European Journal of Radiology 93 (2017) 70–75

Contents lists available at ScienceDirect

European Journal of Radiology

journal homepage: www.elsevier.com/locate/ejrad

Research papers

Clinical evaluation of whole-body oncologic PET with time-of-flight and point-spread function for the hybrid PET/MR system

Kun Shang[a], Bixiao Cui[a], Jie Ma[a], Dongmei Shuai[a], Zhigang Liang[a], Floris Jansen[c], Yun Zhou[d], Jie Lu[a,*], Guoguang Zhao[a,b]

[a] Department of Nuclear Medicine, Xuanwu Hospital of Capital Medical University, Beijing, China
[b] Department of Neurosurgery, Xuanwu Hospital of Capital Medical University, Beijing, China
[c] GE Healthcare, Waukesha, WI, USA
[d] Department of Radiology, Johns Hopkins University, Baltimore, MD, USA

ARTICLE INFO

Keywords:
Time-of-flight
Point-spread function
Hybrid PET/MR
Small lesion detection

ABSTRACT

Purpose: Hybrid positron emission tomography/magnetic resonance (PET/MR) imaging is a new multimodality imaging technology that can provide structural and functional information simultaneously. The aim of this study was to investigate the effects of the time-of-flight (TOF) and point-spread function (PSF) on small lesions observed in PET/MR images from clinical patient image sets.

Materials and methods: This study evaluated 54 small lesions in 14 patients who had undergone ^{18}F-fluorodeoxyglucose (FDG) PET/MR. Lesions up to 30 mm in diameter were included. The PET data were reconstructed with a baseline ordered-subsets expectation-maximization (OSEM) algorithm, OSEM + PSF, OSEM + TOF and OSEM + TOF + PSF. PET image quality and small lesions were visually evaluated and scored by a 3-point scale. A quantitative analysis was then performed using the mean and maximum standardized uptake value (SUV) of the small lesions (SUV_{mean} and SUV_{max}). The lesions were divided into two groups according to the long-axis diameter and the location respectively and evaluated with each reconstruction algorithm. We also evaluated the background signal by analyzing the SUV_{liver}.

Results: OSEM + TOF + PSF provided the highest value and OSEM + TOF or PSF showed a higher value than OSEM for the visual assessment and quantitative analysis. The combination of TOF and PSF increased the SUV_{mean} by 26.6% and the SUV_{max} by 30.0%. The $SUV_{liver}$was not influenced by PSF or TOF. For the OSEM + TOF + PSF model, the change in SUV_{mean} and SUV_{max} for lesions < 10 mm in diameter was 31.9% and 35.8%, and 24.5% and 27.6% for lesions 10–30 mm in diameter, respectively. The abdominal lesions obtained the higher SUV than those of chest on the images with TOF and/or PSF.

Conclusion: Application of TOF and PSF significantly increased the SUV of small lesions in hybrid PET/MR images, potentially improving small lesion detectability.

1. Introduction

Hybrid positron emission tomography/magnetic resonance (PET/MR) imaging is a new multimodality imaging technology that can provide structural and functional information simultaneously [1–3]. This new technology has the potential to expand the success of hybrid imaging modality, such as PET/computed tomography (CT), particularly for oncologic indications [4]. MR is considered as the first-line imaging procedure in the diagnosis and staging of various cancers due to the superior soft tissue contrast compared with CT [5,6]. However, the spatial resolution of PET is relatively low. Incorporation of time-of-flight (TOF) and point-spread function (PSF) information during image reconstruction has been shown to improve the spatial resolution and signal-to-noise ratio (SNR) of PET images [7–10].

The first attempt at TOF PET dated back to the 1980s, and the first TOF PET scanners were based on cesium fluoride (CsF) and barium fluoride (BaF_2). It was not until the development of lutetiumoxyorthosilicate (LSO) and lutetium–yttrium oxyorthosilicate (LYSO) that the TOF PET scanner was successful and introduced commercially. The TOF information provides a difference in arrival times between a pair of coincidence photons and localizes the annihilation points along the line-of-response (LOR). Using this information during reconstruction can reduce image noise and improve contrast [11]. Now, PET/CT systems with advanced TOF capability are available widely. The first

* Corresponding author at: Department of Nuclear Medicine, Xuanwu Hospital of Capital Medical University, 45 Changchunjie, Xicheng District, Beijing 100053, China.
E-mail address: imaginglu@hotmail.com (J. Lu).

http://dx.doi.org/10.1016/j.ejrad.2017.05.029
Received 23 February 2017; Received in revised form 18 May 2017; Accepted 22 May 2017

simultaneous but non-TOF PET/MR (Simens mMR) scanner became commercially obtained in 2011 [12]. Recently, a hybrid TOF-PET/MR system (GE SIGNA) has been developed and introduced in clinical practice [13]. The TOF capability of the new PET/MR scanner improved PET image quality by reducing artifacts compared to non-TOF PET/MR and PET/CT [14].

On the other hand, the modeling of PSF reconstruction effectively positions the LOR at the true geometric locations [15]. If a photon comes from the center of the field-of-view (FOV), the LOR is likely to be correctly localized. However, if a photon is farther away from the center of the FOV, the LOR is more likely to be incorrectly calculated. The PSF information as measured for a large number of points in the FOV can be used to compensate for the geometric distortion caused by the parallax induced by depth of interaction (DOI) effects. Therefore, the PSF correction is expected to improve the spatial resolution and reduce distortions [10].

Use of PSF and TOF together provide a cumulative benefit in lesion detection performance and have the potential to improve image quality [16]. PSF and TOF both increase the standardized uptake value (SUV) of lymph node metastases and have been shown to improve small lesion detectability [15]. Moreover, the combination of TOF and PSF can clearly improve image quality with either lower activity or shorter acquisition time, especially for overweight patients [17,18]. The results described above were mostly obtained with PET/CT systems and such results can also be indicated from TOF enabled simultaneous PET/MR. Comparison of the PET/MR and PET/CT images showed equivalent or improved quality of the PET images for the PET/MR system [19,20]. However, as far as we know, no report has examined the effect of combined TOF and PSF information on images of small lesions in clinical examination with hybrid PET/MR. The aim of this study was to investigate the effects of the TOF and PSF on small lesions observed in PET/MR images from clinical patient image sets.

2. Materials and methods

2.1. Patient population

In total, 21 subjects were included in this study. Fourteen oncology patients (6 males and 8 females) and seven healthy subjects were recruited consecutively for this prospective study (age range: 41–78 years, mean ± SD = 59.1 ± 10.3; Table 1). The average body mass index (BMI) was 23.7 ± 3.6 kg/m^2 (range: 17.6–30.1 kg/m^2). The oncology patient cohort included those with: rectal cancer (1), breast cancer (2), pancreatic cancer (3), and lung cancer (8). The exclusion criteria were claustrophobia, metallic implants, cardiac pacemaker and permanent contraceptive devices. All subjects with a fasting blood sugar level higher than 120 mg/dl were also excluded. The long-axis diameter of all lesions selected for analysis was < 30 mm. The clinical study was approved by the ethics committee of our institution and written informed consent was obtained from all subjects prior to the study.

All subjects were asked to fast for at least 6 h before undergoing PET/MR examination (SIGNA, GE Healthcare). Each subject was scanned under the imaging protocol which consisted of injecting ^{18}F-fluorodeoxyglucose (FDG) and starting the scan after approximately 120 min of uptake. All subjects were scanned in the simultaneous PET/MR system after finishing PET/CT examination. The injected dose per kilogram of subject weight was 3.7 MBq/kg. The subjects received an intravenous injection of 255.3 ± 44.4 MBq (range: 192.4–340 MBq) of ^{18}F FDG, and then rested in a dimly lit room without talking during the uptake time. Immediately following, a whole-body PET/MR scan was started simultaneously.

2.2. Hybrid PET/MR

All studies were performed with a hybrid TOF-PET/MR system (SIGNA, GE Healthcare).The GE SIGNA PET/MR features simultaneous TOF-PET imaging with whole body 3.0T MR with a 60-cm bore. The PET detector uses a silicon photomultiplier (SiPM) that is designed to minimize interaction with the MR system, while precise thermal control ensures no impact on the image quality. The PET component of the system features TOF technology with 400 ps timing resolution, and an axial FOV of 25 cm. The coincidence time window was 4.57 ns, with an energy resolution of 11%.

Table 1
Study population demographics.

No.	Sex	Age (years)	Weight (kg)	BMI (kg/m^2)	Type of subjects	No. of lesions in PET
1	F	66	67	25.52	lung cancer	2
2	F	43	53	20.44	pancreatic cancer	2
3	F	76	53	23.55	breast cancer	2
4	M	61	75	25.95	rectal cancer	5
5	F	48	62	22.77	breast cancer	2
6	M	60	53	18.33	pancreatic cancer	1
7	F	41	75	29.29	lung cancer	5
8	M	78	64	22.67	lung cancer	6
9	F	67	67	24.60	lung cancer	5
10	M	52	64	22.14	lung cancer	4
11	M	55	54	19.36	lung cancer	5
12	F	50	57	22.83	lung cancer	3
13	M	57	52	17.57	lung cancer	2
14	F	70	64	27.70	pancreatic cancer	10
15	M	50	90	30.07	healthy control	0
16	M	62	60	20.53	healthy control	0
17	M	53	72	25.51	healthy control	0
18	M	51	81	25.56	healthy control	0
19	M	67	80	27.04	healthy control	0
20	M	66	78	26.37	healthy control	0
21	F	67	47	18.83	healthy control	0

2.3. Imaging protocol and data reconstruction

The subjects were examined in the supine position, with arms down at the sides. The attenuation MR scan used for PET attenuation correction was a non-diagnostic T1-weighted fast-field echo scan. The subjects were covered with multiple integrated radiofrequency surface coils. PET emission data were acquired for 3.5 min/bed position (89 slices/bed). A complete study typically involves six overlapping bed positions in order to image the subjects from head to thigh. At each PET bed position, T1-weighted, T2-weighted and diffusion-weighted imaging (DWI) sequences were acquired. The total imaging time was 30 min.

The PET data were reconstructed with a baseline ordered-subsets expectation-maximization (OSEM) algorithm, with OSEM + PSF, with OSEM + TOF and with OSEM + TOF + PSF. All PET raw data was reconstructed on the console (SIGNA PET-MR MP24 R02 SOF). The reconstruction parameters included two iterations and 28 subsets for the four different algorithms [21]. The PET images were reconstructed with a full width at half maximum of a Gaussian filter of 3.0 mm. The PET images were reconstructed into a 256 × 256 matrix. The voxel size was 2.34 × 2.34 × 2.78 mm^3.