Preliminary Investigation to Improve Point Spread Function Modeling for a Multi-Pinhole SPECT Camera

Soumyanil Banerjee, *Member, IEEE*, Arda Könik, Joyeeta M. Mukherjee, Kesava S. Kalluri, Justin C. Goding, Luca Caucci, George I. Zubal, Lars R. Furenlid, and Michael A. King, *Senior Member, IEEE*

***Abstract*— Herein we report on the mathematical modeling of the simulated point spread functions (PSFs) of pinhole apertures for clinical I-123 DaTscan imaging on a dual-head SPECT system consisting of fan and multi-pinhole (MPH) collimators on separate heads. The PSFs can be measured sparsely by translating a point source within the volume of interest (VOI). These PSFs were generated using GATE Monte Carlo simulation software and were then modeled using standard 2D Gaussian having 6 parameters, and three other models using higher order polynomial terms as well as cross terms in the exponential. The goal is to efficiently store the parameters of the modeled PSF, measured across the VOI and then interpolate them on the fly during reconstruction. It has been shown that MPH reconstruction can be improved with accurate modeling of the PSF. However, for our application it has been determined that improved accuracy in PSF modeling (reduced NRMSE) can be obtained by incorporating more polynomial terms in the exponential than employed by the standard 2D Gaussian, especially with increased pinhole angulations. In this paper we introduce higher order polynomial terms (degree 3 and 4) as an extension to the Gaussian model and observe that these added terms could significantly reduce the NRMSE.**

***Index Terms*—SPECT, DaTscan, Multi-pinhole (MPH), Point Spread Function (PSF), Gaussian, GaussianC, GaussianCC, Gaussian CC4.**

I. Introduction

System modeling and calibration have been vital to improved image quality for SPECT Imaging [1]. Analytical, experimental, and Monte Carlo methods can be used to generate point spread functions (PSFs) for determination of the system response matrix. In most geometry a Gaussian model is reasonably accurate for the PSF [1].

Manuscript received November 6, 2017. This work was supported by the National Institute of Biomedical Imaging And Bioengineering of the National Institutes of Health under Award Number R01 EB022092 and R01 EB022521. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

Soumyanil Banerjee, Arda Könik, Kesava S. Kalluri, Justin C. Goding and Michael A. King are with Department of Radiology, UMass Medical School, Worcester, MA, USA (e-mail: soumyanil.banerjee@umassmed.edu).

Joyeeta M. Mukherjee, MathWorks, Natick, MA, USA.

George I. Zubal, Z-Concepts LLC, East Haven, CT, USA

Luca Caucci and Lars R. Furenlid, University of Arizona, Dept. of Radiology & The College of Optical Sciences, Tucson, AZ, USA

However, for different pinhole aperture shapes such as square and angled pinholes, the measured PSF which includes effects such as penetration and depth of interaction can have *substantial non-Gaussian components* [2].

II. Methods

A. GATE Monte Carlo Simulation

Nine pinholes arranged in a 3X3 grid were simulated in GATE as per the geometry shown in Fig. 1. The pinhole aperture planes were angled such that all pinholes focused on a point in the center of the putamen and caudate structures of the human brain [3]. Pinholes with circular apertures of radius 1.24 mm were selected to determine the optimal aperture size to be used in quantification of striatal uptake [4]. GATE simulations [5] were performed for an array of point source locations spanning the field of view (FOV) at a series of distances away from the pinhole apertures.

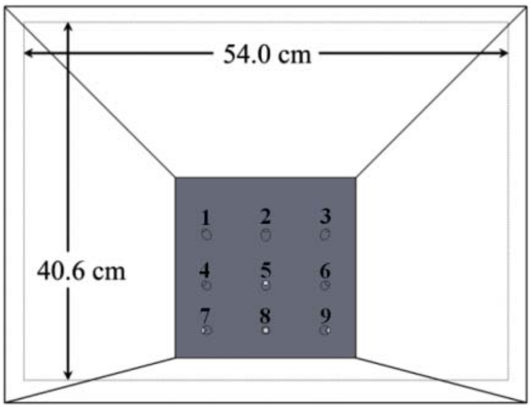


Fig. 1. Front view of the MPH collimator using the circular apertures arranged in a 3x3 grid. PSF analysis of the direct pinhole (number 8) and the most oblique pinholes (number 1 and 3) are presented here.

B. Improved Modeling of PSFs

Four models based on a Gaussian function were investigated for modeling PSFs:

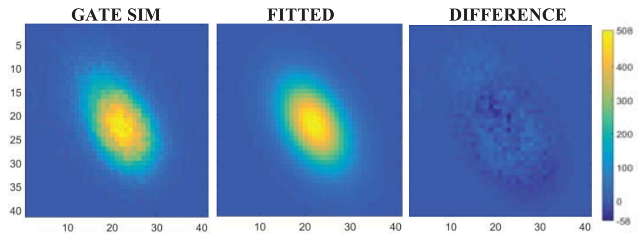
1. Standard Gaussian (*Gaussian*) with 6 parameters.
2. Gaussian + 2 Cubic terms (*GaussianC*) with 8 parameters.
3. Gaussian + Cubic terms + Cross Cubic terms (*GaussianCC*) with 10 parameters.

978-1-5386-2282-7/17/$31.00 ©2017 IEEE

4. Gaussian + Cubic terms + Cross Cubic terms + Fourth Order Polynomial terms (*GaussianCC4*) with 15 parameters.

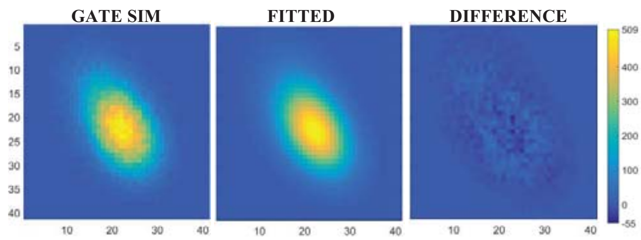
III. Results

Fig. 2 and Fig. 3 compare the GATE simulated PSFs for the most oblique pinhole (number 1 in Fig. 1) to the fitted models and show their difference for a point source located at the focal point of all pinholes (pinhole aperture radius: 1.24 mm). PSF measurements of 9 point sources placed at 14 cm from the aperture plane (across X direction from -4 cm to 4 cm) were obtained. Table I summarizes the average (across X direction) NRMSE for the fitted PSFs using different models (pinhole aperture radius: 1.24 mm). The fourth order terms produce the best performance even for the direct pinhole at the cost of computation time.



(a) (b) (c)

Fig. 2. (a) GATE simulated PSF for a point source at focal point, (b) Fitted PSF using standard Gaussian model, (c) NRMSE = 0.089.



(a) (b) (c)

Fig. 3. (a) GATE simulated PSF for a point source at focal point, (b) Fitted PSF using GaussianC model, (c) NRMSE = 0.075.

Table I. Average NRMSE for Different Models

PinHole	Gaussian	GaussianC	GaussianCC	GaussianCC4
1	0.089	0.075	0.073	0.065
2	0.079	0.070	0.069	0.064
3	0.089	0.080	0.078	0.070
4	0.074	0.069	0.066	0.057
5	0.060	0.060	0.059	0.045
6	0.069	0.065	0.064	0.053
7	0.065	0.063	0.063	0.048
8	0.065	0.065	0.065	0.044
9	0.066	0.064	0.064	0.050

The error for the most oblique pinholes (pinholes 1 and 3) with aperture radius of 1.24 mm were reduced by up to 27% when compared to the standard Gaussian by using the 4th order polynomial terms (*GaussianCC4*) in addition to the standard Gaussian.

IV. Discussions and Conclusion

The extra terms in addition to the standard Gaussian could model the penetration and depth of interaction effects of the oblique pinholes. For the direct pinhole, the additional terms did not appear to improve the accuracy as these effects have less impact when the pinhole is perpendicular to the detector surface.

Gaussian function with higher order polynomials (*GaussianC*) for PSF modeling improved the accuracy of the fit by 15% when compared to the standard Gaussian function with 6 parameters for pinhole 1 of radius 1.24mm.

Using the 4th order polynomial terms does improve the PSF fitting (upto 27%) as it has 15 parameters but the computation time also increases along with an increase in number of storage parameters. Hence we conclude that using the *GaussianC* function to model the PSF for an aperture radius of 1.24 mm is reasonable in terms of accuracy (reduced NRMSE) as well as for optimal storage as it has only 8 parameters to store.

V. Future Work

We will investigate interpolation of the parameters used for PSF modeling. We will also investigate modeling the PSFs, from pinholes with aperture radius larger than 3mm using convolution of a circular pillbox with a Gaussian for direct pinhole and convolution of an elliptical pillbox with Gaussian for oblique pinholes. Further we will use this method to investigate projections from keel-edged pinholes.

Acknowledgment

Research reported in this publication was supported by the National Institute of Biomedical Imaging And Bioengineering of the National Institutes of Health under Award Number R01 EB022092 and R01 EB022521. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

References

[1] B.W. Miller, R.V. Holen, H.H. Barrett, and L.R. Furenlid, “A system calibration and fast iterative reconstruction method for next-generation SPECT imagers”, IEEE Transactions on Nuclear Science, 59(5), 1990-1996, 2012

[2] J. M. Mukherjee, S. Banerjee, A. Könik, K.S. Kalluri, L.R. Furenlid, and M.A. King, “Stepwise Linear Regression Modeling of the Point Spread Functions of a Multi-Pinhole SPECT Camera for I-123 DaTscan Imaging,” in IEEE Nuclear Science Symposium and Medical Imaging Conference, 2016.

[3] M. A. King, J. M. Mukherjee, A. Könik, G. Zubal, J. Dey, and R. Licho, "Design of a Multi-Pinhole Collimator for I-123 DaTscan Imaging on Dual-Headed SPECT Systems in Combination with a Fan-Beam Collimator", IEEE Transactions on Nuclear Science, vol. 63, 2016.

[4] A. Könik, J. M. Mukherjee, S. Banerjee, J. D. Beenhouwer, G. Zubal, and M.A. King, "Optimization of pinhole aperture size of a combined MPH/fanbeam SPECT system for I-123 DAT imaging," in IEEE Nuclear Science Symposium and Medical Imaging Conference, 2016.

[5] S. Jan, G. Santin, D. Strul, S. Staelens, K. Assie, D. Autret, *et al.*, "GATE: a simulation toolkit for PET and SPECT," *Phys Med Biol,* vol. 49, pp. 4543-61, Oct 7 2004.