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PET/MRI for the Evaluation of Patients With Lymphoma: Initial Observations

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Abstract

OBJECTIVE—The objective of our study was to assess the role of recently introduced hybrid PET/MRI in the evaluation of lymphoma patients using PET/CT as a reference standard.

SUBJECTS AND METHODS—In this prospective study 28 consecutive lymphoma patients (18 men, 10 women; mean age, 53.6 years) undergoing clinically indicated PET/CT were subsequently imaged with PET/MRI using residual FDG activity from the PET/CT study. Blinded readers evaluated PET/CT (reference standard), PET/MRI, and diffusion-weighted imaging (DWI) studies separately; for each study, they assessed nodal and extranodal involvement. Each FDG-avid nodal station was marked and compared on DWI, PET/MRI, and PET/CT. Modified Ann Arbor staging was performed and compared between PET/MRI and PET/CT. The maximum standardized uptake value (SUV_{max}) on PET/MRI for FDG-avid nodal lesions was compared with the SUV_{max} on PET/CT. The apparent diffusion coefficient (ADC) for FDG-avid nodal lesions was compared to SUV_{max} on PET/MRI.

RESULTS—Fifty-one FDG-avid nodal groups were identified on PET/CT in 13 patients. PET/MRI identified 51 of these nodal groups with a sensitivity of 100%. DWI identified 32 nodal groups for a sensitivity of 62.7%. PET/MRI staging and PET/CT staging were concordant in 96.4% of patients. For the one patient with discordant staging results, disease was correctly upstaged to stage IV on the basis of the PET/MRI finding of bone marrow involvement, which was missed on PET/CT. DWI staging was concordant with PET/CT staging in 64.3% of the patients. The increased staging accuracy of PET/MRI relative to DWI was significant ($p = 0.004$). SUV_{max} measured on PET/MRI and PET/CT showed excellent statistically significant correlation ($r = 0.98$, $p < 0.001$). There was a poor negative correlation between ADC and SUV_{max} ($r = -0.036$, $p = 0.847$).

CONCLUSION—PET/MRI can be used to assess disease burden in lymphoma with sensitivity similar to PET/CT and can be a viable alternative for lymphoma staging and follow-up.

Keywords

diffusion-weighted imaging (DWI); hybrid PET/MRI; lymphoma; PET/MRI

Non-Hodgkin and Hodgkin lymphomas are common hematologic malignancies accounting for nearly 5% of all cancers in the United States. It was estimated in 2014 that over 75,000 patients would be diagnosed with lymphoma, that nearly 20,000 would die of this disease, and that more than 700,000 patients would undergo active treatment or would be in remission [1]. Whole-body imaging is a mainstay of lymphoma diagnosis and management and is routine both for initial staging and for posttreatment evaluation.

Metabolic ^{18}F -FDG PET combined with anatomic CT (PET/CT) has been shown to be superior to contrast-enhanced CT for the initial staging of lymphoma [2]. PET/CT is also increasingly used in the assessment of treatment response [3, 4]. Because disease in many patients is diagnosed when the patients are young and the patients will require numerous examinations over the course of their treatment and postremission surveillance, follow-up imaging without radiation exposure such as whole-body MRI is of clinical interest.

Whole-body MRI has shown promise in the evaluation of patients with lymphoma [5, 6]. MRI offers superior contrast resolution in the evaluation of extranodal disease, including bone marrow. The apparent diffusion coefficient (ADC) calculated from diffusion-weighted imaging (DWI) is sensitive to nodal disease and bone marrow involvement [7, 8]. Although there is no clear ADC cutoff that can distinguish between malignant and benign lymph nodes, ADC values have been shown to increase in successfully treated nodal disease [9] and pretreatment ADC values may have prognostic implications [9–11]. However, on morphologic MRI including DWI abnormal nodes are identified on the basis of size alone, whereas PET identifies abnormal nodes on the basis of FDG uptake.

The recent introduction of whole-body combined PET and MRI systems (PET/ MRI) offers the ability to combine the high-resolution and functional information of MRI and the metabolic activity information of PET to more accurately assess nodal and extranodal disease in patients with lymphoma. In addition, the correlation of ADC values and PET activity both before and during treatment is of considerable interest because a combination of both may predict treatment response and identify response to treatment before a measurable reduction in tumor size.

Thus, the purpose of this study was to compare the accuracy of a simultaneously acquired PET with a radial T1-weighted free-breathing acquisition (PET/MRI) and of DWI for the detection and staging of disease in lymphoma patients using PET/CT as a reference standard. The secondary aim of this study was to assess the relationship between ADC and SUV_{max} in FDG-avid nodal disease with simultaneously acquired PET and DWI.

Subjects and Methods

This prospective HIPAA-compliant study was performed after we received approval from our institutional review board. All patients undergoing clinically indicated routine ^{18}F -FDG PET/CT examinations are recruited to undergo PET/MRI immediately after completion of the PET/CT study. An FDG tracer was injected before PET/CT, and the PET/MRI data were acquired after PET/CT using residual tracer activity. All patients provided written informed consent for the PET/MRI examinations.

Between August 2012 and October 2012, 886 patients underwent whole-body oncologic PET/CT. Twenty-eight patients (18 men, 10 women) with a diagnosis of lymphoma agreed to undergo PET/MRI after PET/CT and constituted our study cohort; the mean age of the study cohort was 53.6 years (range, 30–85 years). Patients were imaged for the following indications: large B-cell lymphoma ($n = 10$), Hodgkin lymphoma ($n = 8$), follicular lymphoma ($n = 6$), Burkitt lymphoma ($n = 1$), cutaneous T-cell lymphoma ($n = 1$), cutaneous B-cell lymphoma ($n = 1$), and extranodal mucosa-associated lymphoid tissue lymphoma ($n = 1$). Eight patients were undergoing treatment of active disease, five were undergoing surveillance without having undergone a prior treatment, and 15 were in clinical remission according to their history.

PET/CT Examination

All patients fasted for 4 hours before imaging. Insulin was discontinued 6 hours before imaging, and blood glucose levels were verified to be less than 200 mg/dL (< 11.1 mmol/L). All patients received oral barium sulfate. Patients received an average dose of 14.8 mCi (547.6 MBq; range, 13.7–15.3 mCi [506.9–566.1 MBq]) of ^{18}F -FDG IV. Nine of the 28 patients also received a weight-based dose of IV contrast material during the CT examination. For 45 minutes after the injections, patients were required to sit quietly in a dimly lit room. Patients were asked to void before imaging. Images were acquired from the base of the skull to the mid thigh.

The PET/CT examinations were performed on a unit that has a lutetium oxyorthosilicate crystal and a photomultiplier tube (Biograph mCT, Siemens Healthcare). The acquisition parameters for CT included a peak voltage of 120 kVp, a rotation time of 0.3–0.5 second, and a collimation of 16×1.2 mm. An automatic exposure control technique (Care Dose4D, Siemens Healthcare) was used with modulation set to a reference tube current–exposure time product of 95 mAs for unenhanced studies and 140 mAs for IV contrast-enhanced studies. Images were reconstructed with a 3-mm section thickness.

After CT, the PET data were acquired with an imaging time of 2–3 minutes per bed position depending on the patient's weight and uptake time. The PET data were reconstructed using the manufacturer-provided standard software with a 3D ordinary Poisson ordered-subset expectation maximization algorithm, 2 iterations, 21 subsets, and a 2-mm gaussian filter (image matrix, 168×168 ; voxel size, $1.78 \times 1.78 \times 2$ mm). The attenuation correction was based on the CT data.

PET/MRI Examination

PET/MRI examinations were performed on an integrated PET/MRI system that acquires simultaneous PET and MRI data using a 3-T magnet (Biograph mMR, Siemens Healthcare). The PET detector is composed of lutetium oxyorthosilicate scintillation crystals with avalanche photodiodes that are MRI-compatible.

PET/MRI was initiated approximately 57 minutes after PET/CT (range, 31–152 minutes) using residual ^{18}F -FDG from the earlier injection (Fig. 1). The delay between tracer injection and PET/MRI ranged from 61 to 213 minutes. PET and MRI data were acquired

simultaneously. For each bed position, a T1-weighted Dixon gradient-echo sequence was acquired in the coronal plane during a breath-hold of approximately 20 seconds. This sequence was acquired first for attenuation correction; it was used to generate an attenuation map, as described previously [12, 13], with an MRI-based segmentation method that separates fat, soft-tissue, lung, and background attenuations. Immediately after this sequence, the following two MRI sequences were performed in the transaxial plane simultaneously with PET through multiple stations while the patient was breathing freely: a T1-weighted gradient-echo imaging sequence with a radial stack-of-stars trajectory (StarVIBE sequence, Siemens Healthcare) and a DWI sequence with spin-echo single-shot echo-planar imaging.

The parameters for the StarVIBE sequence were as follows: TR/TE, 4.5/2; section thickness, 2.5 mm; flip angle, 12°; 80 axial slices; bandwidth, 400 Hz per pixel; voxel size, $1.4 \times 1.4 \times 2.5$ mm; and quick fat-saturation mode. The acquired PET sinogram was reconstructed using the 3D ordinary Poisson ordered-subset expectation maximization algorithm (4 iterations, 21 subsets). The parameters for the DWI sequence were as follows: TR/TE, 5900/54; frequency-selective fat saturation; parallel imaging factor, 2; and monopolar diffusion gradients with b values of 0, 350, and 750 s/mm². The spatial resolution was $2.6 \times 2.1 \times 6$ mm, and 30 slices were acquired in the transverse plane with 3 signal averages. The acquisition time was 2 minutes 30 seconds.

Image Interpretation

PET/CT—A radiologist and a nuclear medicine physician interpreted the PET/CT images together in consensus. The PET/CT images were interpreted using a fusion viewer (MIMviewer, version 5.4, MIM Software). Readers were blinded to the results of prior studies and to PET/MRI data but were aware that the patients had lymphoma. The PET/CT readers noted the presence and size of the lymph nodes, FDG avidity within the nodes, and the presence of extranodal disease. Nodal groups were categorized into one of 20 nodal groups as previously described [10]. These nodal groups were Waldeyer ring, right and left cervical, right and left axillary, right and left internal mammary or diaphragmatic, anterior mediastinal, paratracheal, right and left hilar, subcarinal or posterior mediastinal, celiac or superior mesenteric, hepatic and splenic hilar, retroperitoneal, inferior mesenteric, right and left iliac, and right and left inguinal regions. Any nodal group with lymph nodes showing FDG avidity was considered to be involved with lymphoma. These findings were annotated, and the images were saved. This consensus PET/CT interpretation was considered the reference standard.

PET/MRI—A board-certified radiologist with 6 years of experience who was blinded to clinical history and prior studies independently interpreted the PET/MRI studies. The PET and MR images obtained from the StarVIBE sequence were interpreted together using the fusion viewer or XD3 software (version 3.6, Mirada Medical). Attenuation-corrected PET images were fused to the MR images (StarVIBE sequence) for this interpretation. Any nodal group with lymph nodes showing FDG avidity was considered to be involved with lymphoma. The presence, size, and FDG avidity of the lymph nodes and the FDG avidity of

extranodal sites were noted for the PET/MRI datasets. All findings were annotated, and the images were saved.

Diffusion-weighted imaging—A board-certified radiologist who was blinded to the PET acquisition interpreted the MR images including the DW images. The MR images obtained using the StarVIBE sequence, the DW images, and the ADC maps were reviewed together at the PACS workstation. Any nodal group with lymph nodes larger than 1 cm in the short axis were considered to be involved with lymphoma.

A study coordinator performed a nodal group comparison by comparing PET/MR images and DW images with the PET/CT images (reference standard). For each patient, the PET/CT images were reviewed together with the PET/MRI and DWI datasets. For each nodal group marked on a PET/CT image, the presence or absence of that nodal group on PET/MR images and DW images was noted. If the nodal group marked on a PET/CT image was not annotated by that reader on a particular PET/MR image or DW image, it was considered missed. Nodal groups marked on PET/MRI or DWI that were not seen on PET/CT were considered false-positives. PET/CT studies and bone marrow biopsy, when performed, were considered the reference standard for extranodal disease.

Quantitative Analysis

The maximum standardized uptake value (SUV_{max}) of nodal groups within each station was measured by a reader on the PET images obtained with PET/CT and with PET/MRI. The reader obtained the SUV_{max} for the lymph node with the highest uptake within each station by manually measuring 3D volumes of interest on the fusion viewer. The corresponding mean ADC value of lymph nodes larger than 1 cm was also measured by manually tracing these nodes on the ADC map while avoiding the outermost pixels to minimize partial volume effects.

Statistical Analysis

Logistic regression for correlated data was used to characterize and compare PET/MRI and DWI in terms of sensitivity for the detection of positive nodal groups relative to PET/CT as the reference standard. Specifically, generalized estimating equations in the context of binary logistic regression were used to model concordance with PET/CT as a function of modality (PET/MRI vs DWI) while accounting for the lack of statistical independence among results derived for multiple lesions within the same patient. The McNemar test was used to compare PET/MRI and DWI in terms of accuracy for staging relative to PET/CT and bone biopsy (when performed) as the reference standard. All statistical tests were conducted at the two-sided 5% significance level using statistics software (SAS, version 9.3, SAS Institute).

Results

Nodal Disease

A total of 51 FDG-avid nodal groups were identified on consensus PET/CT (i.e., the reference evaluation) in 13 patients. PET/MRI detected all 51 of these FDG-avid nodal

groups (Fig. 2) for a sensitivity of 100% (51/51). DWI detected 32 of these nodes as positive based on the size criterion of larger than 1 cm in the short axis; thus, the sensitivity for DWI was 62.7% (32/51). The higher sensitivity of PET/MRI compared with DWI was statistically significant ($p < 0.01$).

PET/MRI identified one nodal group, a right hilar node in a 47-year-old woman with non-Hodgkin lymphoma, as FDG-avid and, hence, as positive for lymphoma, whereas PET/CT showed negative findings. DWI falsely identified five nodal groups as positive for lymphoma based on size, but these five nodal groups did not show FDG avidity on PET/CT (Table 1).

Extranodal Disease

Two extranodal findings were identified in two patients. In one patient, there was bone marrow involvement with lymphoma that was diagnosed at biopsy. This bone marrow involvement was detected on DWI and PET/MRI but not on PET/CT. A pleural nodule in a patient with large B-cell lymphoma was seen on all three modalities.

Staging

Thirteen patients had active disease. According to the modified Ann Arbor staging system, PET/CT findings showed that disease was stage I in two patients, stage II in four patients, stage III in six patients, and stage IVE in one patient. Fifteen patients had no evidence of disease (Table 2).

PET/MRI and PET/CT findings led to concordant staging in 96.4% (27/28) of patients, and DWI and PET/CT findings for disease stage were concordant in 64.3% (18/28) of patients. The increased accuracy of PET/MRI relative to DWI for disease staging was significant ($p = 0.004$) (Fig. 2).

In one case in which PET/CT and PET/MRI were discordant, PET/MRI accurately detected bone marrow involvement that was missed on PET/CT (Fig. 3). PET/MRI correctly upstaged disease in one patient and did not downstage any of the cases compared with PET/CT. DWI was observed to correctly upstage disease in one patient, incorrectly upstage disease in two patients, and incorrectly downstage disease in seven patients when compared with PET/CT.

Maximum Standardized Uptake Value Correlation

The SUV_{max} values in 40 discrete lymph nodes (at least one in each station for each patient) were measured on PET/CT and PET/MR images. The SUV_{max} values ranged from 1.4 to 50.1 on PET/CT images and from 0.59 to 35.1 on PET/MR images. There was a significant and strong correlation between PET/CT and PET/MRI in nodal SUV_{max} ($r = 0.975$, $p < 0.001$). A Bland-Altman analysis showed a higher mean SUV_{max} with PET/CT than with PET/MRI, with a mean difference in SUV_{max} of 1.7 (95% limits of agreement, 9.2 and -5.8) (Fig. 4).

Maximum Standardized Uptake Value and \$SSDUHQW_'LIIXVLRQ_&RHIAFLHQW_&RUUHODWLRQ

Thirty-one of the 40 measured discrete lymph nodes were larger than 1 cm and had corresponding ADC values measured on DWI. The SUV_{max} values on PET/MRI ranged from 0.59 to 35.1, and the mean ADC values ranged from 0.45 to 2.94. There was a weak nonsignificant correlation between nodal SUV_{max} and mean ADC ($r = 0.06$, $p = 0.77$) (Fig. 5).

Discussion

In this study, we compared PET/MRI and DWI with PET/CT in the detection of nodal and extranodal disease in lymphoma patients undergoing clinically indicated PET/CT. Simultaneously acquired PET/MRI had a sensitivity similar to that of PET/CT for the detection of nodal disease and had a higher sensitivity than DWI. In addition, PET/MRI detected extranodal disease in one patient in the bone marrow (proven on bone marrow biopsy) that was not identified on PET/CT. Thus, the modified Ann Arbor staging was concordant for PET/MRI and PET/CT in all cases with the exception of one case. In the latter case, disease was correctly upstaged by the higher sensitivity of PET/MRI for bone marrow involvement. In comparison, DWI understaged disease in a number of patients compared with both PET/MRI and PET/CT, which is similar to the results of prior studies comparing whole-body MRI and PET/MRI [14] and comparing whole-body MRI and PET/CT [5–7].

There was a significant and strong correlation between SUV_{max} values measured with PET/CT and those measured with PET/MRI for involved nodal disease, with a higher SUV_{max} of nodal groups on PET/CT. A number of recent studies have shown a high correlation between PET/MRI and PET/CT for SUV_{max} values of various organs and disease processes [15–17]. One prior study showed higher SUV_{max} values for lung nodules on PET/MRI than on PET/CT [13]. Another recent study showed SUV_{max} values of normal structures (including axillary and inguinal nodes) were higher on PET/CT than on PET/MRI and showed no significant difference between PET/CT and PET/MRI for SUV_{max} of metastatic disease from a breast cancer primary tumor (Pujara AC, et al., presented at the 2013 Radiological Society of North America meeting).

The reason for lower SUV_{max} values of the nodal groups on PET/MRI compared with PET/CT is unclear. One of the possibilities includes tracer washout because PET/MRI was initiated approximately 57 minutes after PET/CT, with residual ^{18}F -FDG. PET/MRI was performed 61–213 minutes after FDG injection, which is longer than usually seen with a dual-injection protocol. Other confounding factors in addition to the delay between PET/CT and PET/MRI include the heterogeneity of the patient population, which included patients with different types of lymphomas in various stages of treatment, and differences in technical factors such as differences in attenuation correction algorithms between PET/MRI and PET/CT. Further work is required to better understand the reasons for the differences between PET/MRI and PET/CT in SUV_{max} values in this study.

There was a weak correlation between SUV_{max} values and mean ADC values measured simultaneously with PET/MRI. The ability to simultaneously measure ADC and SUV_{max} with a hybrid PET/MRI system ensures that these measurements are performed under identical conditions. Although this weak correlation between ADC and SUV_{max} may be partly secondary to a mixed treatment population, previous studies of lymphoma patients have shown moderate to poor inverse correlation [9] and no correlation [18, 19] between these two parameters. A weak correlation or no correlation has also been noted in numerous nonlymphoma malignancies [12, 20–22]. This lack of correlation likely reflects the fact that SUV_{max} and ADC represent different physiologic processes within malignant tissues.

PET/CT is the standard of care for the initial evaluation and staging of lymphoma. PET/CT is also increasingly used for the evaluation of treatment response, including early treatment response after one or two cycles of therapy. Studies suggest that a quantitative measure of a decrease in SUV_{max} may help in the prediction of remission [23–25]. The mean ADC has also been shown to increase after successful initiation of treatment [11, 19, 26]. The recent introduction of PET/MRI will allow simultaneous evaluation of both SUV_{max} and ADC with imaging performed under the same physiologic conditions. Although the significance of baseline ADC values is unclear [11] in terms of long-term prognosis, baseline ADC and change in ADC in combination with SUV_{max} can be evaluated with PET/MRI in a single simultaneous acquisition.

The results of our study suggest that PET/MRI can potentially improve the detection of extranodal lymphoma, particularly in the bone marrow. Because PET/CT has only moderate sensitivity for bone marrow involvement (especially if a patient is taking medications that cause bone marrow stimulation), biopsy is still the reference standard for the evaluation of bone marrow and is often nontargeted. The increased sensitivity of MRI for bone marrow involvement may allow both targeted bone marrow biopsies and more aggressive early treatment in patients with disease that would have previously been understaged. This possibility requires further investigation.

One limitation of our study is that we included mixed categories of lymphoma, including indolent lymphomas that are less reliably staged by PET/CT. The inclusion of patients who had not undergone treatment, patients currently being treated, and patients who had completed treatment also likely affected the correlation of SUV_{max} and ADC. Additionally, we do not routinely perform diagnostic contrast-enhanced CT during PET/CT at our institution. The use of contrast material can potentially increase lesion conspicuity, especially the conspicuity of extranodal disease. However, we also did not perform gadolinium-enhanced examination with PET/MRI. Single but independent readers evaluated DWI and PET/MRI. However, readers with the most expertise in a modality served as the reader for that particular modality. This strategy is important given the relative novelty of PET/MRI and limited experience with DWI for abdominal imaging.

In conclusion, PET/MRI can assess disease burden in patients with lymphoma with a sensitivity similar to that of PET/CT and can be considered a viable alternative for lymphoma staging and follow-up. Furthermore, the additional value of simultaneously performed DWI and of quantitative ADC assessment needs investigation.

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References

1. Howlader, N.; Noone, AM.; Krapcho, M., et al., editors. National Cancer Institute website. [Accessed January 18, 2015] SEER cancer statistics review, 1975–2011. http://seer.cancer.gov/csr/1975_2011/sections.html
2. Cronin CG, Swords R, Truong MT, et al. Clinical utility of PET/CT in lymphoma. *AJR*. 2010; 194:W91–W103. web. [PubMed: 20028897]
3. Juweid ME, Stroobants S, Hoekstra OS, et al. Imaging Subcommittee of International Harmonization Project in Lymphoma. Use of positron emission tomography for response assessment of lymphoma: consensus of the Imaging Subcommittee of International Harmonization Project in Lymphoma. *J Clin Oncol*. 2007; 25:571–578. [PubMed: 17242397]
4. Hutchings M, Barrington SF. PET/CT for therapy response assessment in lymphoma. *J Nucl Med*. 2009; 50(suppl 1):21S–30S. [PubMed: 19380407]
5. Kwee TC, Vermoolen MA, Akkerman EA, et al. Whole-body MRI, including diffusion-weighted imaging, for staging lymphoma: comparison with CT in a prospective multicenter study. *J Magn Reson Imaging*. 2014; 40:26–36. [PubMed: 24307538]
6. van Ufford HM, Kwee TC, Beek FJ, et al. Newly diagnosed lymphoma: initial results with whole-body T1-weighted, STIR, and diffusion-weighted MRI compared with ¹⁸F-FDG PET/CT. *AJR*. 2011; 196:662–669. [PubMed: 21343511]
7. Abdulqadhr G, Molin D, Astrom G, et al. Whole-body diffusion-weighted imaging compared with FDG-PET/CT in staging of lymphoma patients. *Acta Radiol*. 2011; 52:173–180. [PubMed: 21498346]
8. Adams HJ, Kwee TC, Vermoolen MA, et al. Whole-body MRI for the detection of bone marrow involvement in lymphoma: prospective study in 116 patients and comparison with FDG-PET. *Eur Radiol*. 2013; 23:2271–2278. [PubMed: 23591618]
9. Wu X, Kellokumpu-Lehtinen PL, Pertovaara H, et al. Diffusion-weighted MRI in early chemotherapy response evaluation of patients with diffuse large B-cell lymphoma: a pilot study: comparison with 2-deoxy-2-fluoro-D-glucose-positron emission tomography/computed tomography. *NMR Biomed*. 2011; 24:1181–1190. [PubMed: 21387451]
10. Lin C, Luciani A, Itti E, et al. Whole-body diffusion-weighted magnetic resonance imaging with apparent diffusion coefficient mapping for staging patients with diffuse large B-cell lymphoma. *Eur Radiol*. 2010; 20:2027–2038. [PubMed: 20309558]
11. Punwani S, Taylor SA, Saad ZZ, et al. Diffusion-weighted MRI of lymphoma: prognostic utility and implications for PET/MRI? *Eur J Nucl Med Mol Imaging*. 2013; 40:373–385. [PubMed: 23197155]
12. Rakheja R, Chandarana H, DeMello L, et al. Correlation between standardized uptake value and apparent diffusion coefficient of neoplastic lesions evaluated with whole-body simultaneous hybrid PET/MRI. *AJR*. 2013; 201:1115–1119. [PubMed: 24147485]
13. Chandarana H, Heacock L, Rakheja R, et al. Pulmonary nodules in patients with primary malignancy: comparison of hybrid PET/MR and PET/CT imaging. *Radiology*. 2013; 268:874–881. [PubMed: 23737537]
14. Platzek I, Beuthien-Baumann B, Langner J, et al. PET/MR for therapy response evaluation in malignant lymphoma: initial experience. *MAGMA*. 2013; 26:49–55. [PubMed: 22983794]
15. Drzezga A, Souvatzoglou M, Eiber M, et al. First clinical experience with integrated whole-body PET/MR: comparison to PET/CT in patients with oncologic diagnoses. *J Nucl Med*. 2012; 53:845–855. [PubMed: 22534830]
16. Wiesmüller M, Quick HH, Navalpakkam B, et al. Comparison of lesion detection and quantitation of tracer uptake between PET from a simultaneously acquiring whole-body PET/MR hybrid

- scanner and PET from PET/CT. *Eur J Nucl Med Mol Imaging*. 2013; 40:12–21. [PubMed: 23053323]
17. Heusch P, Buchbender C, Kohler J, et al. Thoracic staging in lung cancer: prospective comparison of ^{18}F -FDG PET/MR imaging and ^{18}F -FDG PET/CT. *J Nucl Med*. 2014; 55:373–378. [PubMed: 24504054]
18. Wu X, Korkola P, Pertovaara H, Eskola H, Jarvenpaa R, Kellokumpu-Lehtinen PL. No correlation between glucose metabolism and apparent diffusion coefficient in diffuse large B-cell lymphoma: a PET/CT and DW-MRI study. *Eur J Radiol*. 2011; 79:e117–e121. [PubMed: 21596501]
19. Hagtvedt T, Seierstad T, Lund KV, et al. Diffusion-weighted MRI compared to FDG PET/CT for assessment of early treatment response in lymphoma. *Acta Radiol*. 2014 Feb 28. Epub ahead of print.
20. Varoquaux A, Rager O, Lovblad KO, et al. Functional imaging of head and neck squamous cell carcinoma with diffusion-weighted MRI and FDG PET/CT: quantitative analysis of ADC and SUV. *Eur J Nucl Med Mol Imaging*. 2013; 40:842–852. [PubMed: 23436068]
21. Ho KC, Lin G, Wang JJ, Lai CH, Chang CJ, Yen TC. Correlation of apparent diffusion coefficients measured by 3T diffusion-weighted MRI and SUV from FDG PET/CT in primary cervical cancer. *Eur J Nucl Med Mol Imaging*. 2009; 36:200–208. [PubMed: 18779960]
22. Regier M, Derlin T, Schwarz D, et al. Diffusion weighted MRI and ^{18}F -FDG PET/CT in non-small cell lung cancer (NSCLC): does the apparent diffusion coefficient (ADC) correlate with tracer uptake (SUV)? *Eur J Radiol*. 2012; 81:2913–2918. [PubMed: 22197090]
23. Terasawa T, Nihashi T, Hotta T, Nagai H. ^{18}F -FDG PET for posttherapy assessment of Hodgkin's disease and aggressive non-Hodgkin's lymphoma: a systematic review. *J Nucl Med*. 2008; 49:13–21. [PubMed: 18077527]
24. Cashen AF, Dehdashti F, Luo J, Homb A, Siegel BA, Bartlett NL. ^{18}F -FDG PET/CT for early response assessment in diffuse large B-cell lymphoma: poor predictive value of international harmonization project interpretation. *J Nucl Med*. 2011; 52:386–392. [PubMed: 21321279]
25. Querellou S, Valette F, BodetMilin C, et al. FDG-PET/CT predicts outcome in patients with aggressive non-Hodgkin's lymphoma and Hodgkin's disease. *Ann Hematol*. 2006; 85:759–767. [PubMed: 16871391]
26. Wu X, Pertovaara H, Korkola P, et al. Correlations between functional imaging markers derived from PET/CT and diffusion-weighted MRI in diffuse large B-cell lymphoma and follicular lymphoma. *PLoS ONE*. 2014; 9:e84999. [PubMed: 24454777]

Fig 1.

Schematic of timing of imaging examinations for this study. PET/MRI was performed after clinically indicated PET/CT. PET/MRI used residual tracer activity from single dose of ^{18}F -FDG that was injected before PET/CT.

Fig 2. 30-year-old man with follicular lymphoma

A, On diffusion-weighted image, left paraaortic and right retrocrural nodes are subcentimeter in size and were considered normal based on morphologic size criterion. **B** and **C**, On PET/MR image (**B**) and PET/CT image (**C**), left paraaortic and right retrocrural nodes (arrows, **B**) are FDG-avid, thus indicating lymphoma involvement.

Fig 3. 52-year-old woman with follicular lymphoma

A and B, Right femoral neck lymphoma involvement is seen on diffusion-weighted image (A) and PET/MR image (B). **C and D,** Lesion shown in A and B is not as conspicuous on CT image (C) or PET/CT fused image (D), PET/CT and was not detected by readers. Right femoral neck lymphoma involvement was confirmed on bone biopsy.

Fig 4. Maximum standardized uptake value (SUV_{max})

A, Correlation plot of SUV_{max} in FDG-avid lymph nodes on PET/CT and PET/MRI. There was significant strong correlation between PET/CT and PET/MRI in SUV_{max} ($r = 0.975$, $p < 0.001$). Line = line of best fit. **B**, Bland-Altman plot shows higher mean SUV_{max} with PET/CT than with PET/MRI. Mean difference (solid line) in SUV_{max} is 1.7 (95% limits of agreement [dotted lines], 9.2 and -5.8).

Fig 5. Correlation between maximum standardized uptake value (SUV_{max}) and apparent diffusion coefficient (ADC) on PET/ MRI. There was poor correlation that was not significant ($r = 0.06$, $p = 0.77$) between nodal ADC and SUV_{max} values.

TABLE 1

Nodal Group Detection by Modality Compared With PET/CT

Modality	Sensitivity (%) ^a	False-Negative (No. of Nodal Groups)	False-Positive (No. of Nodal Groups)
PET/MRI	100 (51/51)	0	1
DWI	62.7 (32/51) [42.5–79.3]	19	5

Note—PET/MRI had a significantly higher sensitivity than diffusion-weighted imaging (DWI) for the detection of nodal disease compared with DWI ($p < 0.01$).

^aData in parentheses are no. of nodal group with positive findings/no. of nodal groups with positive PET/CT findings. Data in brackets are 95% CI.

TABLE 2

Modified Ann Arbor Staging by Modality

Stage	PET/CT (No. of Patients)	PET/MRI (No. of Patients)	DWI (No. of Patients)
0 ^a	15	15	17
I	2	2	5
II	4	4	1
III	6	5	3
IV	1	2 ^b	2 ^b
Total	28	28	28

Note—DWI = diffusion-weighted imaging.

^aNo evidence of disease.

^bOne patient with bone marrow involvement, as diagnosed on bone marrow biopsy, was accurately staged by PET/MRI and DWI, whereas PET/CT failed to detect the bone marrow abnormality and understaged disease as stage III in this patient.