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 of any size and shape using a standard ink-jet printer. To test the point sources we used them to measure the resolution of three different tomographs, the Siemens/CTI ECAT 953B, the CPS High resolution tomograph (HRRT) and the Concorde microPET R4. The resolution of these tomographs spans a fairly wide range. Where appropriate, the resolution agrees with published values. A preliminary comparison of the point FWHM obtained with and without additional attenuating material showed no influence of the additional attenuation material on their values, even though the presence of the attenuating material increased the counting statistics by approximately 50%.**

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 for SPECT applications where gamma emitters are used as radioisotopes (1). 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 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 (2), with the CPS high resolution research tomograph (HRRT) (3) and with the Concorde microPET R4 (4). 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 sufficient to produce a reliable resolution measurement we performed some preliminary studies where we imaged the point sources alone and sandwiched between two 0.01 mm layers of aluminum (Al).

II. Methods

A. Manufacturing of the printed sources. The original inkjet cartridge was removed from the HP Deskjet printer and disassembled to both drain the ink and to insert an adapter thus allowing remote delivery of a mixture of ink, water, and radioactivity in close proximity to the ink delivery channels. A 3mL 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 ~0.2mL of ink previously removed from the cartridge and the irradiated water was added directly to this vial with no pre-treatment. This solution was then transferred to the previously modified

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cartridge (figure 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.

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

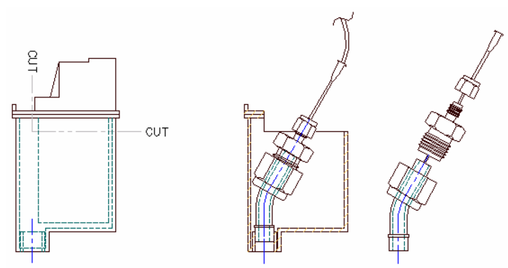

Figure 1 Left: Side View, cut lines on printer ink cartridge. Right: Side View, section and assembly of modified ink cartridge.

C. *Point source manufacturing reproducibility*. Nine 2 mm diameter point sources were printed and their individual radioactivity was measured in a dose calibrator. The manufacturing reproducibility 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.

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 the aluminum foils. Data were reconstructed using FORE + 2D 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 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. For selected source positions the Al foil was placed around the sources. Radial and axial profile FWHMs were obtained by averaging over profiles of the sources located at different z values but at the same x value. Data were reconstructed using a list mode reconstruction algorithm (5).

microPET. In this scanner nine point sources were arranged according to the grid shown in figure 2: at the axial center (in the radial center and at x = ± 2 cm) and in the same radial configuration at z = ± 2 cm). Data were reconstructed using FORE + 2D OSEM.

In all cases data were acquired for 10 minutes.

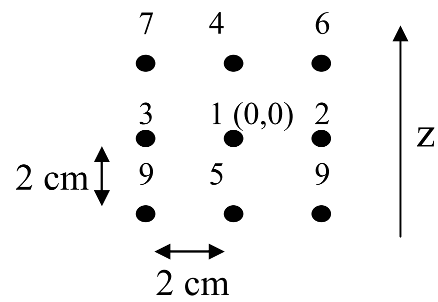

Fig. 2. Point source grid used in the resolution evaluation on the microPET.

E. Effect of additional attenuating medium. 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 after scanning with and without the Al foil. The effect of the attenuating medium on source profile was investigated by comparing the FWHM of the PSF with and without the additional Al foil. This was done on the ECAT 953B and on the HRRT. Since the HRRT has a much better resolution we expected that the data from the HRRT would provide a more sensitive test for the effect of the additional attenuating medium on the resolution. However for technical reasons the exact repositioning of the sources on the HRRT was not possible: therefore we are presenting these results only as preliminary and more detailed studies are currently under way.

III. Results

A. 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%.

B. Point source imaging. ECAT 953B. The resolution measured with paper alone on the 953B is shown in table 1. Results agree very well with previously published values. For this scanner the data obtained using the additional attenuating material yielding almost identical resolution values as can be seen from figure 3, which shows an example of the PSF profile.

TABLE I
RESOLUTION VALUES FOR THE ECAT 953B

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SOURCE POSITION (CM)	X=Y=0	X=2, Y=0	X = 6, Y =0	X = 8, Y = 0	X = 10, Y = 0
FWHM trans (mm)	5.2	5.6	5.6	6.0	6.6
FWHM axial (mm)	5.2	5.6	6.2	6.4	7.2

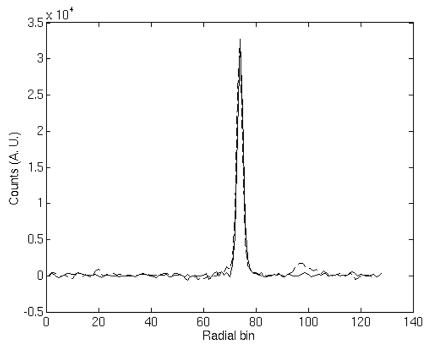

Figure 3. EACT 953B y - profile through a source: dashed lines scan in air, solid line scan with an attenuating medium

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 figure 4. 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, since the scans were not performed with the scanner fully calibrated – the main purpose of this study was to test the point sources. An example of a source profile imaged with and without Al foil is shown in figure 5, while figure 6 shows the image of four sources.

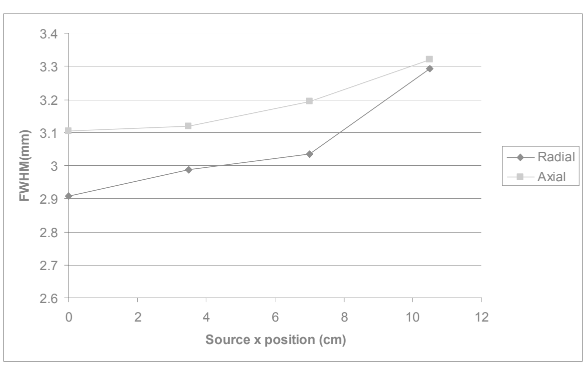

Figure 4. Resolution measured for the HRRT.

microPET. The resolution measured with paper alone on the microPET is shown in figure 7 for each source location (see figure 2). Results agree very well with data published in (4). An example of a source profile is shown in figure 8.

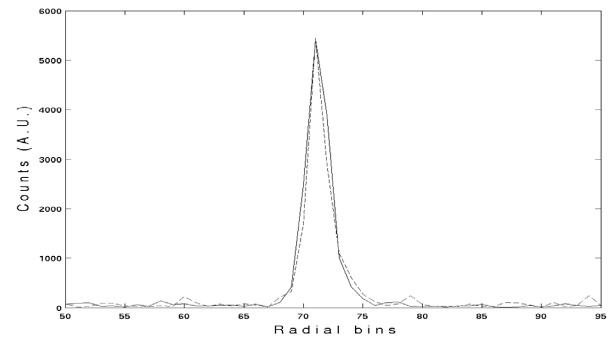

Figure 5. Profile through a source in the HRRT. Dashed line - scan in air, solid line - scan with an attenuating medium.

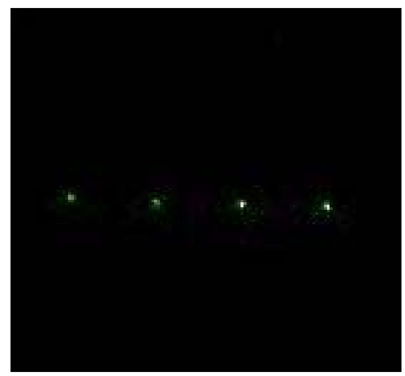

Figure 6. HRRT image of four point sources.

C. *Effect of the additional attenuating material*. The number of counts in a region of interest surrounding the source increased by approximately 50% when the sources were sandwiched between additional attenuating material. Interestingly the number of acquired counts only changed by approximately 5-10% indicating that in the absence of attenuating material around the source a significant fraction of the positrons annihilated in the tomograph gantry. In the ECAT 953B the presence of the attenuating material did not have any effect on the FWHM of the PSF. Preliminary data from the HRRT possibly indicate a minimal effect – with the additional attenuating medium improving the value of the measured resolution by a minimal amount. However the data are not conclusive, since exact repositioning was not possible.

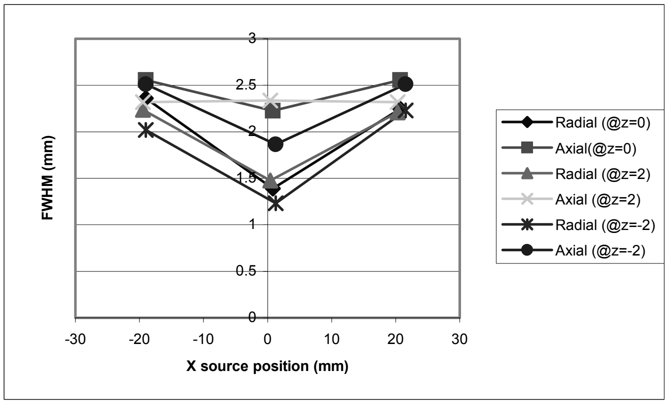

Figure 7. Axial and radial resolution measured for the microPET at various source positions.

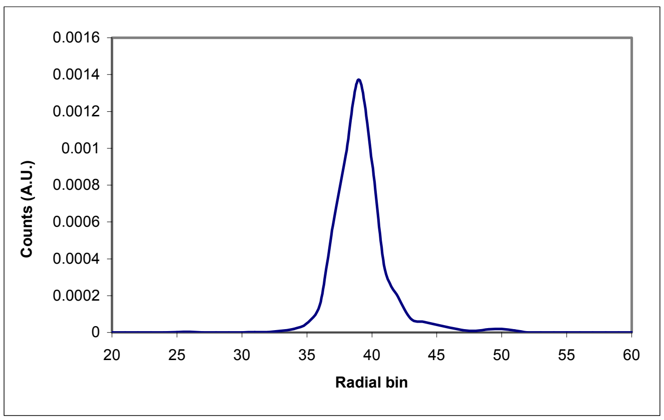

Figure 8. Source profile in the microPET.

IV. Discussion

We have shown that it is possible to manufacture printed positron emitting point sources. Even without additional attenuating material the number of counts acquired in a 10 minute scan provided images of sufficient statistical quality to observe smooth source profiles.

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 somewhat higher than the published values. 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 to the fact the scanner itself was not properly normalized when these data were acquired and cannot thus be considered an appropriate representation of the resolution of this scanner. It must also be noted that these printed sourced were produced with a very old InkJet printer and likely even better results can be achieved by using a more modern printer, which we are currently testing.

V. Future Work

For technical reasons we were at this stage unable to compare PSF profiles obtained with and without additional attenuating medium in all cases. However preliminary results indicate that the addition of attenuating medium does not affect the profiles greatly. Further studies in this direction are currently under way. If some improvement will be found, a glue spraying technique will be used to glue an appropriate Al foil on the printed source.

With a new printer more complex source geometries will be explored. This technique will be ideal to provide line or plane sources that can be used for scanner calibration and performance testing. In addition we are planning to calibrate the printer gray scale to establish a relative isotope concentration – color intensity correspondence. If this proves feasible, this technique can then be used to print more complex phantoms such as brain section or whole body small animal section phantoms, which can be employed in a large variety of applications such as investigation of partial volume effects and resolution recovery.

VI. Conclusion

We have demonstrated a technique that allows 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 printing point sources and 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. Further studies are currently being performed to establish the feasibility of producing more extended and complex printed phantoms.

VII. References

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