Physica Medica 42 (2017) 203–210

Contents lists available at ScienceDirect

Physica Medica

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

Original paper

# Comparison between new-generation SiPM-based and conventional PMT-based TOF-PET/CT

Kei Wagatsuma[a,1], Kenta Miwa[b,*,1], Muneyuki Sakata[a], Keiichi Oda[a,c], Haruka Ono[b], Masashi Kameyama[d], Jun Toyohara[a], Kenji Ishii[a]

[a] Research Team for Neuroimaging, Tokyo Metropolitan Institute of Gerontology, Tokyo, Japan
[b] School of Health Science, International University of Health and Welfare, Ohtawara, Japan
[c] Faculty of Health Science, Hokkaido University of Science, Sapporo, Japan
[d] Department of Diagnostic Radiology, Tokyo Metropolitan Geriatric Hospital, Tokyo, Japan

ARTICLE INFO

*Keywords:*
Silicon-photomultiplier
National Electrical Manufactured Association
Instrumentation
Physical performance
Image quality

ABSTRACT

*Purpose:* This study aimed to determine whether the SiPM-PET/CT, Discovery MI (DMI) performs better than the PMT-PET/CT system, Discovery 710 (D710).
*Methods:* The physical performance of both systems was evaluated using NEMA NU 2 standards. Contrast (%), uniformity and image noise (%) are criteria proposed by the Japanese Society of Nuclear Medicine (JSNM) for phantom tests and were determined in images acquired from Hoffman and uniform phantoms using the DMI and D710. Brain and whole-body [$^{18}$F]FDG images were also acquired from a healthy male using the DMI and D710.
*Results:* The spatial resolution at 1.0 cm off-center in the DMI and D710 was 3.91 and 4.52 mm, respectively. The sensitivity of the DMI and D710 was 12.62 and 7.50 cps/kBq, respectively. The observed peak noise-equivalent count rates were 185.6 kcps at 22.5 kBq/mL and 137.0 kcps at 29.0 kBq/mL, and the scatter fractions were 42.1% and 37.9% in the DMI and D710, respectively. The D710 had better contrast recovery and lower background variability. Contrast, uniformity and image noise in the DMI were 61.0%, 0.0225, and 7.85%, respectively. These outcomes were better than those derived from the D710 and satisfied the JSNM criteria. Brain images acquired by the DMI had better grey-to-white matter contrast and lower image noise at the edge of axial field of view.
*Conclusions:* The DMI offers better sensitivity, performance under conditions of high count rates and image quality than the conventional PMT-PET/CT system, D710.

## 1. Introduction

Positron emission tomography (PET) imaging has become an important diagnostic modality for evaluating staging, recurrence, and the outcomes of treatment in oncology [1], as well as for measuring metabolic, biochemical and pathological abnormalities in the human brain [2]. The hardware (detector material and design) and software (image reconstruction algorithms and correction methods) have been upgraded in newer PET systems to improve imaging quality and quantity [3,4]. Scintillation decay is faster in lutetium-based scintillator (LBS) such as $Lu_2SiO_5$ (LSO) and lutetium-yttrium-orthosilicate (LYSO), than in $Bi_4Ge_3O_{12}$ (BGO) and $Gd_2SiO_5$ (GSO) scintillators [5–7]. Thus, the LBS-PET system can generate high-quality images under a high count-rate condition [6,7] and realize the time-of-flight (TOF) system [8,9]. In terms of detector design, recent PET scanners do not have septa and therefore images are acquired only in three-dimensional (3D) mode [10,11]. Moreover, an axial field of view (AFOV) extended, for instance to > 20 cm [3,4] enables higher sensitivity due to the increased line-of-response (LOR) of the axial direction [3,4]. Furthermore, it can shorten scan durations or reduce dose.

A recent PET system has a point-spread-function (PSF) [12,13] and TOF correction [8,9] incorporated into iterative reconstruction. Detector responses as PSF have been measured at several points using point sources to correct detector-response blurring due to scintillator geometry, inter-crystal scattering, and inter-crystal penetration [12,14,15]. Correction of PSF has improved the quality of whole-body images [16] and the detectability of small lesions such as lymph node metastases [17]. An LBS-PET system with TOF correction can localize

* Corresponding author at: Department of Radiological Sciences, School of Health Sciences, International University of Health and Welfare, 2600-1 Kitakanemaru, Ohtawara, Tochigi 324-8501, Japan.
*E-mail address:* kenta5710@gmail.com (K. Miwa).
[1] Contributed equally.

http://dx.doi.org/10.1016/j.ejmp.2017.09.124
Received 20 June 2017; Received in revised form 19 August 2017; Accepted 13 September 2017
1120-1797/ 

the probability of annihilation events along the LOR from the difference in the arrival times of annihilation photons at the detectors [8]. Time-of-flight correction has improved the signal-to-noise ratio (SNR) and the contrast of small hot spheres [16,9].

New-generation PET detectors have silicon photomultipliers (SiPM) instead of photomultipliers tube (PMT). The main benefits of SiPM comprise compact and rugged, high gain (similar to that of PMTs), good intrinsic timing resolution (< 200 ps), and higher value of photon detection efficiency than PMTs [18–20]. In addition, the SiPM detector is insensitive to the electromagnetic interference and this is the most important feature of the PET/magnetic resonance (MR) system. The first commercial SiPM-PET system is the SIGNA PET/MR (GE Healthcare) [20–22]. This PET/MR instrument was designed to maximize sensitivity and it has the widest axial FOV (25.0 cm) among current commercial PET systems. One benefit of any SiPM-PET system over a conventional PMT-PET system is the better timing resolution of about 390 ps [20–22]. GE Healthcare introduced the first SiPM-PET/CT (Discovery MI; DMI) that combines the small LYSO with the SiPM block design (LightBurst digital detector), for high National Electrical Manufactured Association (NEMA) sensitivity and a wide 20.0 cm extended AFOV.

The present study aimed to determine whether the physical performance of the DMI exceeds that of the conventional PMT-PET/CT system, Discovery PET/CT 710 (D710) based on the NEMA NU-2 standards provided by the vendor for each PET/CT scanner. We also compared previous findings [20,22–28].

## 2. Materials and methods

### 2.1. Discovery MI

The Discovery MI (DMI; GE Healthcare, Milwaukee, WI, USA) is a combined LYSO-SiPM PET tomograph with a 64-slice CT scanner [29,30]. An LYSO scintillator (LightBurst digital detector) unit includes four blocks of detectors aligned in the axial direction, each comprising 19,584 LYSO 3.95 × 5.3 × 25-mm crystals in a 4 × 9 matrix. The DMI enables axial and transaxial fields of view (FOV) of 20 and 70 cm, respectively, with 71 image planes spaced at 2.79-mm intervals. The scanner has 36 detector units per ring and 9792 SiPM channels. The ring diameter is 744 mm. The coincidence window is 4.9 ns, and the lower and higher energy thresholds are 425 and 650 keV, respectively. The timing resolution is 390 ps. Compton scatter within the smaller block detector due to 511 keV photons causes a loss of sensitivity and resolution. One innovative feature of both the DMI and SIGNA PET/MR is that Compton Scatter Recovery detects scattered annihilation photons between adjacent detector blocks, and recovers those in which the summed energy falls within the energy window [20,31]. This feature has conferred a 20% improvement in the system sensitivity of coincidence mode [31,32].

### 2.2. Discovery PET/CT 710

The Discovery PET/CT 710 (D710; GE Healthcare) is a combination of LYSO with a PMT PET tomograph and a 64-slice CT scanner. Details of the scanner configuration and characteristics of the D710 have been described elsewhere [23] and Table 1 summarizes the scanner characteristics of the DMI and D710.

### 2.3. PET reconstruction algorithm

The DMI does not include filtered back projection (FBP) as a reconstruction method [27]. The variable parameters in the three-dimensional ordered-subsets expectation maximization (3D-OSEM) reconstruction algorithm are iterations, subsets, a Gaussian filter (full width at half maximum, FWHM; mm) and a Z-Axis filter (defined as no filter, light, standard and heavy). The more recent GE PET scanners have an innovative algorithm called Q.Clear for Bayesian penalized likelihood (BPL) image reconstruction [33,34]. This reconstruction algorithm can reach full convergence without the detrimental effects of excessive noise found with conventional OSEM. Q.Clear uses the relative difference penalty (RDP) for regularized function to provide activity-dependent smoothing; that is, more and less smooth in regions with less and more radioactivity, respectively. Q.Clear provides a trade-off among contrast recovery, image noise and the visual quality of phantom and clinical images, which improves quantitative accuracy compared with conventional 3D-OSEM [34]. Q.Clear includes PSF modeling. Users can determine a penalty term (β) from 1 to 10,000 that controls the global strength of regularization to suppress image noise [34].

**Table 1**
Scanner characteristics of Discovery MI and Discovery PET/CT 710.

| PET/CT system | Discovery MI | Discovery PET/CT 710 |
|---|---|---|
| FOV (mm) | 700 | 700 |
| Axial FOV (mm) | 200 | 157 |
| Crystal size ($mm^3$) | 3.95 × 5.3 × 25 | 4.2 × 6.3 × 25 |
| Material of crystal | LBS | LBS |
| Crystal array per block | 4 × 9 | 9 × 6 |
| Detector ring diameter (mm) | 744 | 810 |
| Amount of detector rings | 36 | 24 |
| Image planes | 71 | 47 |
| Slice thickness (mm) | 2.79 | 3.27 |
| Amount of detector blocks | 544 | 256 |
| Amount of individual crystals | 19,584 (544/ring) | 13,824 (576/ring) |
| Amount of PMTs | none | 256 (×4 anode; 1024) |
| Amount of SiPMs | 1,632 (×6 anode; 9,792) | none |
| Coincidence window width (ns) | 4.9 | 4.9 |
| Lower energy threshold (keV) | 425 | 425 |

FOV, field of view; PMT, photomultiplier; SiPM, Silicon photomultiplier; LBS, lutetium based scintillator.

### 2.4. PET scanner performance evaluation

We evaluated the performance of the DMI and for D710 PET scanners using NEMA NU 2-2012 and NEMA NU 2-2007, respectively [35,36]. The evaluation software provided by the vendor included a PET/CT console. The temperature and humidity of the locations during NEMA measurements were 22.2 °C and 49.7%, respectively, for the DMI and 23.7 °C and 43.2%, respectively, for the D710.

### 2.5. Spatial resolution

Spatial resolution is a measure of the ability to discriminate between radioactive accumulation at two points on a reconstructed PET image. Three hematocrit capillary tubes each having an inner diameter < 1 mm contained 200 MBq/mL of an $^{18}F$ point source. In the transverse direction, the point sources with an axial extent of activity < 1 mm were positioned at 1, 10 and 20 cm from the center of the plane in the NEMA NU 2-2012 standard for the DMI and at 1 (x = 0 and y = 1) and 10 (x = 0 and y = 10) cm vertically from the center, and 10 (x = 10 and y = 0) cm horizontally from the center in the NEMA NU 2-2007 standard for the D710 [35,36]. Data were acquired for each 60 s at the center of the axial FOV and $^3/_8$ and $^1/_4$ of the axial FOV from the center of the FOV (NEMA NU 2-2012) for the DMI and (NEMA NU 2-2007) for the D710, respectively. The data were reconstructed under the following conditions: 3D-OSEM; 4 iterations; 34 subsets; Gaussian filter, 2.0 mm; 384 matrix size; FOV, 25.0 cm for the DMI, and Fourier-rebinning + FBP; rectangular filter; filter cut-off, 4.3 mm; 256 matrix size; FOV, 25.0 cm for D710. The FWHM and full-width at tenth-