

Voxel Based Quantitative Analysis of Distance Dependent
Resolution Correction in Single Photon Emission Computed
Tomography

by

Daniel Badger

BSc (Hons), The University of Adelaide
PhD, The University of Adelaide

Thesis submitted for the degree of
Master of Science (Medical Physics)
School of Chemistry and Physics
The University of Adelaide

February 2012

Typeset in L^AT_EX 2_ε

© 2012

Daniel Badger



Contents

Contents	iii
Abstract	vii
Signed Statement	ix
Acknowledgements	xi
Dedication	xiii
Conventions	xv
List of Figures	xvii
List of Tables	xix
List of Abbreviations	xxi
Chapter 1. Overview	1
Chapter 2. SPECT and image reconstruction	3
2.1 Planar imaging with a Gamma camera	4
2.1.1 Gamma camera performance	5
2.2 SPECT Reconstruction	8
2.2.1 Simple Backprojection	9
2.2.2 Filtered Backprojection	9
2.2.3 Iterative Reconstruction	10
2.2.4 Acceleration of EM using Ordered Subsets (OSEM)	12
2.3 Corrections	12
2.3.1 Attenuation	13
2.3.2 Scatter Correction	14

2.3.3	Collimator-Detector response	15
2.4	Correction for the collimator-detector response in SPECT	16
2.4.1	Previous investigations of the effect of DDR correction	18
2.4.2	System and collimator characterisation	19
2.4.3	Image acquisition and OSEM implementation	22
2.4.4	DDR orientation validation	23
Chapter 3.	Hardware phantom measurements	27
3.1	Hardware Phantom acquisition	27
3.1.1	SPECT Line Phantom	27
3.1.2	Hoffman Brain Phantom	32
3.1.2.1	Effective resolution comparison	33
3.1.2.2	Partial volume effects	35
Chapter 4.	Clinical SPECT brain images - Methods	41
4.1	Brain imaging	41
4.2	Aging effects in human brains	41
4.3	Brain scan reconstruction with and without DDR correction	42
4.4	Statistical Parametric Mapping (SPM) and statistical analysis of images	44
4.5	Image pre-processing	45
4.5.1	Reorientation	46
4.5.2	Preliminary spatial normalisation	47
4.5.3	Final non-linear spatial normalisation	47
4.5.4	Scaling	47
4.5.5	Smoothing	49
4.6	Statistical Analysis	50
4.7	Ageing effects	53
Chapter 5.	Clinical SPECT brain images - Results	55
5.1	Differences between corrected and uncorrected images	55
5.2	Ageing effect	57
5.3	Gender effects	63
5.3.1	Changes across gender alone	64
5.4	Ageing effects with Gender	64

Chapter 6. Discussion	69
6.1 Phantom studies	69
6.2 Clinical brain scans	70
6.2.1 Differences due to reconstruction	71
6.2.2 Ageing effect	72
6.2.3 Gender differences	75
6.2.4 Ageing effect for separate genders	76
6.3 Comparison with ‘gold-standard’ MRI ageing study	76
6.3.1 VBM and SPECT global effects of age	77
6.3.2 Regional effects of age	78
6.4 Conclusion	80
6.5 Future work	80
Bibliography	83

Abstract

Distance dependent resolution (DDR) correction is commonly applied to single photon emission computed tomography (SPECT) iterative image reconstruction but how much improvement in image quality is gained by the additional computational expense associated with the correction? This work examined the effect of the correction in SPECT imaging of the human brain, firstly by quantitatively determining the resolution improvement in simple phantoms, then in the more complex Hoffman brain phantom. Finally, the effect of DDR correction was investigated in statistical analysis of the brain scans of a large group of normal subjects.

DDR correction takes into account the geometric blurring which increases with distance from the collimator. This reduction in resolution with distance is due to the finite width of the collimator holes, a necessary compromise in order to allow gamma rays to enter the NaI scintillator crystal detector to form the image. Modelling this effect during image reconstruction improves the final image quality, at the expense of a large increase in the computation required for the reconstruction.

Significant improvement in resolution was found in phantom studies when the DDR correction was applied. The full width at half maximum (FWHM) of images of a 1 mm ID tube containing ^{99m}Tc decreased from around 8 mm to around 4 mm when 32 iterations of ordered subset expectation maximisation (OSEM) iterative reconstruction with the DDR correction were performed, when compared to four iterations of the reconstruction without the correction. Increasing iteration numbers in the latter reconstruction increased noise without improving resolution. Improvements in spatial resolution without increasing noise were found when simulating detector blurring of the known radionuclide distribution in the Hoffman phantom in order to match the effective spatial resolution of reconstructed images. Images of the Hoffman phantom showed a significant improvement in differentiation of grey and white matter, due to a reduction in the partial volume effect, when the DDR correction was applied.

When 104 normal subject brain scans (65 female, 39 male, age range 18-81) were reconstructed using the DDR correction, significant group differences were detected when compared to uncorrected images using Statistical Parametric Mapping (SPM). Ageing effects in the brain and gender differences were found to be significantly stronger when the DDR corrected images were used in the comparison rather than the uncorrected images.

New evidence is presented for cerebral blood flow losses with age in the dorsal anterior cingulate cortex, local white matter volume loss with age in the internal capsule, frontal lobe and parahippocampal area, and higher perfusion in females than males at three foci in the frontal pole.

Signed Statement

I, Daniel Peter Badger, certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library catalogue and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

SIGNED: DATE:

Acknowledgements

I would like to thank Dr Leighton Barnden for his guidance and advice in this research project, as well as Dr Judith Pollard, Mr Ben Crouch and the staff of the Department of Nuclear Medicine, The Queen Elizabeth Hospital. Your assistance and support has been invaluable. Many thanks also to my wife Karina, who helped me to keep plugging away in the latter stages.

I would like to acknowledge the Department of Nuclear Medicine, The Queen Elizabeth Hospital, for funding my research and medical physics training and accreditation program.

Dedication

This body of work is dedicated to Karina, now I will have more time for you. Also to Heather and Aidan, I know you will go on to do great things in your lives.

Conventions

This thesis is typeset using the MiKTeX 2.9 software implementation of TeX by Donald E. Knuth. WinShell 3.1.0.10 was used as an interface to MiKTeX. Harvard style is used for referencing and citation in this thesis. Australian English spelling is adopted, as defined by the Macquarie English Dictionary.

List of Figures

2.1	Schematic diagram of a gamma camera	4
2.2	Septal Penetration	6
2.3	Collimator geometry	7
2.4	Diagram illustrating the geometric effect on projections	15
2.5	Ray driven <i>versus</i> pixel driven projectors	17
2.6	Rotation based projection	18
2.7	Line phantom at distances from crystal face	20
2.8	Resolution measurements and linear regression line for the LEHR collimator	21
2.9	Polar plot of gamma camera orbit	24

3.1	Photograph of the SPECT line phantom in a tub of water	29
3.2	FWHM measurement of three 1mm diameter line sources in water - DDR .	30
3.3	FWHM measurement of three 1mm diameter line sources in water - no DDR	31
3.4	A slice through the triple line phantom in water	32
3.5	Three axis view of Hoffman Phantom	34
3.6	Hoffman Phantom effective resolution	36
3.7	Grey and white portions of the Hoffman phantom	38
3.8	Histograms of the voxel values of the Hoffman phantom	39

4.1	Reconstruction times for different iteration numbers with and without DDR correction	43
4.2	Images of a brain scan of a healthy subject	43
4.3	Image pre-processing steps	46
4.4	Pre-scaling mask	49
4.5	SPM design matrices	51

4.6	SPM design matrices with contrasts	52
4.7	Illustration of relative preservation	53
<hr/>		
5.1	Differences between DDR and no DDR reconstruction	56
5.2	Changes in CBF with age	58
5.3	T statistics for reduction in CBF	59
5.4	SPM analysis: CBF changes with gender.	63
5.5	SPM analysis: CBF reduction with age in gender.	65
5.6	SPM analysis: CBF preservation with age in gender.	66
<hr/>		
6.1	Effects of improved resolution	73
6.2	Preservation and atrophy	74
6.3	Reproduction of figures 4 and 5 from Good (2001)	79

List of Tables

2.1	Resolution loss with distance	19
2.2	The result of modelling the effect of a 1 mm diameter tube on the point spread function	22
3.1	FWHM measurement of three 1mm diameter line sources in water - DDR .	29
3.2	FWHM measurement of three 1mm diameter line sources in water - no DDR	30
3.3	Minimum NMSE and effective resolution for varying iteration numbers ('d' signifies DDR correction)	35
5.1	Locations of the most significant clusters	60
5.2	Voxel Z statistics and P values	61
5.3	Rate of change for each cluster	62
5.4	Gender differences in DDR corrected images	64
5.5	Cluster P values for Males and Females	67
6.1	Ageing rates	78

List of Abbreviations

- ^{99m}Tc - a metastable nuclear isomer of technetium-99
- ANCOVA - analysis of covariance
- CBF - cerebral blood flow
- CDRF - collimator-detector response function
- CSF - cerebrospinal fluid
- CT - computed tomography - previously known as computed axial tomography or computer aided tomography (CAT)
- DDR - distance dependent resolution (correction)
- ECD - bicusate (ethyl cysteinate dimer, trade name Neurolite)
- EEG - electroencephalography
- EM - expectation-maximisation
- FBP - filtered backprojection
- fMRI - functional magnetic resonance imaging
- FT - Fourier transform
- FWE - family wise error
- FWHM - full width at half maximum
- GLM - general linear model
- GM - grey matter
- HMPAO - exametazime (hexamethylpropyleneamine oxime, trade name Ceretec)
- IDL - Interactive Data Language
- LEHR - low energy high resolution (collimator)

- MEG - magnetoencephalography
- MRI - magnetic resonance imaging
- NMSE - Normalised mean square error
- OSEM - ordered subset expectation-maximisation
- PET - positron emission tomography
- PMT - photo multiplier tube
- PRF - point response function
- rCBF - Regional Cerebral Blood Flow
- SPECT - single photon emission computed tomography (also known as SPET)
- SPM - Statistical Parametric Mapping
- Tc - technetium (element with atomic number 43)
- VBIS - voxel based iterative scaling
- VBM - voxel based morphometry
- WM - white matter