Chapter 10
Recent Developments with Large-Bore PET/CT

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Abstract Large-bore positron emission tomography and computed tomography (PET/CT) combo scanners have recently been developed and released for use. The large bore not only provides a spacious and comfortable environment for the patient, but it also allows the operator to observe and interact with the patient more easily during the examination, thus maximizing safety and minimizing patient anxiety. However, the increased size of the bore may affect image quality and the sensitivity of the PET scanner. To compensate for the diminished image quality, it is necessary to develop different technologies, including a time-of-flight (TOF) function. In this chapter, we introduce recent developments in the field of large-bore PET/CT, using the Celesteion as an example.

Keywords Large bore • PET/CT • Time of flight • TOF

10.1 Introduction

Ever since the emergence of the combination of positron emission tomography (PET) and computed tomography (CT) into one system, the size of the common bore (patient port) of the PET/CT scanner has been approximately 700 mm (Table 10.1). This size is adequate for most patients; however, when the patient is over-weight or devices such as holding fixtures for radiotherapy and artificial ventilators are present, a larger bore is needed. Large-bore PET/CT scanners have recently been developed, including the Celesteion by Toshiba Medical Systems (Tochigi, Japan), which has bores of 900 mm for the CT section and 880 mm for the PET section. In addition, the scanner has a wide-scan field of view (FOV) of up to 700 mm. This large bore size not only provides the patient with a spacious and

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Table 10.1 Size of PET/CT scanners. The Celesteion has the largest patient port size

| Model name | Company | Patient port size [mm] | | PET detector ring | FDA cleared |
		PET	CT	Diameter [mm]	[year]
ECAT Accel	CTI (Siemens)	562	N/A	824	2000
Discovery LS	GE Healthcare	600	700	927	2001
Biograph Duo	Siemens Healthcare	700	700	824	2002
Discovery ST	GE Healthcare	700	700	886	2003
Aquiduo	Toshiba Medical Systems	700	720	830	2005[a]
GEMINI TF Big Bore	Philips Healthcare	850	850	900	2009
Biograph TruePoint 16	Siemens Healthcare	700	700	842	2009
Ingenuity TF	Philips Healthcare	700	700	900	2011
TruFlight Select	Philips Healthcare	700	700		2011
Discovery PET/CT 600	GE Healthcare	700	700	810	
Discovery PET/CT 610	GE Healthcare	700	700	886	2012
Discovery PET/CT 690	GE Healthcare	700	700	886	
Discovery PET/CT 710	GE Healthcare	700	700	886	2012
Biograph mCT	Siemens Healthcare	780	780	842	2012
Celesteion	Toshiba Medical Systems	880	900	907	2014

Data were obtained from Imaging Technology News Online and Journal of Nuclear Medicine
[a]Japanese FDA only

comfortable environment, but it also allows the operator to observe and interact with the patient more easily during the examination, thus maximizing safety and minimizing patient anxiety (Fig. 10.1). However, the larger bore size may affect image quality, especially the sensitivity of the PET scanner. Thus, Toshiba incorporated a time-of-flight (TOF) feature into the Celesteion. In this chapter, we discuss recent developments in the field of large-bore PET/CT, using the Celesteion as an example.

10.2 The Celesteion

The Celesteion PET/CT scanner combines a high-speed helical 16-slice CT scanner with a newly designed PET scanner, which harbors a lutetium–yttrium oxyorthosilicate (LYSO) scintillator block detector. The CT scanner has 16 rows of tube detectors with 994 detector cells per row, and each revolution of a detector can cover up to 32 mm. The scintillator block detector system of the PET scanner contains LYSO crystals arranged in 48 rings. The crystals have a transaxial length of 4 mm and an axial length of 4 mm, which are arranged in detection units (blocks) consisting of 48 × 16 crystals coupled to a photomultiplier. The 48-ring system can obtain 95 PET

Fig. 10.1 The subject, who weighed 100 kg and was 176 cm tall, was larger than the average of Japanese male. However, there was plenty of space inside the gantry of the Celesteion to accommodate him

images (48 direct and 47 cross plane), separated by 2 mm and covering an axial FOV of 19.6 cm. The PET scanner can acquire data in three-dimensional (3D) configurations. The energy window of the system is set to 425–650 keV, and the coincidence time window is set to 1.6–4.2 ns, depending on the size of the FOV. The temporal resolution of the TOF is <450 ps.

10.2.1 Spatial Resolution

The National Electrical Manufacturers Association (NEMA) NU 2 2012 protocol [2] recommends using an F-18 fluorodeoxyglucose (FDG) point source (size <1×1 ×1 mm) inside a 75-mm-long glass capillary tube with an inner diameter of 0.9–1.0 mm and a 0.4-mm-thick wall. The total activity should be low enough to keep dead-time losses and randomness below 5% of the total events. Data were acquired at three transaxial locations (x,y), i.e., (1,0, 10,0, 20,0) cm, and at two axial positions (z) within the PET FOV, i.e., center FOV. At least 2×10^6 coincidence events were acquired at each position. TOF information was not used in this measurement. No attenuation and scatter correction and no post-smoothing filter were applied. The transverse and axial resolutions at the different positions of the point source are summarized in Table 10.2, which lists the full width at half-maximum (FWHM) values at 1, 10, and 20 cm. These data are provided by Toshiba Medical Systems.

10.2.2 Sensitivity

A 70-cm-long polyethylene tube (inner diameter = 1 mm; outer diameter = 3 mm) was filled with 4.5 MBq of FDG (at the start of acquisition) and placed inside of five concentric aluminum sleeves all with the same length and known diameters [2]. Data were acquired for each aluminum sleeve for 300 s (11.9×10^6 prompts in the

Table 10.2 Spatial resolution measured for the PET component of the Celesteion system (NEMA NU2-2012)

Spatial resolution	Distance (cm)	FWHM(mm)
Transverse radial	1	4.61
Transverse tangential	1	4.71
Axial	1	4.02
Transverse radial	10	4.63
Transverse tangential	10	4.85
Axial	10	4.52
Transverse radial	20	4.73
Transverse tangential	20	5.38
Axial	20	5.42

All data was provided by Toshiba Medical Systems

first acquisition). The measurements were taken at the center of the FOV and at a 10-cm radial offset. Online random subtraction was applied using a delayed coincidence window. The corrected true coincidence count rate was recorded as a function of sleeve thickness and extrapolated to a zero-thickness sleeve. The system sensitivity was then computed as the ratio of the true count rate with no absorption to the initial activity.

The Celesteion system has sensitivities of 3.90 and 3.71 kcps/MBq for the 0- and 10-cm off-center positions, respectively (from Toshiba Medical Systems data release). These sensitivities are lower than those of standard PET/CT scanners, probably because the detectors are farther apart in the large-bore scanner. To compensate for this potential disadvantage of the Celesteion system, certain steps were taken, as outlined below.

10.2.2.1   Increase the Axial FOV

The Celesteion was given more detector rings than previous scanners to increase the axial FOV. This increases the number of counts per bed position, while the larger bore decreases the number of bed positions required for the same axial coverage.

10.2.2.2   Time-of-Flight (TOF) Technique

While a conventional PET system can only localize the target to a straight line between the two detectors, a TOF PET system can determine more accurately the location of the target, by measuring the difference in the arrival times of two gamma rays. The Celesteion system has a temporal resolution of <450 ps, which enables the diameter of the positron source to be limited to <6.7 cm.
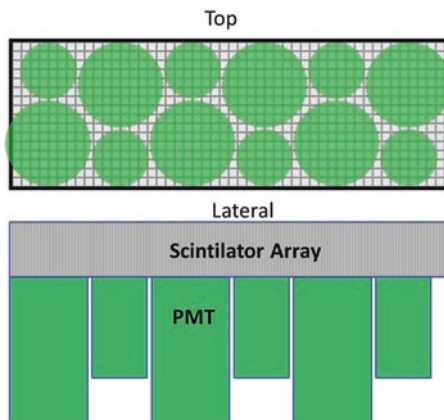
10.2.2.3   Scintillator

The advantages of the LYSO crystals contained in the multiple-ring scintillator block detector system of the Celesteion are the high light output and density, quick decay time, excellent energy resolution, and low cost. Table 10.3 compares the

Table 10.3   Properties comparison for LYSO, GSO, and BGO

Properties	LYSO	GSO	BGO
Density (g/m^3)	7.3	6.7	7.13
Attenuation (cm^{-1})	0.87	0.67	0.96
Decay Constant (ns)	50	50	300
Light yield (%) NaI (Tl)	75	35	25
Photofraction (%)	30	25	40
Energy resolution (511 kev, %)	20	12	16

Fig. 10.2 Array consisting
of two types of PMTs with
different apertures so that
they cover 79.4% of the
area of the scintillator
array

properties of LYSO crystals with those of two other widely used crystals, bismuth germinate oxide (BGO) and gadolinium oxyorthosilicate (GSO). While the thickness of the scintillator affects temporal and spatial resolution, a thinner crystal has better temporal resolution but lower sensitivity due to the increased number of penetrating gamma rays. On the other hand, a thicker scintillator has decreased spatial resolution due to the increased variability in the location of scintillation. In general, non-TOF PET systems do not need good temporal resolution but have a thick scintillator to increase the sensitivity. Toshiba Medical Systems has not released the exact thickness of the crystal used in the Celesteion, but it appears to be thin.

10.2.2.4 Arrangement of Photomultiplier Tubes (PMTs)

Column-shaped PMTs are used to cover square-shaped crystals so it is impossible to completely cover the entire area of the crystals. The Aquiduo, an earlier PET/CT system from Toshiba Medical Systems, had PMTs of only one size that covered 69.1% of the area of the crystals. The Celesteion has PMTs of two sizes that cover 79.4% of the area of the scintillator array (Fig. 10.2). The increased coverage increases the sensitivity of the system.

10.2.2.5 Design of Electronic Circuits

The electronic circuits detect the coincidence events, record time information, configure the energy window, discriminate the pulse shape, and so forth. The Celesteion required fewer PMTs to detect a gamma ray, enabling an accurate count of coincidence events in a high count rate setting.

10.2.3   Image Quality

A NEMA image quality phantom (International Electrotechnical Commission (IEC) body phantom) containing six spheres with internal diameters of 10, 13, 17, 22, 28, and 37 mm was used to evaluate the image quality of the Celesteion. A cylindrical insert (diameter = 5 cm), containing a low-density material with an average density of 0.3 g/ml, was positioned in the center of the phantom to simulate lung tissue and provide a nonuniform attenuation distribution. The phantom was filled with a solution of water and ^{18}F-FDG with a background activity concentration of ~5.3 kBq/ml. The four smallest spheres were filled to a target-to-background ratio (TBR) of 8:1 (for the first set of scans) and 4:1 (for the second set of scans). The remaining two largest spheres were filled with nonradioactive water. The phantom was positioned so that all the spheres were aligned within the same transaxial image plane in the center of the FOV.

For a PET scan, the matrix size was 144, the pixel size was 4 mm, and the slice thickness was 4 mm. CT scanning was performed using a 120-kV tube voltage. The FOV was set to 550 mm.

PET images were reconstructed using TOF list-mode ordered subset expectation maximization (TOF-LM-OSEM) with a 450-ps TOF temporal resolution kernel [3]. The TOF-LM-OSEM method is a TOF-OSEM algorithm that uses area-simulating volume (ASV) and calculates the geometric probabilities in the system matrix of 3D PET systems. The PET images were Gaussian filtered. For a 2-min PET scan, we varied the number of iterations and the parameters for the Gaussian filter to obtain the most suitable reconstruction conditions, which were then used in reconstructing PET images with other scan times.

Figure 10.3 shows the images of the IEC body phantom obtained with and without the TOF function. The TOF image from a 2-min scan had better spatial resolution than the non-TOF image from a 5-min scan. The smallest sphere (diameter = 10 mm) had a higher maximum standardized uptake value (SUVmax) and looked clearer on the TOF image.

Figure 10.4 shows the clinical images obtained with and without the TOF function. In our institution, patients received an intravenous injection of 3.5–5.0 MBq/kg of ^{18}F-FDG after at least 6 h of fasting, followed by an uptake phase of 60 min. The image in Fig. 10.4a was obtained without the TOF function from the scan, at a rate of 4 min/bed position. The images in Fig. 10.4b–d were obtained with the TOF function from the scans at rates of 1, 1.5, and 2 min/bed position. In our opinion, the image obtained with the TOF function at a scan rate of 1.5 or 2 min/bed position (Fig. 10.4c and d) corresponds to the image without the TOF function from the scan at a 4 min/bed position rate (Fig. 10.4a).
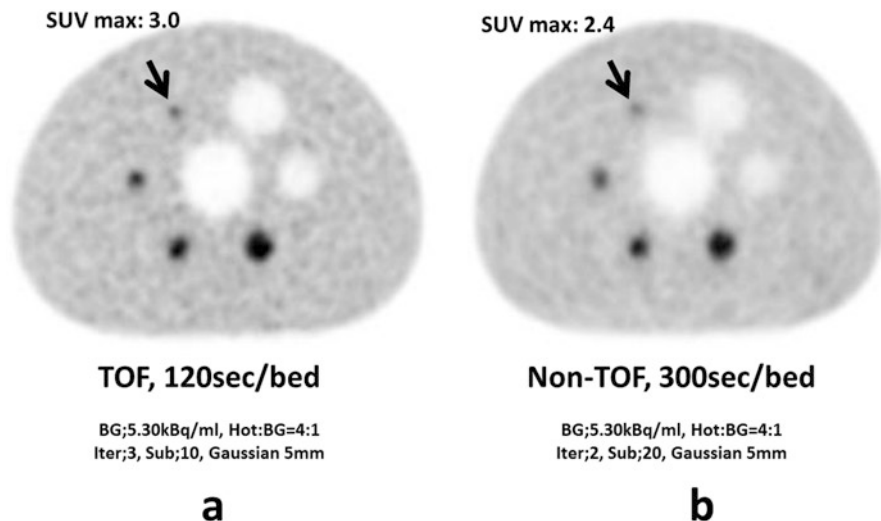
Fig. 10.3 Images of the IEC body phantom obtained with and without the TOF function. (**a**) The image of the 2-min scan obtained with the TOF function has better spatial resolution than that of (**b**) the 5-min scan without TOF. The smallest sphere (diameter = 10 mm) had the higher SUVmax and looked clearer on the TOF image
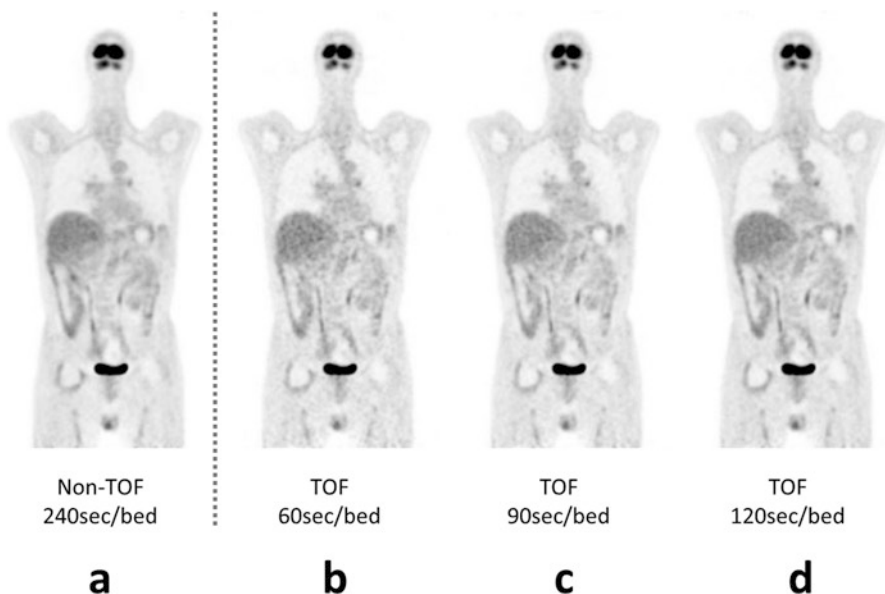

Fig. 10.4 Clinical FDG PET images obtained with and without the TOF function. (**a**) Image obtained without the TOF function from the scan with 4 min/bed position. (**b–d**) Images obtained with the TOF function from the scans with 1, 1.5, and 2 min/bed position. The images in (**c**) and (**d**) appear to be similar to the image in (**a**)
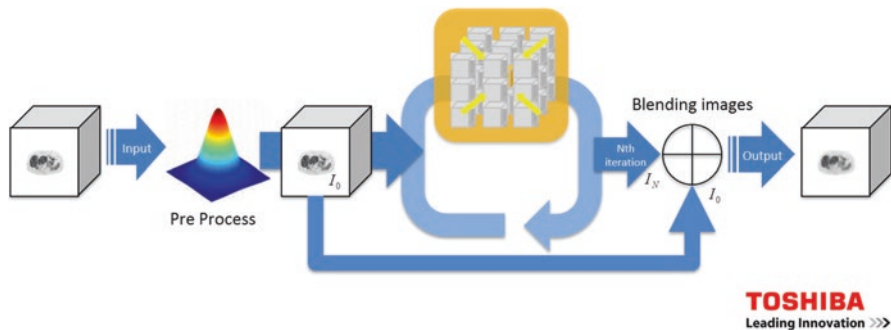
Fig. 10.5 The frame format of STONES. After preprocessing the input image with overall smoothing, the image undergoes iterative comparisons and smoothing of adjacent voxels. After the iterative process, the final image and the input image undergo post-processing. They are weighted and blended to produce an output image
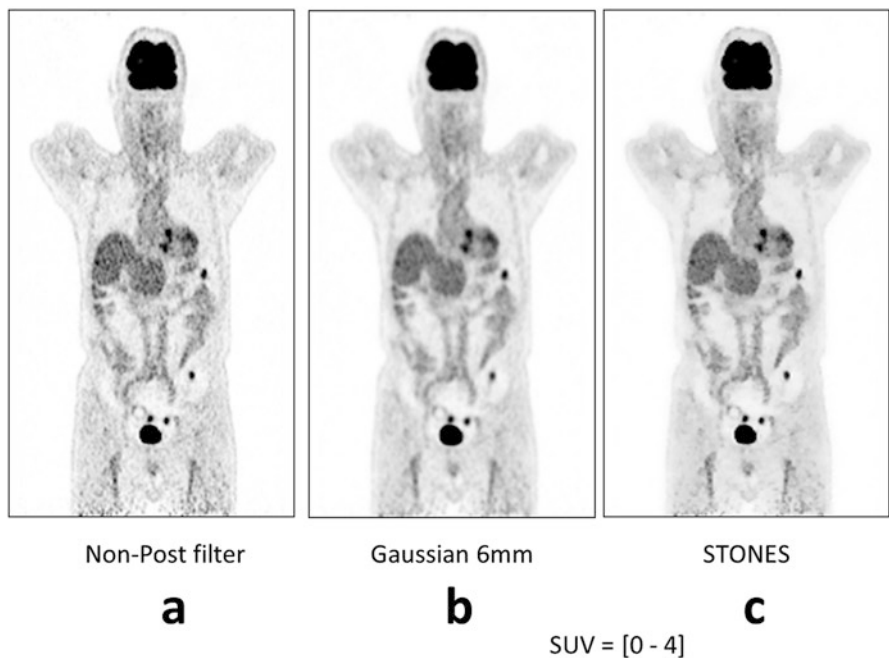

Fig. 10.6 Sample FDG PET images obtained with and without STONES. Compared to the non-post-filtered image, the image obtained with a Gaussian filter (**b**) is smoother than the image with no post-processing filtering (**a**) but has low contrast. (**c**) The STONES image has low noise and high contrast

10.2.4   *Statistical Transfer with Optimizing Noise and Edge Sensing (STONES)*

Toshiba Medical Systems developed a new anisotropic diffusion filter, Statistical Transfer with Optimizing Noise and Edge Sensing (STONES), to reduce the statistical background in PET images while preserving the contrast and edges of the structures. This should improve the quality of images and make the acquisition time shorter. Figure 10.5 presents the frame format of STONES. The loop in the center indicates that the adjacent voxels are iteratively compared and smoothed, which decreases noise without loss of contrast. Before the selective smoothing in the iterative loop, a preprocessing filter performs overall smoothing. After selective smoothing, the weighted input image and the weighted output image of the loop are blended in post-processing procedure. Toshiba Medical Systems is in collaboration with Yokohama City University (Yokohama, Japan) to optimize the STONES for use in the Celesteion. Figure 10.6 presents sample FDG PET images obtained with and without STONES. Compared to the non-post-filter image (Fig. 10.6a), the image with the Gaussian filter (Fig. 10.6b) is smooth but with low contrast. The image taken with STONES (Fig. 10.6c) has low noise and high contrast.

10.3   Conclusion

We introduced a recently developed large-bore PET/CT system. The large bore provides a spacious and comfortable environment for the patient, but it may affect image quality, especially via the sensitivity of the PET scanner. To compensate for these deficiencies, it was necessary to develop different technologies, including a TOF function.

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