Performance Evaluation of the microPET®-Focus - F120

Richard Laforest, Desmond Longford, Stefan Siegel, Danny F. Newport, Jeffrey Yap

microPET®-Focus-F120 is the latest model of dedicated small animal PET scanners from CTI-Concorde Microsystems LLC, (Knoxville, TN). This scanner, based on the geometry of the microPET-R4, takes advantage of several system design changes and modifications to the coincidence processing electronics that improve the image resolution, sensitivity, and counting rate performance as compared to the predecessor models. This work evaluates the performance of the Focus-F120 system and shows its improvement over the earlier models. In particular, the spatial resolution has been shown to improve from 2.20 to 1.75 mm at 0.5mm radial distance, the peak absolute sensitivity to increase from 4.1% to 7.1% in comparison to the microPET-R4. The counting rate capability, expressed in NECR, was shown to peak at over 800 kcps at 88 MBq, while the microPET-R4 peak is reached at 167 MBq, in a mouse phantom. For this small phantom, the NECR counting rate is limited by the data transmission bandwidth between the scanner and the acquisition console. Evaluation of image quality and quantitation accuracy was also performed using specially designed phantoms and animal experiments.

INTRODUCTION

The constant need to develop positron emission tomographic (PET) cameras capable of higher resolution has led to the development of the microPET camera[1]. The commercial version of this experimental prototype was developed by CTI Concorde Microsystems, LLC, and was initially produced in two distinct models: the microPET-P4[2] and the microPET-R4[3]. These models were built using 4 rings of detector to increase sensitivity relative to the prototype. Lately, the microPET-Focus-220 was released[4]. The two main modifications of this system were: 1) the use of novel block detectors constructed from the assembly of smaller crystals in a finer pitch, 1.51mm vs 2.2 mm for the P4 or R4 generation, 2) double sampling of the energy signals and double packing of events for transmission. The motivation was to provide a camera with higher resolution and sensitivity. More recently, this manufacturer offered a new model using the same geometry as the microPET-R4 but employing the FOCUS block detectors. The smaller radius of the F120, combined with the high efficiency-high resolution FOCUS detector, thus enables a higher level of performance. The purpose of this work is to present a first performance evaluation of the microPET-F120 and to present an updated evaluation of the microPET-R4 in light of the latest system innovations.

I. SYSTEM DESCRIPTIONS

The microPET®-Focus-F120 consists of 96 scintillation detectors, arranged in 4 rings, with a 14.7 cm diameter and a 7.6 cm axial extent. Each detector consists of a 12x12 array of 1.52x1.52x10mm Lutetium oxyorthosilicate (LSO) crystals optically coupled to a position sensitive photomultiplier tube (PS-PMT) via an 8x8 optical fiber bundle of square fibers. An innovative crystal-cutting technology was employed that reduced the gaps between adjacent crystals from 380 to 78 microns, giving a 1.59mm crystal pitch in both axial and transverse directions. Moreover, the scintillation light collection was improved by adding a specular reflector between individual optical fibers. The new detector block provides a higher packing fraction of 91.0% as opposed to the 73.5% of previous generation detectors. The relatively small diameter of the scanner leads to large solid angle coverage.

This scanner benefits from the improvement brought by the FOCUS front-end and coincidence processing electronics. Higher counting-rate can now be handled with more efficiency and more crystals can be resolved. These improvements include doubling the clock speed of the electronics, doubling the packing of single transmission events in the listmode stream, and doubling the sampling of the flash ADC when determining the position and energy of individual events.

Additional performance gains were accomplished by a novel data transmission procedure where only the prompt coincidences are transmitted to the host PC. Traditionally, PET data consists of prompt and delayed coincidences, where the delayed coincidences, as measured with a delayed window technique, provide the measurement for the random coincidences. In the new data transmission model, only the prompt coincidences are transmitted to the host PC, thus allowing the maximum bandwidth to prompt coincidences. The random sinograms are now estimated from the individual singles block counting rate weighted by individual crystal efficiencies.

The intrinsic performance evaluation, namely the energy resolution and the detector spatial resolution have been measured on a microPET-Focus 220 and were previously reported[4]. In summary, the individual FOCUS detectors are
capable of 18% energy resolution and 1.36mm spatial resolution. In the following work, the performance evaluation of the Focus-F120 was done in terms of sensitivity, reconstructed resolution, counting rate performance and image quality using procedures similar to clinical NEMA standards [5] but modified to accommodate the smaller FOV. Performance evaluation of the microPET-R4 and –P4 can be found in [2, 3]. However, we will see that the counting rate capability of the microPET-R4 as been improved relative to [3].

II. PERFORMANCE MEASUREMENTS

II.1 System sensitivity

The system sensitivity was measured using a 20 cm glass tube with inner diameter of 1.59 mm which was filled with 18.5 MBq of [F-18]FDG over 15 cm of its length. The glass line source was sealed at both ends and inserted into the smallest of a set of 5 concentric Aluminum sleeves with a wall thickness of 2.5mm. Measurements were performed with the line source aligned along the scanner axis at 0 cm radial offset. The data were acquired in listmode and sorted in 2D sinograms by single-slice rebinning (SSRB), for each decreasing number of sleeves. The true coincidence rates for each slice were normalized to the source activity per slice to provide the absolute slice sensitivity. Corrections were also applied for camera dead time (less than 2%), beta decay branching ratio (96.7% for \(^{18}\text{F}\)), and for radioactive decay. The scatter and attenuation corrected sensitivity was extrapolated to zero wall thickness from an exponential fit to the slice sensitivity plotted as a function of the number of sleeves. The sensitivity averaged over all slices provided the absolute system sensitivity. Sensitivity measurement was performed for 2 acceptance energies (250-750 keV and 350-650 keV) and two coincidence timing window widths (6 and 10ns).

II.2 Reconstructed Resolution

The reconstructed image resolution was measured with a Na-22 point source (0.5 mm diameter) that was placed at radial offsets of 0.5, 2.0 and 4.0 cm from the center of the FOV, at the center of the axial length and at ¼ of the axial length. Images were reconstructed from 3D sinograms (span of 3, ring difference of 47) followed by a filtered back-projection (FBP) algorithm with Ramp filter cut off at the Nyquist frequency, and a zoom of 10. Tangential, radial and axial resolutions were estimated from three orthogonal profiles traced through the pixel with maximum intensity in the reconstructed images. The width of the profile was set to approximately twice the full width at half maximum (FWHM). The FWHM and FWTM were determined from the extracted profiles by linear interpolation.

II.3 Counting Rate Performance

Counting-rate performance was measured using “NEMA-like” phantoms to simulate a mouse body and a rat body. Both phantoms were made of high density polyethylene (density 0.96 g/cm\(^3\)) with the following dimensions: 1) mouse - 2.5 cm in diameter and 7 cm long, 2) rat – 5 cm in diameter and 15 cm long. A 3.2 mm channel was drilled through the entire length of the phantom at a 12 mm (20 mm for the rat) offset from its center to allow insertion of a line source. The line source, 1 cm in length shorter than the phantom and made flexible tubing, was filled with over 600MBq (16 mCi) of C-11 solution for each phantom. The phantoms were placed at the center of the tomograph and the data were collected for 1 minute initially, and then for 2 minutes for later datasets. The phantom was scanned in approximately 10 minute intervals using the same energy and timing windows as for the sensitivity measurements. Data were acquired in listmode and 2D sinograms were generated by sorting the data using SSRB. Separate prompt and random sinograms were produced by turning off the online random subtraction. Prompt, true, delayed, scatter and noise equivalent count rates (NEC) were estimated from the prompt sinograms only according to the NEMA NU2-2001 [5] technique modified to take into account the smaller size of the phantom and FOV. All counts outside a band 3.6 mm larger than the phantom were set to zero. The peaks in the projection data corresponding to the line source were shifted and aligned so that the peak of the line source for all view angles was in the same projection channel so that all views might be summed together. A second band of 1.4 cm was then centered on the line source peak of the summed profile. All counts outside the line source band and below a linear curve interpolated between the two edges of the true peak band correspond to the random and scatter counts, while the true coincidence count rate was calculated from the number of counts above the scatter and random in the line source peak band. The scatter fraction was defined as the ratio of counts in the scatter distribution over the total number of counts.

The natural radioactivity of Lu-176 contained in the LSO scintillator material contributes to the generation of additional prompt and random coincidences. Modifications to the NEMA procedure have been proposed to take into account the natural radioactivity present in the scintillator material[6]. The proposed modifications suggests the use of the measured delayed sinograms, in this case estimated from the singles rates, to determine the number of random coincidences and consequently the scatter fraction for each phantom.

II.4 Count Loss and Dead time correction accuracy

Count loss analysis was performed using the data sets acquired for the counting rate measurement. Using the rat-phantom data acquired in the previous section, the true coincidence rate was plotted as a function of activity in the line source. The expected true rate was extrapolated from the 5 data points of lowest activity where the dead time was assume to be negligible. The activity level generating 50% dead time was then extracted by interpolation. The accuracy of the dead time correction model was then verified by reconstructing the NEC rate data by FBP using the manufacturer provided algorithm without normalization, attenuation or scatter. An ROI centered on the phantom and encompassing the whole phantom diameter was then drawn on twenty adjacent reconstructed image slices to extract the average reconstructed image intensity.
II.5 Image Quality Phantom

Image quality was evaluated with several phantoms. The first one consisted of a specially designed image quality phantom containing 4 fillable spheres (diameter 4, 6.2, 9.8 and 12.4 mm) and three 16mm diameter cylinders (two fillable and 1 solid polytetrafluoroethylene) immersed in a cylindrical chamber of 6 cm diameter by 8 cm long. The spheres and one cylinder contained FDG in activity concentration with a ratio of 8.5:1 relative to the warm background. Recovery coefficient as defined by the ratio of the measured (maximum in a ROI centered on the sphere) to the expected activity concentration was measured for both cameras. The phantom was imaged first in the microPET-R4 and then in the microPET-F120. 3D sinograms were then created for both systems where the frame duration in the F-120 dataset was adjusted for two cases where the sinograms contained 1) the same number of decays and 2) the same count density. Data were then reconstructed with Fourier rebinning followed by FBP, with scatter and calculated attenuation correction.

In addition, image resolution was assessed with a miniature Derenzo phantom, consisting of 6 sectors of fillable rods. The diameters of the rods were 0.8, 1.0, 1.25, 1.5, 2.0 and 2.5 mm, respectively. Center to center distances between adjacent rods was twice the rod diameters. The phantom was filled with 0.5 mCi of $^{18}$F solution and scanned for 20 minutes. Images were reconstructed using 3DRP.

III. RESULTS

III.1 Sensitivity

The system sensitivity is shown in Fig. 1 for the microPET-R4 and the microPET-F120. The system sensitivity axial distribution exhibits the typical triangular shape resulting from the 3D geometry and the use of the maximum allowable ring difference. The peak system sensitivity was found to reach 7.1% at the center of the tomograph, corresponding to a 62.5% improvement compared to the 4.0% of the microPET-R4 system at the same settings. The average system sensitivities are 3.5% and 2.1% respectively, approximately half of the peak. The radial profile has a similar shape as described in [2] and thus exhibits an almost uniform radial sensitivity.

### Table 1. Reconstructed spatial resolution of the microPET-F120 and microPET-R4. FWHM (FWTM) are presented in mm.

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<th>Radial (mm)</th>
<th>Axial (mm)</th>
<th>Volumetric (µL)</th>
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R4

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R4

Fig. 2. Volumetric Spatial resolution of microPET-F120 and microPET-R4.

### III.2 Spatial Resolution

The measured tangential, radial and axial spatial resolutions are reported in Table 1 and the volumetric reconstructed spatial resolution is presented in Fig. 2. At 0.5 cm offset from the CVOF, transverse and axial resolutions are 1.75 and 1.67 mm FWHM, respectively. Resolution degraded at larger distances from CVOF, and in particular at 4 cm, the spatial resolutions are 1.91, 3.51, 2.41 mm FWHM, respectively for the tangential, radial and axial components. The volumetric system resolution comparison to the microPET-R4 shows a two--fold improvement compared to the previous system. The radial component is shown to degrade with due to depth of interaction effect.

### III.3 Counting Rate Performance

The counting rate performance of the system with different energy and timing windows is shown in Fig. 3 for the mouse and rat-size phantom. The NEC-1R rates were plotted as a function of total activity in the phantom. For the mouse phantom, a peak NEC-1R value of 809 kcps with an activity of 88 MBq (2.4 mCi) was obtained with a 250-750keV energy window and 6 ns timing window. The use of 6 ns timing window permits higher NEC-1R performance as it reduces the number of random coincidences. microPET-R4 NEC-1R data yields a peak rate at 833 kcps at 167 MBq. Similar peak sensitivities are reached using the mouse phantom, the counting rate performance is limited by the data throughput that can be

![Fig. 1. Measured absolute sensitivity with an $^{18}$F18 line source measured extrapolated from the 5 concentric Al sleeve technique.](image-url)}
transmitted to the host PC. The maximum transmission rate is 4.5 million events per second. Scatter fractions for these two phantoms at 250-750 keV (350-650 keV) were: 27%(20%) for mouse phantom and 37%(21%) for the rat phantom. The scatter fractions, as measured with the modified NEMA procedure using the delayed sinogram for random estimation, were of 12.5%(8%) for the mouse and 27%(18%) for the rat. The minimum activity in the microPET-R4 which generates the same amount of true coincidence as the number of LSO random coincidence was estimated to be 370 KBq (10 μCi).

III.4 Count Loss and Dead time correction accuracy

Fig. 4 presents the true count rate extracted from the NEC-rate data of the rat-phantom measurement, plotted as a function of total activity in the phantom. The solid line represents the extrapolated true coincidence rate extrapolated from negligible dead-time acquisition. Interpolation on the graph yields a 50% dead time occurring at 152 MBq (4.1 mCi) in the rat phantom. Reconstructed images showed that quantitation accuracy of 5% or better is maintained up to 75 MBq (2 mCi).

III.5 Image Quality

The gain in spatial resolution results in greater quantitative accuracy due to smaller volume averaging effect. This was confirmed in the recovery coefficients shown in Fig. 5. The improved recovery coefficients are more noticeable for the smallest spheres where improvements of 52% and 15% are observed for the spheres of 4 and 6.2 mm diameter. Activity concentrations in the air and bone-like (polytetrafluoroethylene cylinder) areas were 1% and 19% relative of the warm background activity concentration.

Images of the miniature Derenzo phantom from Focus120 and R4 systems are shown in Figure 5. Rods of 1.00 mm in diameter and above could be identified by Focus-120. In contrast, the R4 can not clearly separate rods of 1.5 mm in diameter, demonstrating the significant improvement in image resolution attained with the Focus-120.

Image quality can also be appreciated in animal experiments. FDG mouse images reconstructed with USC-MAP are presented in Fig.7. The myocardium, brain, Harderian glands and spine are easily identified. One can also clearly identify the gray matter cortex on the transverse image of the mouse brain.

DISCUSSION

The improved intrinsic spatial resolution and improved crystal packing fraction are responsible for the better spatial resolution and the increased sensitivity of the microPET-F120.
as compared to the microPET. The peak sensitivity of the F120 model reaches 7.1% at the center of the FOV, a 78% increase. We have to note here that the reported sensitivities were measured using the same concentric sleeve and the same line source. The microPET-R4 sensitivity reported here are similar to values reported by Knoess et al. [3] with an average sensitivity of 2.2% with a $^{68}$Ge line source, and a peak of 4.4% as measured with a centered point source.

The counting rate performance of the microPET-F120 has been measured with mouse-like and rat-like cylindrical phantoms. The peak NEC for the mouse like phantom reached ~800 kcps for both systems. The peak is reached at a lower total activity level in the F120 model due to its higher sensitivity. For the rat-phantom, the peak NEC-1R is ~300 kcps and is again reached at a lower total activity in the phantom as compared to the R4 model. Since the new firmware treating the data transmission to the host-PC does not transmit the delayed coincidences, the prompt rate limit is higher leading to greater NEC values. In addition, since the delayed sinograms are calculated from high count singles rates, the NEC-1R can be applied to describe the system performance. These factors explain the higher NEC rate reported in this work relative to the previously published data in [3] for the R4. The mouse NEC-1R datasets plateau at the same value for both cameras, indicating the point of maximum data transmission has been reached. In the case of the rat-phantom, scatter is more important, and the peak NEC is reduced.

IV. CONCLUSIONS

The microPET®-Focus-120 demonstrates significant improvements in the image resolution, system sensitivity, and counting rate performance. It uses the latest technological development of commercial small animal PET systems and, due in part to the new detector block and to a reduced ring diameter, provides unsurpassed sensitivity. The counting rate performance has also been improved due a more efficient transmission of the data to the host computer and to the use of calculated random rates.

ACKNOWLEDGEMENTS

The authors wish to thank A. Perkins (Philips Medical System) and S. Surti (Univ. Pennsylvania) for providing line sources and calculation of line source position, as well as the NEMA small animal PET standard committee.

REFERENCES


Fig. 7 Transaxial (through brain) and sagittal (mid-sectional showing spine, brain, heart and bladder) images of a mouse imaged on the microPET-120 after injection of [F-18]-FDG. Images were reconstructed with USC-MAP.