UNIVERSITY OF LEEDS

This is a repository copy of *Integration of advanced 3D SPECT modeling into the open-source STIR framework*.

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/88658/

Version: Accepted Version

Article:

Fuster, BM, Falcon, C, Tsoumpas, C orcid.org/0000-0002-4971-2477 et al. (5 more authors) (2013) Integration of advanced 3D SPECT modeling into the open-source STIR framework. Med Phys, 40 (9). 092502. ISSN 0094-2405

https://doi.org/10.1118/1.4816676

© 2013 American Association of Physicists in Medicine. This is an author produced version of a paper published in Medical Physics. Uploaded in accordance with the publisher's self-archiving policy.

Reuse
Unless indicated otherwise, fulltext items are protected by copyright with all rights reserved. The copyright exception in section 29 of the Copyright, Designs and Patents Act 1988 allows the making of a single copy solely for the purpose of non-commercial research or private study within the limits of fair dealing. The publisher or other rights-holder may allow further reproduction and re-use of this version - refer to the White Rose Research Online record for this item. Where records identify the publisher as the copyright holder, users can verify any specific terms of use on the publisher's website.

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

White Rose
university consortium
Universities of Leeds, Sheffield & York

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Integration Of Advanced 3D SPECT Modelling Into The Open-Source STIR Framework

Berta Marti Fuster[1,2], Carles Falcon[2,3], Charalampos Tsoumpas[4], Lefteris Livieratos[4,5], Pablo Aguiar[6], Albert Cot[1,2], Domenec Ros[1,2], Kris Thielemans[4,7,8]

1. Physiological Sciences Department I - Biophysics and Bioengineering Unit, University of Barcelona, Casanova 143, 08036, Barcelona, SPAIN
2. Grupo de Imagen Biomédica de la Universidad de Barcelona (GIB-UB), Biomedical Research Networking Center in Bioengineering, Biomaterials and Nanomedicine (CIBER-BBN), Casanova 143, 08036, Barcelona, SPAIN
3. Medical Imaging Platform, August Pi i Sunyer Biomedical Research Institute (IDIBAPS), Rosselló 153 08036, Barcelona, SPAIN
4. Department of Biomedical Engineering, Division of Imaging Sciences and Biomedical Engineering, King's College London, King's Health Partners, St. Thomas' Hospital, London, SE1 7EH, UK
5. Nuclear Medicine, Guy's & St Thomas Hospitals NHS Foundation Trust, Great Maze Pond, London SE1 9RT, UK
6. Grupo de Imagen Molecular e Oncoloxía. Fundación Ramón Domínguez, Instituto de Investigacións Sanitarias (IDIS), Travesía de Choupana, s/n. 15706 Santiago de Compostela, SPAIN
7. Algorithms & Software Consulting, London SW15 5HX, United Kingdom
8. Institute of Nuclear Medicine, University College London, London NW1 2BU, UK

Purpose: The Software for Tomographic Image Reconstruction (STIR, http://stir.sourceforge.net) package is an open source object-oriented library implemented in C++. Although its modular design is suitable for reconstructing data from several modalities, it currently only supports Positron Emission Tomography (PET) data. In this work we present results for Single Photon Emission Tomography (SPECT) imaging. Methods: This was achieved by the complete integration of a 3D SPECT system matrix modelling library into STIR. Results: We demonstrate the flexibility of the combined software by reconstructing simulated and acquired projections from three different scanners with different iterative algorithms of STIR. Conclusions: The extension of the open source STIR project with advanced SPECT modelling will enable the research community to study the performance of several

algorithms on SPECT data, and potentially implement new algorithms by expanding the existing framework.

I. INTRODUCTION

STIR[1] (Software for Tomographic Image Reconstruction) is an open source C++ library which provides a Multi-Platform Object-Oriented framework for research in processing and reconstruction of emission tomography studies. Currently, the emphasis is on iterative image reconstruction in Positron Emission Tomography (PET). The extension of STIR to other modalities such as Single Photon Emission Computed Tomography (SPECT) is of interest as it allows performing reconstruction in both modalities, SPECT and PET, in an integrated platform. To achieve this, we have integrated parts of the SPECT Reconstruction Library developed at the University of Barcelona (SRL-UB)[2-5] into STIR. The SRL-UB library accounts for effects such as the attenuation and spatially variant collimator-detector response correction by incorporating them into the projection matrix.

The aim of this note is to demonstrate the capabilities of the combined STIR/SRL-UB framework for SPECT reconstruction. Reconstruction algorithms implemented in STIR have been validated extensively with PET data.[6-7]

II. TECHNICAL DESCRIPTION

The new STIR release includes a dedicated reader for SPECT projection data in interfile format[8] and a SPECT projector class. The SPECT interfile reader takes into account the characteristics of SPECT projections as the type of acquisition (circular or non-circular), the rotation radius for each projection, the direction, the extent of the rotation and its initial angle. The new projector for SPECT was created as a matrix projector type derived from the existing STIR ProjMatrixByBin class. This projector provides any necessary information for generation of the projector matrix using the SRL-UB routines. SRL-UB allows modelling of attenuation and Point Spread Function (PSF) in the projection matrix. [2-5]

The geometric part of the projection matrix can be calculated in two different ways: (A) if the PSF correction mode is selected, the collimator-detector response is modelled as a spatially variant 1D or 2D Gaussian distribution in the image plane parallel to the detector plane (with width dependent on the distance between the plane containing the voxel and the detector); (B) else if it is not selected, a geometrical approach is used computing the orthogonal projection of the voxel on the detector. The geometrical approach provides higher computational speed and reduced memory requirements than the PSF approach, but is less accurate.

In order to reduce computational burden and memory requirements, SRL-UB provides a mask option which allows computing/storing just those projection matrix elements belonging to voxels in the mask. SRL-UB allows PSF modelling using parallel and convergent collimators however, only parallel collimators were tested in the current STIR integration.

Attenuation contribution depends on the attenuation coefficients of the medium and is computed as a (discretised) line integral of the attenuation between the centre of the voxel and the centre of the detector element.[9] This contribution is obtained from an attenuation map, which in the current implementation is expected to have the same dimensions as the reconstructed image, with the values of the attenuation coefficients in cm^{-1}.

In contrast to other implementations, the projection calculations are not performed on-the-fly but instead the matrix is computed and stored in STIR's sparse matrix format. The projection matrix can be kept in memory or calculated per projection angle. In the latter case, the memory is released before a new angle is started, reducing memory requirements but increasing computation time for iterative reconstruction algorithms, as illustrated in the next section.

III. MATERIALS AND RESULTS

In this section we show results on simulated and acquired data reconstructed using STIR as an illustration of its new capabilities.

A. Simulated data

The SimSET Monte Carlo code[10] was employed using the 2.9 version to simulate SPECT projections of a cylindrical phantom (diameter: 210 mm, length: 174 mm). The phantom had three different regions: a uniform region, a region with six hot cylinders, and a region with six cold cylinders. The diameters of the cylinders were 10, 15, 20, 30, 40 and 50 mm. The size of the activity and attenuation maps used for the SimSET simulation was $256 \times 256 \times 200$ with voxel size $1 \times 1 \times 1$ mm^3. SimSET was configured to generate photon emission projections using ^{99m}Tc as a radioisotope. A dual detector hybrid SPECT/CT imaging system based on Infinia$^{\text{TM}}$ Hawkeye$^{\text{TM}}$ 4 of GE Healthcare equipped with a Low Energy High Resolution (LEHR) parallel hole collimator was modelled. The characteristics of the collimators were: hexagonal holes, 0.15 mm in diameter, 0.02 mm in septal thickness and 35 mm of length. One hundred twenty simulated projection views (128×64, 3.32×3.32 mm^2) were generated using a 20% energy window centred on 140 keV. The simulation characteristics are based on brain acquisitions from Hospital Clinic of Barcelona.[11]

Figure 1 shows a sinogram of the hot cylinders region of the original phantom obtained by (A) SimSET; and (B) the new STIR forward projector (`ProjMatrixByBinSPECTUB`) including the PSF and attenuation effects. Visual agreement between these sinograms supports that the implementation of the projector matrix in STIR is suitable, thereby indicating a good integration between both libraries. Furthermore, it provides the insight that STIR may be also used for fast analytic simulations of different cameras, as recently demonstrated with STIR for PET.[12]

To compare the different types of corrections available in SPECT reconstruction, the simulated projections were reconstructed using Ordered Subsets Expectation Maximization[13] (OSEM) on a $128 \times 128 \times 64$ grid with voxel size $3.32 \times 3.32 \times 3.32$ mm^3. Figure 2 allows a visual comparison of the reconstructed phantom without corrections (left), with attenuation correction (middle) and with attenuation and PSF correction (right). All reconstructions were performed by using 8 subsets and 40 subiterations.

As regards to computational aspects, Table 1 summarizes time and memory requirement for different types of reconstructions, keeping the matrix in memory or (re)calculating it for every projection angle. All the reconstructions were performed using a Linux workstation with two Intel® Xeon® CPU X5670 @2.93 GHz 96.00 GB RAM system with Ubuntu and gcc 4.6.3 without multi-threading. Here, we have not used the MPI capabilities of STIR which allow it to perform several computations in parallel.

The time column of Table 1 represents the total computational time to reconstruct the simulated data using 8 subsets and 40 subiterations. All configurations keeping the matrix in memory required more RAM but less computational time than when recalculating it per projection angle. The matrix size depends only on the PSF modelling and, as a consequence, reconstructions with equal PSF modelling require the same memory independent if attenuation is used or not. By using a mask (last row of Table 1) both memory and computational time were reduced significant.

Table 1. Maximum RAM and computational time required in SPECT reconstruction. Reconstructions were performed with OSEM algorithm (8 Subsets and 40 subiterations). N-C: No correction; A-C: Attenuation correction; PSF-C: PSF correction; PSFA-C: PSF and attenuation correction; PSFAM-C: PSF and attenuation correction using mask option.

	Matrix in memory		Matrix per projection	
	Max RAM (Mb)	Time (s)	Max RAM (Mb)	Time (s)
N-C	2825	37	187	88
A-C	2825	89	187	368
PSF-C	37400	324	400	885
PSFA-C	37400	1241	400	5626
PSFAM-C	9181	185	119	341

In addition to the OSEM algorithm, STIR includes other iterative algorithms such as: (A) the ordered subset version of the One Step Late algorithm[14,15] with optional inter-update and/or inter-iteration filtering called OSMAPOSL and (B) the Ordered Subsets Separable Paraboloidal Surrogate (OSSPS) with relaxation.[16] As an illustration of the different algorithms performances, we compared the signal-to-noise ratio (*SNR*) throughout the number of subiterations. The *SNR* was calculated as the quotient between the contrast, obtained in the hot or cold cylindrical regions, and the coefficient of variation (*CV*) in a uniform cylindrical region of the phantom. The contrast (*CON*) for each cylinder *i* was defined as:

$$CON_i = \left| \frac{A_i - A_{ref}}{A_i + A_{ref}} \right| \qquad (1)$$

where A_i and A_{ref} are the activity mean values in the cylinder *i* and a reference region (*ref*), respectively. The attenuation map was used for the delineation of the regions of interests for each cylinder. Cylindrical reference areas (radius: 20 mm; length: 35 mm) were drawn between the two smallest cylinders of the phantom in hot and cold regions. From (1), the ideal contrast value is 1 in both hot and cold cylinders. *CV* was obtained using a centred cylinder (radius: 66.4 mm, length: 16.6 mm) on the uniform region. Figure 3 shows the SNR against the number of subiterations for each reconstruction algorithm: (A) OSEM, (B) OSMAPOSL with median prior (MRP) (penalization factor, PF = 1.0) and (C) OSSPS with uniform quadratic prior (UQP) (PF = 0.04). The PFs were selected empirically based on reasonable visual appearance. OSSPS was initialized using the OSEM image at 80 subiterations. In OSEM reconstruction, the SNR reaches a maximum after few subiterations and then decreases as expected,[13] while in OSMAPOSL-MRP and OSSPS-UQP, the SNR converges to a stable value, which depends on the value of PF. To qualitatively illustrate the performance of the different algorithms, Figure 4 displays reconstructed axial views at 200 subiterations of cold and hot regions of the simulated phantom for OSEM (left), OSMAPOSL-MRP (middle) and OSSPS-UQP (right).

B. Acquired data

Real data were also reconstructed with the new SPECT projector of STIR using projections acquired from three of the most commonly used scanner manufactures, GE Healthcare, Philips and SIEMENS. Each acquisition was reconstructed by using one of the three iterative algorithms available in STIR as an example of its new capabilities.

A Data Spectrum torso phantom was acquired following a myocardial perfusion imaging protocol on a Phillips Precedence SPECT/CT system equipped with LEHR collimators. Sixty four projections were acquired over 180º in a 64×64 matrix with a pixel size of 6.39×6.39 mm^2 in a non-circular acquisition with a mean rotation radius of 27 cm (24.1-29.2 cm). Data were reconstructed using OSEM with CT-based attenuation and PSF correction (8 subsets and 80 subiterations).

SPECT projections of the skeleton approximately 3 hours after injection of ^{99m}[Tc]-MDP were acquired by a SIEMENS SYMBIA S dual-headed gamma-camera equipped with LEHR collimators. The radius of rotation was on average 25.8 cm (16.5-35.1 cm) and 128 projections (128×128 matrix and 4.80×4.80 mm^2 pixel size) were acquired over 360º. Bone SPECT data were reconstructed by using OSSPS-UQP (PF=0.04) algorithm including PSF modelling on the projection matrix (8 subsets and 80 subiterations). OSSPS was initialized using the OSEM image at 80 subiterations.

DaTSCAN© projections were acquired using an Infinia™ Hawkeye™ 4 (GE Healthcare) dual-head SPECT imaging system equipped with LEHR parallel-hole collimators. The radius of rotation was 14.7 cm and 120 projections (128×128 matrix and 2.95×2.95 mm^2 pixel size) were acquired over 360º. Projections were reconstructed using OSMAPOSL-MRP (PF=1.0) with 8 subsets and 80 subiterations. PSF and attenuation corrections were applied.

Figure 5 shows an example of each reconstructed data: axial view of Data Spectrum torso phantom (left), maximum intensity projection (MIP) image of the bone SPECT data (middle) and axial view of the DaTSCAN© study (right).

IV. DISCUSSION

Our findings show the feasibility of using the STIR framework and SRL-UB for reconstruction of SPECT projections. Simulated and real data were reconstructed in order to test the integration of SRL-UB library into STIR. Different types of reconstruction algorithms were tested illustrating that for optimal SNR, OSEM needs tuning in terms of iterations while penalised versions such as OSMAPOSL-MRP and OSSPS-UQP would require tuning in terms of the penalty factor. The results from simulated data indicate that the optimal parameter settings are dependent on the object size, activity and background. A potential advantage of penalised algorithms is that this dependency can be studied analytically, making it possible to change the penalty in order to achieve uniform SNR[17] or resolution.[18]

In addition, we demonstrated the versatility of STIR in the reconstruction of acquired data from different commercial scanners with the availability of different reconstruction algorithms into one framework.

The integrated software will be included in STIR release 3.0. Future extensions to the library could integrate scatter correction, multi-pinhole collimators, motion compensated image reconstruction,[19] dynamic imaging and multi-tracer protocols, using existing tools in either STIR or SRL-UB.

V. CONCLUSIONS

In this work an extension of a PET reconstruction library to SPECT has been presented using simulated and acquired data from scanners of different manufacturers. Following the integration of the advanced SPECT modelling in the open source STIR project, we hope to enable the wider research community to study the impact of more advanced algorithms in several SPECT imaging scenarios and with different scanners.

ACKNOWLEGMENTS

This work was supported in part by Multimodal Imaging tools for Neurological Diseases (MIND-t) project of Biomedical Research Networking Center in Bioengineering, Biomaterials and Nanomedicine (CIBER-BBN), Spanish Ministry of Science & Innovation (SAF2009-08076) and Fondo de Investigaciones Sanitarias (PI12-00390). B. Martí Fuster was awarded a PhD fellowship (App Form – Call 07-2009) of Institute for Bioengineering of Catalonia (IBEC). This research was also supported by the UK National Institute for Health Research (NIHR) Biomedical Research Centre at Guy's and St Thomas' NHS Foundation Trust, King's

College London, University College London Hospital and University College London. The views expressed are those of the authors and not necessarily those of the NHS, the NIHR or the Department of Health. We thank Benjamin Thomas, Kjell Erlandsson and Alexandre Bousse for help with acquired data and discussions.

REFERENCES

[1]K. Thielemans, C. Tsoumpas, S. Mustafovic, T. Beisel, P. Aguiar, N. Dikaios, and M. W. Jacobson, “STIR: software for tomographic image reconstruction release 2”, Phys. Med. Biol. **57**, 867–883 (2012).

[2]C.M. Falcon, “Métodos Iterativos De Reconstrucción Tomográfica En SPECT”, PhD disseration. Universitat de Barcelona. Departament de Física Aplicada i Òptica. Available from: http://hdl.handle.net/10803/1785 (1999).

[3]A. Cot, C. Falcon, C. Crespo, J. Sempau, D. Pareto, S. Bullich, F. Lomena, F. Calvino, J. Pavia, and D. Ros, “Absolute quantification in dopaminergic neurotransmission SPECT imaging using a Monte Carlo based scatter correction and fully 3D reconstruction”, J. Nucl. Med. **46**, 1497–1504 (2005).

[4]D. Pareto, A. Cot, C. Falcon, I. Juvells, J. Pavia, and D. Ros, “Geometrical Response Modeling in Fan-beam collimators. A numerical simulation”, Trans. Nucl. Sci. **49**, 17–24 (2002).

[5]D. Pareto, A. Cot, J. Pavia, C. Falcon, I. Juvells, F. Lomena, and D. Ros, “Iterative reconstruction with compensation of the spatial variant fan beam collimator response in neurotransmission SPECT imaging”, Eur. J. Nuc. Med. **30**, 1322 – 1329 (2003).

[6]V. Bettinardi, E. Pagani, M.C. Gilardi, S. Alenius, K. Thielemans, M. Teras and F. Fazio, “Implementation and evaluation of a 3D one step late reconstruction algorithm for 3D positron emission tomography studies using median root prior”, Eur. J. Nucl. Med. **29,** 7–18 (2002).

[7]M. Jacobson, R. Levkovitz, A. Ben-Tal, K. Thielemans, T. Spinks, D. Belluzzo, E. Pagani, V. Bettinardi, M.C Gilardi, A. Zverovich, and G. Mitra, “Enhanced 3D PET OSEM reconstruction using inter-update Metz filtering”, Phys Med Biol. **45**, 2417-2439 (2000).

[8]A. Todd-Pokropek, T.D. Cradduck, F. Deconinck, "A file format for the exchange of nuclear medicine image data: a specification of Interfile version 3.3," Nucl. Med. Commun. **13**, 673-699 (1992).

[9]R.L. Siddon, “Fast calculation of the exact radiological path for a three-dimensional CT array”. Med Phys. **12,** 252-255 (1985).

[10]R.L. Harrison, S.D. Vannoy, D.R. Haynor, S.B. Gillispie, M.S. Kaplan, and T.K. Lewellen, “Preliminary Experience With The Photon History Generator Module Of A Public-domain Simulation System For Emission Tomography”, IEEE Nucl. Sci. Symp. Conf. Rec. **37**, 1154–1158 (1993).

[11]X. Setoain, J. Pavia, E. Seres, R. Garcia, M. Carreno, A. Donaire, S. Rubí, N. Bargalló, J. Rumià, T. Boet, L. Pintor, D. Fuster, F. Pons, “Validation of an automatic dose injection system for Ictal SPECT in epilepsy”, J. Nucl. Med. **53**, 324–329 (2012).

[12]C. Tsoumpas, C. Buerger, A.P. King , P. Mollet, V. Keereman, S. Vandenberghe, V. Schulz, P.J. Schleyer, T. Schaeffter and P. Marsden, “Fast generation of 4D PET-MR data from real dynamic MR acquisitions”, Phys. Med. Biol. **56**, 6597–6613 (2011).

[13]H. Hudson, and R. Larkin, “Accelerated image reconstruction using ordered subsets of projection data”, IEEE Trans. Med. Imaging **13**, 601–609 (1994).

[14]P.J. Green, “On use of the EM algorithm for penalized likelihood estimation”, J. R. Stat. Soc. **52**, 443–452 (1990).

[15]S. Ahn, and J.A. Fessler, “Globally convergent image reconstruction for emission tomography using relaxed ordered subsets algorithms”, Medical Imaging, IEEE Transactions on. **22**, 613–626 (2003).

[16]C. E. Floyd, R. J. Jaszczak, and R. E. Coleman, “Convergence of the maximum likelihood reconstruction algorithm for emission computed tomography”, Phys. Med. Biol. **32**, 463-476 (1987).

[17]J. Qi, and R. M. Leahy, “A theoretical study of the contrast recovery and variance of MAP reconstructions from PET data,” Medical Imaging, IEEE Transactions on, **18**, 4, 293-305 (1999).

[18]J. Nuyts, and J.A. Fessler, “A penalized-likelihood image reconstruction method for emission tomography, compared to postsmoothed maximum-likelihood with matched spatial resolution,” Medical Imaging, IEEE Transactions on, **22**, 1042-1052 (2003).

[19] C. Tsoumpas, I. Polycarpou, K. Thielemans, C. Buerger, A.P. King, T. Schaeffter, and P.K. Marsden, “The effect of regularization in motion compensated PET image reconstruction: a realistic numerical 4D simulation study”, Phys. Med. Biol. **58**, 1759-1773 (2013).

FIGURE CAPTIONS

FIG 1. Projection of original hot region displayed in a 2D sinogram arrangement. A) SimSET data (left) and forward STIR projections adding PSF and attenuation degradations (right).

FIG 2. Simulated data. Axial views of OSEM reconstruction (8 subsets, 40 subiterations). From left to right: no correction, attenuation correction and PSF + attenuation correction.

FIG 3. SNR plots comparing OSEM (solid line), OSMAPOSL with median root prior (dotted line) and OSSPS with uniform quadratic prior (dashed line) over subiterations. Top left: SNR of cylinder with 1.5 cm of radius on the cold region; Top right: SNR of cylinder with 1.5 cm of radius on the hot region; Bottom left: SNR of cylinder with 4 cm of radius on the cold region; Bottom right: SNR of cylinder with 4 cm of radius on the hot region.

FIG 4. Simulated data. Axial views of the reconstructed phantom by OSEM (left) and OSMAPOSL-MRP (PF=1.0) (middle) at 200 subiterations and OSSPS-UQP (PF=0.04)(right) at 120 subiterations, all using 8 subsets.

FIG 5. Acquired data reconstruced by STIR using OSEM (left), OSSPS-UQP (PF=0.04) (middle) and OSMAPOSL-MRP (PF=1.0) (right) with 8 subsets and 80 subiterations.

APPENDIX

This appendix shows an example of part of a STIR parameter file in order to use the SPECT UB projector as a STIR projector type. A detailed description of each variable of the parameters file can be found in the user manual

```
projector pair type := Matrix
Projector Pair Using Matrix Parameters :=

Matrix type := SPECT UB

Projection Matrix By Bin SPECT UB Parameters:=

;minimum weight stored in the matrix
minimum weight:= 0.001

;PSF type of correction { 2D // 3D // Geometrical }
psf type:= 3D
;number of sigmas to consider in the Gaussian distribution for the PSF
maximum number of sigmas:= 2.0
;next 2 parameters define the PSF.
;the PSF is modelled as a Gaussian with sigma dependent on the distance from the
collimator
;sigma_at_depth = collimator_slope * depth_in_cm + collimator sigma 0(cm)
collimator slope := 0.0163
collimator sigma 0(cm) := 0.1466

;Attenuation correction { Simple // Full // No }
attenuation type := Full
;Values in attenuation map in cm-1
attenuation map := attenuation_map.hv

;Mask properties { Cylinder // Attenuation Map // Explicit Mask // No}
mask type := Explicit Mask
mask file := mask.hv

keep all views in cache := 0

End Projection Matrix By Bin SPECT UB Parameters:=
```