI-MRI, nine were cervical regions, two were inguinal regions, and one was a pelvic region; one cervical region was false negative (Supplementary Table S2). With regard to extranodal regions, the spleen was rated false positive in one patient, and the liver false negative in another patient, on follow-up DWI-MRI. There was a significant difference, in terms of agreement between DWI-MRI and 18F-FDG-PET/CT, between nodal and extranodal regions ($P = 0.017$).

For the 51 interim follow-up examinations (after 1–3 therapy cycles), region-based agreement of DWI-MRI with 18F-FDG-PET/CT was 99.2%. For the 48 end-of-treatment examinations, region-based agreement of DWI-MRI with 18F-FDG-PET/CT was 99.8% (Tables 2 and 3). With regard to the agreement between DWI-MRI and 18F-FDG-PET/CT, no significant difference between interim and end-of-treatment examinations was observed ($P = 0.21$).

Region-based interobserver agreement, calculated for all 102 follow-up examinations combined, was high for both DWI-MRI and 18F-FDG-PET/CT, with $k$ values of 0.89 ($P < 0.0001$) and 0.97 ($P < 0.0001$), respectively. $k$ values for Hodgkin lymphoma, aggressive NHL, and indolent NHL were 0.87, 0.81, and 0.94 for DWI-MRI, and 1.0, 0.96, and 0.97 for 18F-FDG-PET/CT, respectively.

Restaging and response status
At baseline, Ann Arbor stage was 0 in 6 patients; stage I in 19 patients; stage II in 11 patients; stage III in 8 patients; and stage IV in 20 patients; according to our reference standard. With regard to the IHP response status, DWI-MRI agreed with 18F-FDG-PET/CT in 99 of 102 follow-up examinations (97.1%), with a $k$ value of 0.94 ($P < 0.0001$; see Table 4, and Figs. 1 and 2). Of the three cases of disagreement between DWI-MRI and 18F-FDG-PET/CT, one occurred at interim restaging of a patient with follicular lymphoma, and two occurred at both interim and end-of-treatment restaging in a single patient with Hodgkin lymphoma. All three cases were rated as complete remission on 18F-FDG-PET/CT, and as partial remission, due to a false-positive result in a single nodal region, on DWI-MRI.

Discussion
The results of our study suggest that DWI-MRI is almost equal to 18F-FDG-PET/CT for follow-up and therapy response assessment in patients with lymphoma, in accordance with the results of previous smaller-sized studies (13–20). This is of interest, because only the image pattern, but not the underlying information (i.e., tumor property) assessed is similar between the two techniques: DWI visualizes intercellular space narrowing, and thus, cell density (35); whereas 18F-FDG-PET visualizes glucose metabolism, which in turn has been shown to correlate with cell proliferation (36, 37). We hypothesize that the reason for our findings is that, at least in the FDG-avid lymphomas included in the present study, there is more glucose consumption in areas of higher cell density, such a correlation between cell density and glucose metabolism has already been reported for malignant lung nodules and pancreatic adenocarcinoma (38, 39). In other, very slowly growing lymphomas (e.g., in a certain percentage of MALT lymphomas and SLL/CLL), there may, however, be no such association between cellularity and glucose metabolism.

Notably, our study is the first to apply the IHP criteria for response classification of lymphoma to DWI-MRI. This was done because we felt that, although they rely on different physiological properties, DWI-MRI is a functional imaging technique just like 18F-FDG-PET/CT, and should therefore be used in the same way. For instance, the criterion for complete remission on DWI-MRI was the resolution of lesions with restricted diffusion at follow-up, regardless of whether or not a residual mass was still visible—this resembles the criterion for complete remission on 18F-FDG-PET/CT, where residual masses are permitted as long as there is no increased tracer uptake. Using this strategy, overstaging by DWI-MRI at follow-up occurred in only three of 102 examinations (partial instead of complete remission), and understaging did not occur at all (Table 3). Accordingly, region-based overstaging was also observed more frequently than understaging (Table 2), with the cervical lymph node regions being the most common sites for...
false-positive results (Supplementary Table S2). Our results are thus in good accordance with a previous study, which reported that DWI-MRI has a tendency to overestimate, rather than underestimate, the extent of disease, compared with 18F-FDG-PET/CT (40).

With 64 patients, our study is presently the largest on this topic— the largest previous, prospective study included 27 patients (17), and the largest retrospective study included 39 patients (20). Unlike these previous studies, we also included a considerable number of indolent lymphomas— actually, half of our patients were diagnosed with an indolent NHL, and MALT lymphoma was, with 17 patients, even the most common subtype in our study. This atypical distribution is probably due to the fact that one of the referring oncologists is a specialist for the management of MALT lymphoma. Although 18F-FDG-PET/CT is generally not recommended in MALT lymphoma and SLL/CLL (3), it is well known that 50% to 60% of patients with MALT lymphoma, and about 80% of patients with SLL/CLL, may show an increased FDG uptake (41). Because we only included such FDG-avid cases of MALT lymphoma and SLL/CLL, we considered it justifiable to also use 18F-FDG-PET/CT as reference standard for these. Although the low number of patients misclassified by DWI-MRI, in terms of restaging ($n = 2$), prevented us from performing a dedicated statistical analysis, we did not observe any trend toward a better, or poorer, performance of DWI-MRI in indolent NHL, compared with Hodgkin lymphoma or aggressive NHL.

The concept of interim restaging in lymphoma, which is typically performed after one to three therapy cycles, has received considerable attention over the last couple of years, and is still controversial. Even for Hodgkin lymphoma and DLBCL, there is, at present, still no official recommendation for interim restaging outside of clinical trials, even though some 18F-FDG-PET/CT studies have suggested that this imaging technique potentially enables an early outcome prediction, particularly when the FDG uptake in the liver is used as a reference (31). Therefore, a Deauville score of $\geq 4$ was used as the criterion for residual disease in Hodgkin lymphoma and DLBCL on interim 18F-FDG-PET/CT, as previously recommended (33), whereas for all other lymphoma subtypes, the unmodified IHP criteria for PET were used, because the Deauville criteria have not yet been evaluated here. We not only found that DWI-MRI was equally suitable for interim restaging, compared with 18F-FDG-PET/CT, but we also found that there was no statistically significant difference, in terms of region-based sensitivity/specificity, between DWI-MRI-based interim restaging and end-of-treatment restaging. These results suggest that the value of DWI-MRI for follow-up imaging in lymphoma does not depend on the treatment duration. It is important to note, however, that our results are based on imaging after extended time periods posttreatment, during which cell death, which DWI can capture due to a reduction of cell density, may have occurred. Although there are presently no comparative data available with regard to this topic, it seems unlikely that DWI would be able to capture very early treatment response— for instance, only hours after treatment initiation— because, unlike PET, it cannot directly assess treatment-induced functional and metabolic changes at a cellular level. In a previous study, it was shown that 18-FDG-PET can capture treatment-induced changes as early as 2 hours after treatment (42).

Apart from its diagnostic value, DWI is also attractive from an economic point of view, and in terms of general availability. Originally introduced into clinical practice for neurologic applications (e.g., stroke), DWI is now considered a standard pulse sequence that is suitable for whole-body imaging, and is provided for all modern 1.5- or 3-Tesla MR scanners. A German study demonstrated that, with regard to oncologic staging of the five most frequent tumors, the overall cost for whole-body MRI is lower by a factor of 1.8 to 2 (43), compared with 18F-FDG-PET/CT. Thus, whole-body MRI techniques, including DWI, may be an interesting alternative to 18F-FDG-PET/CT in an era of limited financial resources and increasing healthcare costs. A drawback of the use of DWI, however, is the sensitivity of this technique to artifacts (see Fig. 1), in particular insufficient fast suppression artifacts due to magnetic field inhomogeneity, motion artifacts (in

![Figure 1.](image_url)
of different lymphoma subtypes, our patient population was heterogeneous with regard to the treatment regimens used. However, prediction of outcome and survival after different types of therapy were not within the scope of our study—instead, we focused on a comparison between DWI-MRI and 18F-FDG-PET/CT. Finally, no quantitative data from PET (e.g., standardized uptake values) or DWI (i.e., ADCs) were collected as markers for treatment response, because, for 18F-FDG-PET, the current IHP guidelines recommend a purely visual assessment, and hence, we saw no justification for using a different approach for DWI. Should future treatment response criteria rely on quantitative, rather than on qualitative imaging parameters, the possible role of DWI must be reevaluated, because of the known shortcomings of this technique, such as a sensitivity of ADC values to the choice of scanner model and vendor, field strength, gradient system and coils, pulse-sequence design, acquisition parameters (including b values), and artifacts related to susceptibility effects or eddy currents (44).

In conclusion, our results provide further evidence that DWI-MRI may be a feasible alternative to 18F-FDG-PET/CT for the follow-up of lymphoma patients, as previously suggested by smaller-sized studies. This includes treatment response assessment, according to the IHP response criteria; DWI-MRI in this regard appears to be suitable for both interim and end-of-treatment restaging. Despite these encouraging results, an additional follow-up, noninferiority study that uses progression-free survival as the reference standard, as well as larger multicentric studies, involving MRI systems from different vendors, but using a predefined MRI protocol, are required to further evaluate the role of DWI-MRI for treatment response assessment in lymphoma in day-to-day practice. Because DWI-MRI demonstrated a tendency toward overstaging, definition of reference tissues for response evaluation, similar to the Deauville criteria for 18F-FDG-PET, should be considered.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

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