Printed Sources for Positron Emission Tomography (PET)

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***Abstract*—We have developed a method that allows manufacturing of ^{18}F radioactive printed sources using a standard ink-jet printer. Although previously used in printing and imaging single gamma emitter sources, such techniques have not been, to our knowledge, applied to the manufacturing of positron emitting sources. The added complication in the latter instance is a nonzero positron range and, thus, the need for some attenuating material surrounding the positron emitting atoms. The point sources were first imaged on a phosphor imager and then scanned on three different tomographs (Siemens/CTI ECAT 953B, CPS high-resolution reserach tomograph (HRRT) and Concorde microPET R4) to measure their point spread functions (PSFs). Where appropriate, the resolution agrees with published values. A comparison of the full width and tenth width half maxima of the point source profiles obtained with and without additional attenuating material showed no effect of the additional attenuation material on their values. The presence of the attenuating material however increased the number of counts in the point source image several fold due to a larger fraction of the positrons annihilating in the region close to the printed source. The results show that printed sources either on paper alone or on paper sandwiched between some additional attenuating material provide a practical means to obtain positron emitting sources.**

***Index Terms*—Positron emission tomography imaging, printed radioactive sources, resolution.**

I. Introduction

TOMOGRAPH spatial resolution is often determined by estimating the full width at half maximum (FWHM) of the point spread function (PSF) characterizing the imaging system response. A point source is generally used to measure the FWHM of the PSF. In order to accurately assess the system PSF, the source dimensions must be much smaller compared to the PSF FWHM. The spatial resolution achievable with modern tomographs is of the order of (1–3 mm)^3. It is, thus, becoming increasingly difficult to manufacture practical point or line sources that are sufficiently small so as not to influence the determination of the PSF FWHM.

We have developed a technique to print radioactive point sources on paper using high concentrations of ^{18}F and using a modified standard ink-jet printer (HP DeskJet). This technique requires minimal human intervention, thus, allowing to safely deal with relatively high concentrations of radioactivity. Printed point sources have been previously developed and successfully used in SPECT applications where gamma emitters are used as radioisotopes [1]–[4]. Their feasibility for positron emission tomography (PET) imaging, although anticipated in principle, has never been practically demonstrated [3]. The added complication in PET is the fact that the positrons must annihilate to produce the two 511 keV gamma rays that are detected by the PET scanner. Due to the finite positron range it remained questionable if ordinary paper would provide enough material for a sufficient number of positron annihilations to provide a statistically reliable resolution measurement in a reasonable length of time and/or an accurate representation of resolution. Resolution in PET is typically measured using ^{18}F since this radioisotope emits the lowest energy positron amongst those commonly used in PET ($E_{\max} = 0.635$ MeV), and therefore its positron range (^{18}F positron range is approximately 1 mm in water or tissue) has the minimal impact on the resolution determination. For the very same reason, it requires the minimal amount of material for the positron to annihilate. We have, thus, used an ^{18}F ink solution to print the point sources and have imaged them with the Siemens/CTI ECAT 953B [5], with the CPS high-resolution research tomograph (HRRT) [6] and with the Concorde microPET R4 [7]. The resolution of these tomographs spans quite a wide range (approximately (1.8 mm)^3 for the microPET, (2.8 mm)^3 for the HRRT and (5.5 mm)^3 for the ECAT 953B), thus, offering a large range of source testing conditions. To estimate if printed sources without additional attenuating material are adequate to produce a reliable resolution measurement, we performed some studies where we imaged the point sources alone and sandwiched between several 0.016-mm layers of aluminum (Al).

To further characterize the printed sources we also imaged a set of fifteen 0.5 m diameter sources in a phosphor imager with 480 μm resolution, which is comparable to the size of the source itself.

II. Methods

A. Manufacturing of the Printed Sources

An important consideration when manufacturing the radioactive sources was the requirement of no human intervention since relatively high amounts of radioactivity are required to produce a very high radioactivity concentration ink solution. This was achieved by removing the original inkjet cartridge from the Hewlett Packard Deskjet printer (model C2170A) and installing

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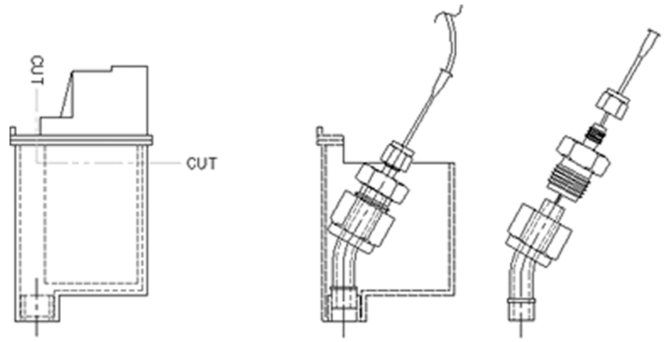

(a) (b)

Fig. 1. (a) Side view—cut lines on printer ink cartridge. (b) Side View—section and assembly of modified ink cartridge.

a modified cartridge. An HP 51626A cartridge was disassembled to drain the ink, to remove all other components, and to insert an adapter which was custom machined to fit an extant round port in the bottom of the cartridge. A swagelok (Columbia Valve & Fitting) fitting coupled the adapter to a 22 gauge needle allowing the use of standard luer fittings for fluid delivery. These modifications minimized the volume of liquid which needed to be in the cartridge to allow printing. A 3 mL vial was mounted on the printer and connected through remote controlled solenoid valves to the printer cartridge and a supply of low pressure (1–2 psig) helium. ^{18}F was produced in a conventional niobium bodied water target by irradiating ^{18}O-H_2O. For these tests the vial was preloaded with $\sim$ 0.2 mL of ink previously removed from the cartridge and the irradiated water was added directly to this vial with no pretreatment. Specific activity was not measured. This solution was then transferred to the previously modified cartridge (Fig. 1) using a low pressure helium system. The pattern of radioactivity to be printed was created as a drawing in AutoCAD drafting software or Microsoft Word where the diameter of the dots or thickness and length of the line were specified. The initial page to be printed started with a large block of solid ink approximately 4 cm by 16 cm to ensure a uniform flow of ink before the printing of the sources of interest. The source distributions imaged in the tomographs and in the phosphor imager were all printed on multipurpose 20lb paper (Econosource).

Two additional aspects of the printed source manufacturing were investigated: affect of the addition of radioactivity to the ink and impact of the choice of paper. To determine if the addition of ink would degrade the source size we printed 10 0.64 mm radioactive and 10 nonradioactive sources with the same printer and proceeded to enlarge the points with a photocopier to determine their diameter. Taking into account the outcome of this experiment we tested the influence on point size degradation of five kinds of paper using cold ink: HP Premium Photo paper, Econosource paper, Lexmark Premium InkJet paper and heavy bond paper.

B. Point Sources

In order to measure resolution, sources with 0.5-mm diameter were used. We also printed sources with 2-mm diameter that were used as an additional test of the reproducibility of source manufacturing. Typical radioactivity levels for the 0.5-mm diameter were 1 μCi, while for the 2-mm diameter sources the radioactivity levels were approximately 9 μCi.

C. Point Source Manufacturing Reproducibility

Nine 2-mm diameter point sources were printed and their individual radioactivity was measured in a dose calibrator of known accuracy. The manufacturing reproducibility in terms of radioactivity was assessed by evaluating the radioactivity mean and standard deviation between the sources. The same procedure was performed with sixteen 0.5-mm point sources.

The reproducibility of the source size was tested by imaging fifteen sources with a phosphor imager with 480 μm resolution. The FWHM of the source profile was measured and the source size was determined after correction for the imager resolution.

D. Point Source Imaging

ECAT 953B. A set of five point sources was placed in the axial and vertical center of the scanner. The sources were placed at $x = 0$, 2, 4, 8, and 10 cm off centre. The sources were scanned alone and sandwiched between two 0.016-mm aluminum layers. Data were reconstructed using Fourier rebinning (FORE) + two-dimensional (2-D) filtered backprojection (FBP).

HRRT. Sixteen point sources were used. They were placed on a 3.5 cm grid, where the grid coordinates spanned approximately one quarter of the field of view (FOV): one edge of the grid was located at the centre of the FOV $(x = y = z = 0)$ and the other edge was located at $x = z = 10.5$ cm, $y = 0$ cm. The sources were scanned in air and sandwiched between two Al layers. Radial and axial profile FWHMs were obtained by averaging over the FWHM of the profiles of the sources located at different z values but at the same x value. Data were reconstructed using a list mode reconstruction algorithm [8].

microPET. In this scanner, nine point sources were arranged in a 3×3 grid with 1.5 cm pitch with the grid centered in the FOV. Data were reconstructed using FORE + 2-D OSEM. In this scanner four scans were performed: paper alone, and with 1, 2, 3, and 4 0.016-mm Al layers on each side of the paper for a total layer thickness on each side of 0.064 mm (total on both sides = 0.128 mm).The exact repositioning of the sources after the addition of each Al layer was checked by performing a 1 minute scan after each intervention and ensuring that the peak of sources profiles was always in the same location. Data are presented as averages over the FWHM of the profiles of the sources located at different z values but at the same radial position.

In all cases data were acquired for 10 minutes. The sheet of paper with the printed sources was taped to a lateral styrofoam support (placed away from the printed sources) and the correct source positioning was ensured by verifying the source position in the sinogram space before performing the scan used for analysis. The PSF FWHM and full width tenth maximum (FWTM) were estimated following the NEMA NU2–2001 protocol [9].

E. Effect of Additional Attenuating Medium

The data acquired on the microPET were used for a detailed study of the effect of the attenuating medium on both the reso-

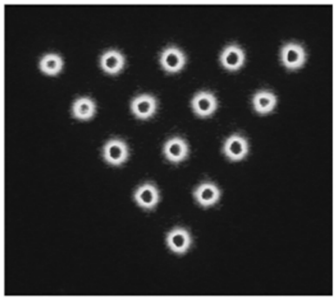

Fig. 2. Image of fifteen 0.5-mm diameter point sources as obtained with the phosphor imager.

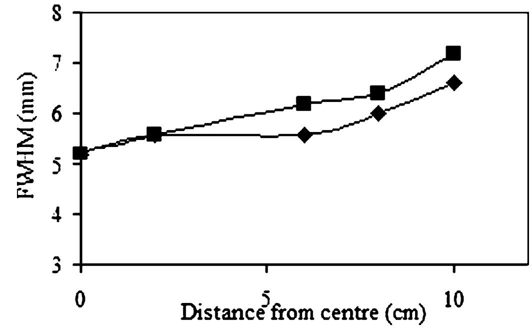

Fig. 3. Axial (squares) and radial (diamonds) resolution measured for the ECAT 953B.

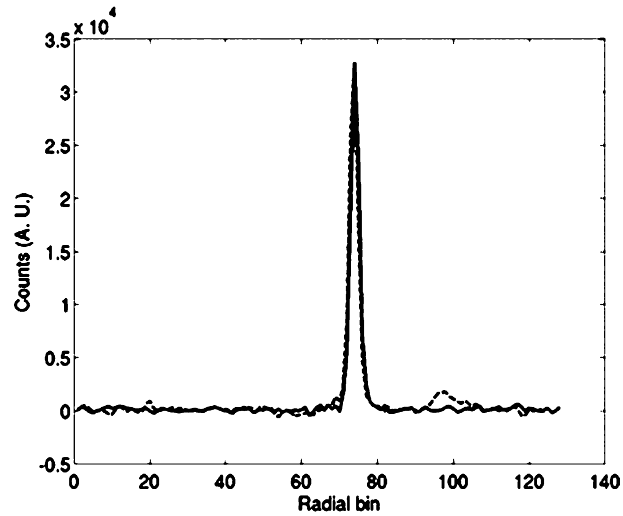

Fig. 4. EACT 953B y—profile through a source: dashed lines scan in air, solid line scan with an attenuating medium.

lution evaluation and the number of counts originating from the source region. This scanner was selected since it has the best resolution amongst those used and was, thus, deemed to provide the most sensitive test to possible changes in the resolution evaluation due to the presence of the attenuating medium. The effect of the attenuating medium on the source profiles was investigated by comparing the FWHM and FWTM of the PSF with and without the additional Al foils. The effect of additional attenuating medium on the number of acquired counts was investigated by comparing the number of counts in a region of interest placed around the source image obtained from the scans with paper alone after scanning with and without the Al foil. Only a qualitative comparison of the source profiles was done on the ECAT 953B and HRRT.

III. Results

A. *Effect of the Radioactive Ink and Paper Choice on Point Source Size*

The mean value of the size of the sources that had been produced with the radioactive ink was 0.67 ± 0.03 mm while for those that were produced with the cold ink was 0.68 ± 0.04 mm, demonstrating that the procedure of introducing radioactivity into the ink did not affect printing quality.

Both the HP Premium Photo paper and the Econosource photocopy paper gave spots that had diameters within 5% of the intended diameter as determined by the photocopy enlargement method. These two types of paper also gave the most homogeneously spherical points. The other papers tested gave spots that were on average 16% larger than the intended diameter (range 5%–32% increase). The Econosource paper was therefore chosen for all the imaging experiments.

B. *Point Source Manufacturing Reproducibility*

0.5-mm sources. The radioactivity mean value and standard deviation between the 16 sources were 1.01 ± 0.08 μCi indicating a variability of approximately 8%.

2 mm-sources. The radioactivity mean value and standard deviation between the nine sources were 9.27 ± 0.3 μCi, indicating a variability of approximately 3%.

The size of the sources imaged with the phosphor imager (Fig. 2) after correction for the instrumentation resolution was measured to be 0.504 ± 0.014 mm, which demonstrated both printing accuracy and high reproducibility.

C. *Point Source Imaging*

ECAT 953B The resolution measured with paper alone on the 953B is shown in Fig. 3. Results agree very well with previously published values [2]. An example of the qualitative comparison of the source profiles with and without the Al layer is shown in Fig. 4.

HRRT. The FWHM of the axial and radial resolution as a function of radial position measured with paper alone on the HRRT is shown in Fig. 5. The resolution follows the expected pattern dictated by the parallax effect, which is greatly reduced by the depth of interaction decoding abilities of this scanner. These data are however not to be considered a final characterization of the resolution of this scanner as discussed in Section III-D. An example of a source profile imaged with and without Al foil is shown in Fig. 6.

microPET. The FWHM of the PSF measured with paper alone and for each subsequent addition of one Al layer on each side is shown in Fig. 7 while Fig. 8 shows the FWTM. Results agree very well with data published in [4].

D. *Effect of the Additional Attenuating Material*

The effect of the additional attenuating material on resolution is shown in Figs. 7 and 8 that compare the FWHM and FWTM values of the PSF profiles obtained without and with

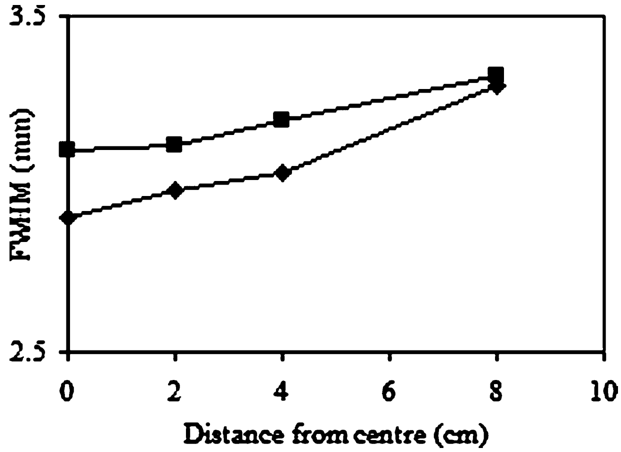

Fig. 5. Axial (squares) and radial (diamonds) resolution measured for the HRRT.

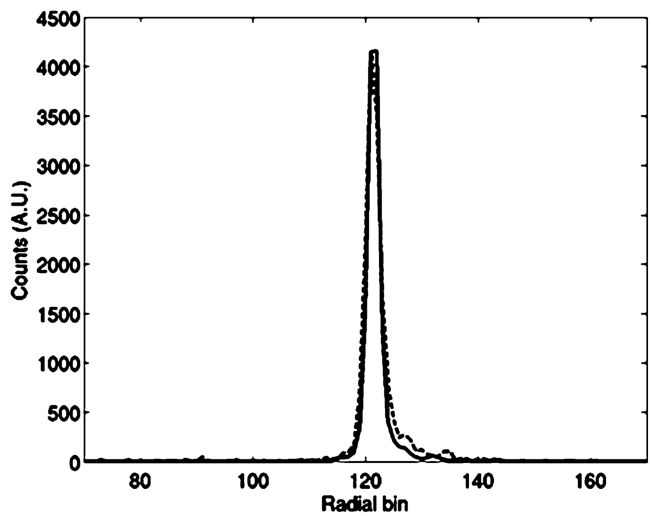

Fig. 6. Profile through a source in the HRRT. Dashed line—scan in air, solid line—scan with an attenuating medium.

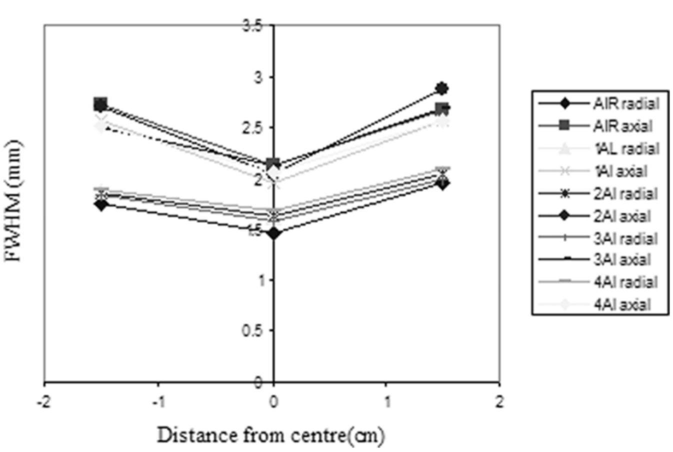

Fig. 7. Axial (top set of curves) and radial (bottom set of curves) PSF FWHM measured for the microPET.

the Al layers. An example of the point source images obtained on the microPET is shown in Fig. 9.

There is no overall consistent difference in the FWHM values obtained with and without the Al layers. In particular, the results obtained in air and with a single Al layer agree within approximately 0.1 mm which was found to be the measurement reproducibility: for example the radial FWHM appears slightly better with the paper scanned in air while the axial FWHM appears slightly better when one Al layer on each side was added. For the FWTM the values with and without one Al layer almost completely coincide.

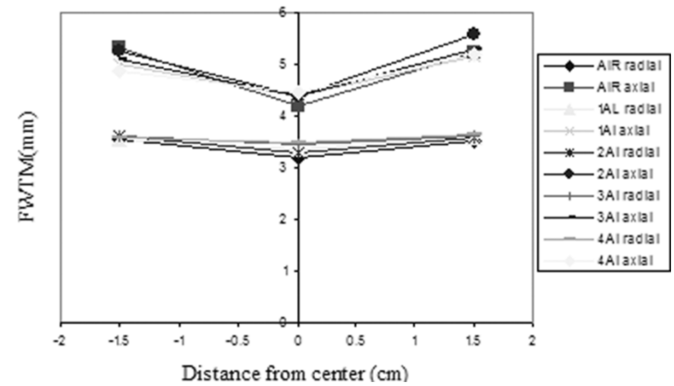

Fig. 8. Axial (top set of curves) and radial (bottom set of curves) PSF FWHM measured for the microPET.

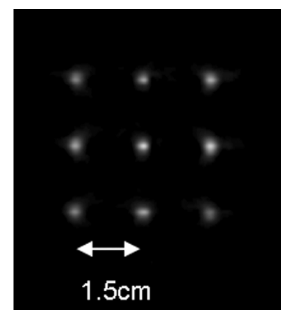

Fig. 9. Image of the 9 point sourced scanned in the microPET. The distance between point sources is 1.5 cm (see Methods).

The effect of the attenuating material on the number of detected events originating from the source position could not be estimated directly from number of total acquired counts; many annihilation in-fact occur in the scanner material such as the gantry when the source is placed in air. The effect was, thus, estimated by evaluating the count density in a region of interest placed around the source in the various scanning situations. A 3.4, 5.3, 6.1, and 6.7 fold increase in the count density was observed when adding 1, 2, 3, and 4 Al layers on each side, respectively.

IV. Discussion

We have shown that it is possible to manufacture printed positron emitting point sources by developing an automated method to print radioactive point sources that does not require human handling of high amounts of radioactivity. Ordinary paper was found to be of sufficient quality to provide highly reproducible and reliable printed sources as determined by an independent radioactivity measurement and high resolution imaging. We have also shown that ordinary paper thickness provides enough material for a significant fraction of the positrons to annihilate—however if counting statistics need to be maximized, a thin layer of attenuating material can be added without negatively affecting the resolution evaluation. In the present study, we have found that even a single 0.016-mm thick Al layer placed on each side of the paper increases the number of counts originating from the source position by a factor of 3.4. It can be, thus, decided on a case by case basis if it is more practical to use paper alone or paper surrounding by some material—procedural simplicity might be an advantage of the first method while some additional rigidity added to the paper and increased number of counts could be useful in the second method. In particular, it might be possible and desirable to laminate the paper sheet within clear plastic, which would have the added advantage of allowing visual determination of the source location while providing rigidity and attenuation.

It must be noted that the resolution data presented here are not meant to fully represent the resolution of the three scanners. The main purpose of using the three scanners was to demonstrate that the printed point sources could be used to measure resolution for a range of scanners with different resolution performance. For the ECAT 953B and the microPET the data are in good agreement with published values [2], [4]. They exhibit the expected radial resolution degradation pattern with the values in the center being lower. The data from the HRRT show resolution values that are slightly higher than the values published for the first HRRT prototype. This should likely not be attributed to the point sources themselves, since the same point sources were used in the resolution measurement in the microPET and produced better resolution values. Rather, these values can be attributed either to the fact the scanner itself was not properly normalized when these data were acquired or to the fact that a fully optimized reconstruction method for this scanner is currently being investigated.

V. Conclusion

We have demonstrated a technique that allows one to print radioactive point sources and that requires minimal human intervention. The radioisotope produced, in this case ^{18}F, is channeled directly into the modified printer cartridge where it is mixed into an ink solution. Currently we have tested the method by first imaging the sources in a phosphor imager and then by using them to evaluate the resolution of three different scanners. We have shown that even without the presence of additional attenuating medium the point sources can be imaged and they produce resolution values that are very close to previously published values. Having, thus, demonstrated the feasibility of using printed radioactive sources for PET we are presently investigating the feasibility of printing more complicated source geometries, the establishment of a correspondence between printer color scale and radioactivity concentration in the ink solution and degree of uniformity over a more extended printed area. Once these issues are resolved this simple and cheap technique will offer a practical and easy method to produce almost completely arbitrary phantoms that can be used both for scanner performance evaluation and for quality control procedure.

Acknowledgment

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