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Evaluation of diagnostic performance of whole-body simultaneous PET/MRI in pediatric lymphoma

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Abstract

Background—Whole-body ¹⁸F-fluorodeoxyglucose (FDG) positron emission tomography/computed tomography (PET/CT) is the standard of care for lymphoma. Simultaneous PET/MRI (magnetic resonance imaging) is a promising new modality that combines the metabolic information of PET with superior soft-tissue resolution and functional imaging capabilities of MRI while decreasing radiation dose. There is limited information on the clinical performance of PET/MRI in the pediatric setting.

Objective—This study evaluated the feasibility, dosimetry, and qualitative and quantitative diagnostic performance of simultaneous whole-body FDG-PET/MRI in children with lymphoma compared to PET/CT.

Materials and methods—Children with lymphoma undergoing standard of care FDG-PET/CT were prospectively recruited for PET/MRI performed immediately after the PET/CT. Images were evaluated for quality, lesion detection and anatomical localization of FDG uptake. Maximum and mean standardized uptake values (SUV_{max/mean}) of normal organs and SUV_{max} of the most FDG-avid lesions were measured for PET/MRI and PET/CT. Estimation of radiation exposure was calculated using specific age-related factors.

Results—Nine PET/MRI scans were performed in eight patients (mean age: 15.3 years). The mean time interval between PET/CT and PET/MRI was 51±10 min. Both the PET/CT and PET/MRI exams had good image quality and alignment with complete (9/9) concordance in response assessment. The SUVs from PET/MRI and PET/CT were highly correlated for normal organs (SUV_{mean} r²: 0.88, *P*<0.0001) and very highly for FDG-avid lesions (SUV_{max} r²: 0.94, *P*=0.0002). PET/MRI demonstrated an average percent radiation exposure reduction of 39 % ± 13% compared with PET/CT.

Conclusion—Simultaneous whole-body PET/MRI is clinically feasible in pediatric lymphoma. PET/MRI performance is comparable to PET/CT for lesion detection and SUV measurements. Replacement of PET/CT with PET/MRI can significantly decrease radiation dose from diagnostic imaging in children.

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Compliance with ethical standards

Conflicts of interest None

Keywords

Children; Lymphoma; Positron emission tomography/Computed tomography; Positron emission tomography/Magnetic resonance imaging; Magnetic resonance imaging

Introduction

[F-18]2-fluoro-2-deoxyglucose positron emission tomography CT (F-18 FDG PET/CT) is an established imaging modality for staging and response evaluation of pediatric lymphoma patients [1, 2]. Several studies have demonstrated higher diagnostic imaging accuracy of FDG-PET/CT compared to conventional anatomical imaging for evaluation of pediatric lymphoma [3]. Advances in therapy have significantly improved the outcome of pediatric lymphoma with current 5-year survival of pediatric Hodgkin lymphoma and non-Hodgkin lymphoma estimated at 97% and 85%, respectively [4, 5]. As a result, there has been a shift in treatment paradigm, with emphasis on reducing iatrogenic toxicity and late side effects of chemotherapy. This can be achieved by modifying therapy based on early response assessment, and decreasing exposure to diagnostic and therapeutic ionizing radiation. Children with lymphoma and neuroblastoma have been shown to have the highest cumulative effective dose from diagnostic radiation, among all pediatric cancer patients [6]. The cornerstone of imaging safety is the As Low As Reasonably Achievable (ALARA) principle, and there is general consensus that reducing radiation exposure is desirable, particularly in children and young adults. Since the majority of children with lymphoma have good long-term survival, reducing the radiation dose from diagnostic imaging is highly desirable because it may decrease the risk of developing radiation-related malignancies later in life. Whole-body MR has shown potential in the evaluation of children with lymphoma and solid tumors [7–9]. It provides better soft-tissue contrast than CT and allows for incorporation of functional imaging information, which can add information about tumor behavior, improving diagnosis and treatment monitoring [10, 11]. However, differentiation between benign and malignant lymph nodes remains challenging even with the combination of diffusion-weighted imaging and anatomical criteria [12–15].

Several adult oncology studies have shown that clinical integrated PET/MRI is technically feasible, and has good image quality and excellent diagnostic accuracy for whole-body staging compared to conventional PET/CT [16–19]. However, these results cannot be directly extrapolated to pediatric oncology given the physiological differences in children (such as red vs. fat marrow, brown fat distribution) and differences in tumor biology. The technical performance and diagnostic accuracy of PET/MRI imaging needs to be independently assessed in children and, to date, data on the clinical performance of PET/MRI in pediatric oncology is limited [20, 21].

In this study, we evaluated the feasibility, dosimetry, and the diagnostic and quantitative accuracy of simultaneous whole-body FDG-PET/MRI in children with known lymphoma. The accuracy of PET/MRI for lesion detection, response assessment and standardized uptake values (SUV) measurement was evaluated using clinical PET/CT as the reference standard.

Materials and methods

This is an institutional review board approved, Health Insurance Portability and Accountability Act (HIPAA) compliant study. Children undergoing a clinical FDG-PET/CT were prospectively recruited for a research whole-body PET/MRI between October 2012 and May 2013. Written informed consent was obtained from all study participants and their legal guardians. The inclusion criteria were age 8 to 18 years, histologically proven lymphoma and clinically indicated standard of care FDG-PET/CT. The exclusion criteria were contraindication to MR or the need for sedation.

PET/CT imaging parameters

FDG-PET/CT examinations were performed with a Siemens mCT PET/CT scanner or Siemens Biograph 40 HD PET/CT systems (Siemens Healthcare, Erlangen, Germany). The PET/CT examinations followed the standard low-dose non-enhanced CT protocol used for clinical care at our institution. All patients fasted for at least 4 h before imaging and their glucose levels were verified to be less than 200 mg/dl (mean: 98.6 mg/dl $\pm$ 5.26). Intravenous injection of standard of care, weight-adjusted doses of FDG were administered following our institutional standard of care pediatric dosage of 0.07 mCi/pound (0.15 mCi/kg), with an average dosage of ^{18}F -FDG of 8.7 ± 1.4 mCi (328 ± 52 MBq) with a range of 6 mCi to 9.9 mCi (220 MBq to 366.3 MBq). The PET/CT acquisitions were started 57 ± 6 min (range: 50-71 min) after the administration of tracer with a mean delay between PET/CT and PET/MRI of 51 ± 10 (range: 43-74 min). The average duration of the PET/CT scan was approximately 25 min. The scan protocol adheres to the ALARA guideline for exposure to ionizing radiation. A spiral CT scan for attenuation correction and anatomical localization of PET findings was obtained from the skull base through the upper thighs. Standardized, weight-adjusted protocols, including optimized dose modulation (CARE Dose; Siemens Healthcare, Erlangen, Germany) were used. Images were reconstructed with and without attenuation correction with a 3D-Ordered-Subset Expectation Maximization (3D-OSEM) algorithm with HD (TrueX) or time of flight (TOF). Scatter, decay and dead time corrections were used, as implemented by the equipment manufacturer.

PET/MRI imaging parameters

PET/MRI examinations were performed on a simultaneous PET/MRI system, 3.0-T Siemens Biograph mMR (Siemens Health Care, Erlangen, Germany). PET/MRI was initiated 109 ± 10 min after ^{18}F -FDG injection (range: 94-126 min) using the activity from the clinical FDG-PET/CT study. The average duration of the PET/MRI scan was approximately 60 min. The acquisition was performed on multiple-station mode for whole-body imaging and consisted of standard of care MR sequences with simultaneous PET acquisition for 2-5 min per bed position adjusted as needed based on subject height, weight and injected dose. The MR sequences include whole-body Dixon, T2 half-Fourier acquisition single-shot turbo spin-echo (HASTE), short tau inversion recovery (STIR) and diffusion-weighted imaging (DWI) (Table 1). Dual-echo VIBE (volume interpolated breathhold examination) Dixon sequence was acquired for attenuation correction and used for the MR-based segmentation map [22]. The PET/MRI images were acquired from skull vertex to mid-thigh level without administration of an MR imaging contrast agent (Fig. 1).

Image interpretation

The PET/MRI were evaluated qualitatively and semiquantitatively in consensus by two radiologists, one with subspecialty training in nuclear medicine (J.M. with 5 years of experience) and the other with subspecialty training in pediatric radiology (G.K. with 11 years of experience). After a minimum time interval of 30 days, the PET/CT images were evaluated by the same readers in consensus. The readers knew that the patients had biopsy-proven lymphoma, were aware of the indication of the clinical PET scan and had access to the prior PET/CT study that was performed 42-183 days before the PET/MRI scan. This provides for better image interpretation, follows standard clinical practices and is necessary for assessing interval response. They were blinded to the results of all other clinical information, including the clinical PET/CT report. A commercially available software package (MIM Encore version 6.4.1; MIM Software, Inc., Cleveland, OH) was used for imaging viewing, fusion and SUV measurements of the PET/MRI and PET/CT images.

Subjective assessments of image quality and PET alignment quality were assessed following the definitions presented in Table 2. For interpretive purposes, each scan was divided into four regions (head and neck, thorax, abdomen/pelvis and extremities) to determine the number of malignant lesion(s) per region (0, 1, 2, 3 and 3+) and the confidence level associated with the malignant process (confidence level: 1=low, 2=moderate and 3=high). An overall assessment was assigned to each scan, which was defined as complete metabolic response, partial metabolic response, stable disease and progression of disease compared to the immediate prior study [23, 24].

Maximum and mean standardized uptake values (SUV_{max} and SUV_{mean}) of normal organs were obtained from MR attenuation-corrected (DIXON-based segmented μ map) PET images and compared with values obtained from CT-based attenuation correction PET/CT. The SUVs of normal organs were measured using a 1.5-cm region of interest (ROI) within the respective organs, these being lung (right upper lobe), mediastinal blood pool (right atrium), bone (L4 vertebral body) and muscle (psoas muscle) by a third radiologist with dual training in pediatric radiology and nuclear medicine (M.R.P. with 10 years and 3 years of experience, respectively). Additionally, SUV_{max} measurements were made in the most FDG-avid lesions in each of the four defined body regions using a gradient-based segmentation method to delineate tumor contours (PET edge mode tool) [25].

Estimation of radiation exposure

The total effective dose from the FDG injection and CT scan was evaluated for each patient using specific age-related factors. The effective dose from the FDG injection was obtained by multiplying the International Commission on Radiological Protection (ICRP) publication 106 [26] age-related effective dose by the injected activity with the following age breakdown: 18-year-old used 0.019 mSv/MBq, 17- to 15-year-old used 0.024 mSv/MBq, 14- to 12-year-old used 0.024 mSv/MBq and 11- to 7-year-old used 0.037 mSv/MBq. The CT whole-body effective doses were calculated using the dose-length product (DLP) with pediatric correction factors [27]. An average dose length product to ED conversion factor of 0.017 mSv/mGy.cm [28] was employed along with pediatric correction factors of 1.0 for 18-year-old, 1.1 for 17- to 15-year-old, 1.15 for 14- to 12-year-old and 1.2 for 11- to 7-year-old

[27]. The percent dose reduction from eliminating the CT component of PET/CT, performed for attenuation correction and localization, was calculated as the ratio of the effective dose from the CT divide by the total effective dose from the PET/CT for each scan run. The average and standard deviation for the percent dose reduction using PET/MRI was obtained from the set of scan runs ($n=9$).

Data analysis

Pearson correlation coefficients (r^2) were calculated to quantify the correlation between SUV values on attenuation correction PET/CT and PET/MRI images. The SUV values are expressed as means $\pm$ standard deviations. The r^2 were interpreted as following: 0.9 to 1.0, very high correlation; 0.7 to 0.90, high positive correlation; 0.50 to 0.70, moderate correlation; 0.30 to 0.50, low positive correlation, and 0.00 to 0.30, negligible correlation [28]. Image quality and alignment were expressed in absolute numbers.

Results

Nine PET-MRI studies were performed on 8 patients (6 boys and 2 girls) with a mean age of 15.3 years (range: 12-17.5 years). The lymphoma histologies were as follows: 4 Hodgkin lymphoma, 2 diffuse large B-cell lymphoma and 2 Burkitt lymphoma. The patient characteristics are given in Table 3.

Image quality

The image quality was evaluated independently for MRI sequences and PET images as well as together for image alignment quality between the two imaging modalities. All nine PET/CT exams were rated as having image quality and image alignment scores of good. The image quality scores of PET/MRI studies was as follows: excellent, $n=1$; good, $n=7$, and acceptable, $n=1$. The alignment scores for PET/MRI studies were as follows: good, $n=7$, and acceptable, $n=2$. The quality of the PET/MRI μ map was good in five patients and acceptable in four patients. The cause of acceptable quality on the PET/MRI μ map was the presence of attenuation artifacts from the child's dental braces ($n=2$) projecting over the frontal lobes and face (Fig. 2), artifacts in the chest related to the child's port catheter ($n=1$), and lungs on the Dixon sequences affecting the μ map ($n=1$). An additional artifact was observed in one child at the lung base related to breathing motion (Fig. 3).

Quantitative analysis

SUV_{mean} of normal organs derived from PET/MRI and PET/CT studies showed a high correlation ($r^2=0.88$, $P<0.0001$). Correlation coefficient for SUV_{mean} was highest for bone ($r^2=0.90$), liver ($r^2=0.86$) and muscle ($r^2=0.78$) and moderate for lung ($r^2=0.65$) and blood pool ($r^2=0.61$) (Fig. 4). One of the children presented with bone marrow stimulation, associated with high SUVs. If this child is excluded from the analysis, the correlation coefficient for bone is 0.73.

SUV_{max} in 16 lesions was measured on the PET/MRI images and PET/CT images. The PET/MRI SUV_{max} values ranged from 2.2 to 21.4, and the PET/CT SUV_{max} values ranged from 2.1 to 19.6. There was very high correlation of SUVmax of FDG-avid lesions as

measured on PET/MRI and PET/CT ($r^2 = 0.94$, $P < 0.0002$) (Fig. 4). The mean SUV_{max} for FDG-avid lesions was 1.6 % higher for PET/MRI than PET/CT.

Qualitative analysis

Table 4 summarizes the number of malignant lesions identified per case and the response assessment at PET/MRI and PET/CT. There was complete (9/9) concordance between PET/CT and PET/MRI regarding response assessment. A few discrepancies were observed between PET/CT and PET/MRI in terms of number of lesions identified. In one child, PET/CT detected two foci of FDG uptake in residual anterior mediastinal mass while PET/MRI showed only one area of focal uptake in the residual anterior mediastinal mass (case 1). In case 2, PET/MRI detected two lesions with increased FDG uptake in the neck while PET/CT detected one lesion in this region. Finally, case 3 had a renal lesion with markedly increased FDG uptake that was obscured by excreted activity in the urine and not detected on PET/CT but was readily identified on PET/MRI on the diffusion-weighted sequences due to restricted diffusion (Fig. 5). PET/CT imaging follow-ups were available for all patients with the time interval between the research PET/MRI and clinical follow-up PET/CT of 3 to 20 months. The clinical and imaging follow-up confirmed the PET/CT and PET/MRI findings with the results reported in Table 4.

Radiation dose

The mean effective dose of whole-body PET/CT examinations was 13.8 ± 3.9 mSv, with PET accounting for 8.0 ± 0.9 mSv and CT accounting for 5.8 ± 3.3 mSv. PET/MRI demonstrated an average radiation exposure reduction by $39\% \pm 13\%$ compared with PET/CT. The average volume CT dose index ($CTDI_{vol}$) was 3.07 mGy (range: 1.4-6.13 mGy).

Discussion

The purpose of our study was to evaluate the feasibility, qualitative and quantitative diagnostic performance of simultaneous whole-body FDG-PET/MRI in children with lymphoma compared to PET/CT.

In a cohort of prospectively recruited children who underwent whole-body simultaneous PET/MRI and PET/CT on the same day, we have shown that PET/MRI has similar diagnostic performance as PET/CT for response assessment with complete concordance noted in all nine scans. PET/MRI accurately identified all sites of disease noted on PET/CT. PET/MRI also accurately detected the number of pathological lesions in these disease sites in all cases except one, where PET/CT showed two foci of FDG uptake in the anterior mediastinum while PET/MRI showed only one SUV avid area in the residual anterior mediastinal mass. The reason for this discrepancy is unclear but may be due to redistribution of FDG between the PET/CT and PET/MRI acquisitions. In addition, the superior soft-tissue contrast of PET/MRI helped detect a pathological neck lymph node, and the DWI sequence allowed for the assessment of diffusion restriction assisting in the detection and characterization of a FDG-avid renal lesion that was missed on PET/CT due to being obscured by adjacent excreted activity in the renal collecting system. This case illustrates the complementary benefits of combining molecular information from PET data with high-

resolution anatomical information provided by MR, and the ability to measure metabolic and biochemical parameters. More studies in larger patient populations are needed to determine if these potential advantages of MRI over CT lead to superior diagnostic accuracy with PET/MRI. One previous pediatric study showed improved detection of solid organ and bone lesions at PET/MRI compared to PET/CT. The prior study had a heterogeneous patient population with a variety of malignant tumors [21]. Currently, there are no standards for the MRI sequences used in PET/MRI scans. For aggressive lymphomas, which are almost universally FDG-avid, lesion detection is usually not an issue unless adjacent to a site of high physiological FDG accumulation (e.g., brain and genitourinary system). Thus, anatomical localization is likely sufficient in this particular clinical setting. Additionally, we acquired diffusion-weighted sequences to provide functional information that complement the anatomical information from the axial HASTE and STIR sequences. MRI may play a much larger role in other malignancies, which have variable and, in some cases, low FDG uptake. Based on our study and prior publications, we recommend that DWI should be a standard sequence in whole-body PET/MRI protocols in pediatric oncology.

Two children in our cohort had pulmonary lesions. PET/MRI accurately identified pulmonary involvement in both patients. Previous studies have shown the limitations of PET/MRI in detecting pulmonary metastasis. We believe lymphomatous involvement of lung is well depicted by PET/MRI as these masses are typically more than a few millimeters in diameter. However, children with solid tumors undergoing PET/MRI still need a diagnostic chest CT as both PET and MR have been shown to have limited sensitivity for detecting pulmonary nodules <5 mm in diameter [29].

In terms of PET quantification obtained with MR- and CT-based attenuation correction, our results show good correlation of the mean and maximum SUVs obtained for normal organs and FDG-avid lesions, implying reliable SUV quantification with PET/MRI. Prior adult studies have shown strong correlation between SUVs estimated by MR-based attenuation correction and CT-based attenuation correction [30, 31]. Due to physiological differences between children and adults, these results cannot be directly extrapolated to the pediatric population. To the best of our knowledge, only two prior publications have evaluated this issue in children [21, 32]. Our study adds to the body of evidence that PET/MRI provides reliable SUV quantitative assessment in children. The median SUVs for PET/MRI were lower than the respective values for PET/CT for all normal organs as has been observed in adults. This difference could be due to technical factors such as the performance characteristics of the different PET technologies and differences in attenuation correction methodology, as well as the interval between image acquisitions [33]. The Siemens Biograph mMR (Siemens Healthcare, Erlangen, Germany) PET/MRI with absolute sensitivity of 15 kcps/MBq [34] measured in air has better performance characteristics than the Siemens Biograph 40 HD (Siemens Healthcare, Erlangen, Germany) PET/CT with an absolute sensitivity of 8.1 kcps/MBq [35]. The two studies were performed sequentially with an average delay between PET/CT and PET/MRI of 51 ± 10 min resulting in a longer post-injection acquisition time for all PET/MRI studies. The increased post-injection delay contributes to changes in biodistribution and washout of ^{18}F -FDG from normal organs. The radiation decay accounted, in part, for longer scanning time per/bed position (2 min in PET/CT, 2.5-5 min in PET/MRI) and, thus, image statistics were similar in PET/CT and

PET/MRI. However, PET/MRI benefited from a slightly more favorable biodistribution relative to PET/CT in our measurements. On the other hand, the mean SUV_{max} for FDG-avid lesions at PET/MRI was 1.6% higher than that estimated at PET/CT, and this difference can be again explained by the mean delay between PET/CT and PET/MRI, which extends the uptake phase increasing trapping of the tracer within pathological lesions as previously reported [36].

In our cohort of older children, we have shown that eliminating the CT component of PET/CT would decrease the effective dose by an average of 39%. This is in contradistinction to the 73-80% radiation dose reduction reported in previous studies [20, 21]. This difference is likely because our clinical PET/CT is comprised of a low-dose CT performed for attenuation correction and localization only. We do not use this for diagnostic purposes and do not administer iodinated intravenous contrast for PET/CT. As the radiopharmaceutical contributes substantially to the overall radiation dosimetry, reduction of the administered amount of FDG potentially compensated by longer PET acquisition times could further reduce the overall patient radiation exposure. The extra time at each bed position can be utilized to obtain additional MR sequences given the simultaneous scanning capability of the PET/MRI scanner. Further reductions in radiation exposure are expected as PET/MRI technology advances. The development of PET detectors with better performance characteristics would allow for lower dose of injected radiotracers because of the better imaging sensitivity. Additionally, longer PET acquisition times along with multisequence MRI collection may further reduce the amount of activity administered.

PET/MRI artifacts were observed, related to abnormal attenuation correction leading to incomplete evaluation of the cervical lymph node chains, in one child. Breathing artifact simulating increased uptake in the right lung base was noted in another patient. Errors in attenuation correction within the lung can be caused by respiratory misalignment of PET and MR data due to the difference in the duration of the two examinations resulting in mismatch of PET emission and MR attenuation data. This type of tissue misclassification could be reduced by adopting MR-guided non-rigid motion correction techniques [37, 38] or respiratory gating [39].

A major limitation of our study is the small sample size. However, this data in conjunction with the literature in adult studies comparing PET/MRI to PET/CT for whole-body staging indicate that whole-body PET/MRI has a diagnostic performance comparable to PET/CT in the pediatric lymphoma population. Currently, our main indication for clinical whole-body PET/MRI scanning are pediatric oncological patients who need a whole-body scan in lieu of a PET/CT, especially if the child needs a whole-body PET scan and a diagnostic regional MRI. This allows for both studies to be performed as a “one-stop shop” under the same sedation. The primary limitation of this approach is the need for an additional chest CT in children with malignancies at risk for pulmonary metastasis. We typically perform this as a non-sedated, non-contrast chest CT as the mediastinum is well evaluated by PET/MRI. Given the inclusion criteria of this study, only non-sedated patients were enrolled with an age range of 12.0–17.5 years.

Another limitation of our study is that not all children had evidence of disease at the time of the research scan. However, several patients had multiple lesions with good correlation between the two methodologies. Despite our focus on pediatric patients with lymphoma, the clinical indication for the PET/CT was heterogeneous and included patients who were still undergoing therapy as well as children who had completed therapy. The lack of pathological correlation of malignant/suspicious findings is another limitation since it was not feasible in all the cases due to ethical concerns. Thus, our reference interpretations were based on PET/CT imaging follow-up, histological findings when available and clinical follow-up.

Our goal was to demonstrate that FDG-PET/MRI is feasible in children and offers substantial dose reduction without reducing diagnostic accuracy compared to PET/CT. There is extensive literature addressing the accuracy of FDG-PET and FDG-PET/CT for aggressive lymphomas in adults and to a lesser extent children [3, 40, 41] and, thus, FDG-PET/CT is a reasonable reference standard for our study.

Conclusion

Our results suggest that ^{18}F -FDG-PET/MRI is a clinically feasible modality that has high correlation with PET/CT for both qualitative and quantitative diagnostic performance of response assessment in pediatric lymphoma and perhaps other pediatric malignancies. The superior soft-tissue contrast and functional imaging capabilities of MR can aid in lesion detection at PET/MRI, especially in solid organs. PET/MRI decreases exposure to ionizing radiation in this patient population.

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Fig. 1. Representative images of the whole-body PET/MRI protocol in a 15-year-old boy with relapsed Hodgkin lymphoma (case 2). **a** U-map is used for MR-based attenuation correction of the PET data and is generated from the following four Dixon sequences: **(b)** water-weighted, **(c)** opposed-phase, **(d)** fat-weighted and **(e)** in-phase images. **f** PET maximum intensity projection (MIP), **(g)** PET/MRI fusion and **(h)** DWI demonstrate multiple malignant lymph nodes that are FDG-avid and restrict diffusion

Fig. 2. PET/MRI artifact in a 15-year-old boy (case 6) with braces. There is significant degradation of image quality and loss of signal on the fused PET/MRI image (**a**) and the MR-based attenuation corrected PET image (**b**) in the region of the braces. The non-attenuated PET image (**c**) demonstrates normal FDG activity in the region of the head and neck

Fig. 3.
Images (a–c) demonstrate a breathing artifact in a 15-year-old boy with non-Hodgkin lymphoma (case 6): (a) PET images from PET/MRI, (b) fusion PET/MRI and (c) PET/CT. The breathing artifact simulates a lung base nodule (*arrows* in a and b). Lung window CT (c) demonstrates no abnormalities

Fig. 4.
Correlation plots of PET/CT and PET/MRI for all selected normal organs (a) and FDG-avid lesions (b) with the corresponding correlation coefficients (r^2)

Fig. 5. PET/MRI (a–c), and PET/CT (d–f) in a 17-year-old boy with large B-cell lymphoma with left renal infiltration (case 3). The presence of restricted diffusion on DWI (arrows in a–c) and the excellent PET/MRI coregistration allowed better identification of a renal lesion and differentiation from excreted FDG in the collecting system than PET/CT (arrowheads in d–f)

Table 1

Whole body MR imaging sequence parameters

Sequence	Axial Dixon	Axial HASTE	Axial DWI	Axial STIR
Parameters				
Acquisition time (mins)	0.33	3	3	2
Echo time (TE) (ms)	1.23, 2.46	116	85	89–97
Repetition time(TR) (ms)	3.6	3000	10000	2910–3690
Bandwidth (Hz/pixel)	965	710	1628	260
Matrix size	192×79	320×240	128×96	320×163×218
Slice thickness	3.1	5	5	5–6
Flip angle (degree)	10	160	90	140
Inversion time (TI) (ms)				220
B values (mm ² /s)			50,400,800	

DWI diffusion weighted imaging, *HASTE* half-Fourier acquired single-shot turbo spin echo, *STIR* short-tau inversion recovery

Table 2

Image interpretation. Definitions of subjective assessment of image quality (**a**) and PET alignment used for image interpretation (**b**)

a Images Quality	
1	Poor quality, not diagnostically acceptable for interpretation
2	Suboptimal quality, worse than routine images with excessive image noise
3	Acceptable quality, diagnostic interpretation possible but noise more than routine images
4	Good quality, noise similar to routine images
5	Excellent quality, no image noise

b Quality of positron emission tomography (PET)/CT alignment	
1	Poor alignment, complete lack of alignment
2	Suboptimal alignment, differs by more than 25 mm
3	Acceptable alignment, differs >5 but <25 mm
4	Good alignment, differs <5 mm
5	Excellent alignment, no misalignment

Table 3
Study patients' characteristics. There are eight patients and nine scans since case 4 received two scans.

Case No.	Age (yrs)	Sex	Diagnosis	Primary tumor site(s)	PET/CT indication
1	17.5	Male	Hodgkin lymphoma (classical type)	Mediastinal mass	Treatment monitoring
2	15.6	Male	Hodgkin lymphoma (classical type)	Neck and mediastinal lymph nodes	Restaging after completion of chemotherapy
3	17.0	Male	Non-Hodgkin lymphoma (diffuse large B-cell)	Mediastinal mass	Restaging after completion of chemotherapy
4(a)	14.8	Female	Hodgkin lymphoma (classical type)	Mediastinal mass, axillary and cervical lymph nodes	Restaging after completion of chemotherapy
4(b)	15.3	Female	Hodgkin lymphoma (classical type)	Mediastinal mass, axillary and cervical lymph nodes	Suspected recurrence
5	12.0	Male	Non-Hodgkin lymphoma (diffuse large B-cell)	Mediastinal mass	Restaging after completion of chemotherapy
6	15.0	Male	Non-Hodgkin lymphoma (Burkitt)	Small bowel	Treatment monitoring
7	15.3	Male	Non-Hodgkin lymphoma (Burkitt)	Ascending colon	Restaging after completion of chemotherapy
8	15.5	Female	Hodgkin lymphoma (classical type)	Mediastinal mass	Treatment monitoring

Table 4

Detection of malignant lesions and response assessment by PET/MRI vs. PET/CT

Case No.	Number and location of suspected malignant lesion(s)		Response assessment compared to immediate prior scan		Imaging follow-up number and location of suspected malignant lesion(s)	
	PET/CT	PET/MRI	PET/CT	PET/MRI	PET/CT	PET/CT
1	2, anterior mediastinum	1, anterior mediastinum	Partial response	Partial response	0, anterior mediastinum 1, posterior mediastinum ⁿ	
2	1, neck >3, chest	2, neck >3, chest	Progressive disease	Progressive disease	>2, neck ^s >3, chest ⁱ >3 bone lesions ⁿ	
3	1, chest 1, retroperitoneal lymph node	1, chest 1, retroperitoneal lymph node 1, kidney	Progressive disease	Progressive disease	0, chest 0, retroperitoneal lymph node 0, kidney	
4 (a)	0	0	Complete response	Complete response	0	
4 (b)	0	0	Complete response	Complete response	0	
5	1, anterior mediastinum	1, anterior mediastinum	Stable disease	Stable disease	1, anterior mediastinum ^s	
6	0	0	Complete response	Complete response	0	
7	0	0	Complete response	Complete response	0	
8	0	0	Complete response	Complete response	0	

ⁿ new lesion detected on the PET/CT follow-up

ⁱ increase in number of suspected lesion(s)

^s stable lesion since previous PET/CT and PET/MRI