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Modelling and Reconstruction of Whole-Body parametric maps in PET-MRI Pharmacological imaging

Zacharias Chalampalakis

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Modelling and Reconstruction of
Whole-Body parametric maps in
PET-MRI Pharmacological imaging
*Modélisation et reconstruction de cartes
paramétriques corps-entier en imagerie
pharmacologique TEP-IRM*

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Acronyms

A-FOV Axial Field of View.

CASToR Customizable and Advanced Software for Tomographic Reconstruction.

CT Computed Tomography.

DSB Dynamic Single Bed.

DWB Dynamic Whole Body.

EM Expectation Maximisation.

FDG Fluorodeoxyglucose.

FOV Field of View.

HYBRID Healthcare Yearns for Bright Researchers for Imaging Data.

IDIF Image Derived Input Function.

LOR Line of Response.

MIP Maximum Intensity Projection.

MLEM Maximum Likelihood Expectation Maximisation.

MR Magnetic Resonance.

NHP Non-Human Primate.

NSCLC Non-Small-Cell Lung Carcinoma.

OSEM Ordered Subsets Expectation Maximisation.

PCG Preconditioned Conjugate Gradient.

PET Positron Emission Tomography.

PMT Photomultiplier Tube.

SiPM Silicon Photomultiplier.

SOP Standard Operating Procedure.

SPECT Single-photon Emission Computed Tomography.

TAC Time Activity Curve.

TOF Time of Flight.

VOI Volume Of Interest.

Résumé de thèse

Introduction

La tomographie par émission de positons (TEP) est passée, dans les dernières décennies, d'un outil utilisé principalement dans les applications de recherche à un outil d'imagerie clinique qui a un rôle majeur dans de nombreuses applications cliniques et applications de recherche clinique [2]. En combinaison avec plusieurs radiotraceurs disponibles, qui permettent à l'imagerie TEP de cibler et de recueillir des informations sur la fonction au niveau moléculaire, la TEP peut fournir des informations uniques sur les biomarqueurs. La nature non invasive de l'imagerie TEP, combinée à son potentiel de reproductibilité entièrement quantitative et fiable des informations sur les biomarqueurs, sont des aspects très importants qui la rendent désirable dans le cadre de la médecine de précision [2, 3]. La plupart des applications cliniques actuelles de la TEP se concentrent sur l'imagerie statique et des mesures qualitatives et semi-quantitatives. Mais la TEP a la capacité de fournir des paramètres biologiquement pertinents entièrement quantitatifs, en surveillant la cinétique du traceur et le comportement dynamique avec un balayage dynamique sur une période de temps. Ces informations peuvent être utilisées pour générer des images paramétriques qui décomposent les informations en paramètres de modèles qui guident le comportement dynamique. Ceux-ci peuvent être utilisés pour identifier les différentes régions qui contribuent à un comportement différent d'absorption du traceur et peuvent être liés à des différences dans la fonction sous-jacente et la pathophysiologie, avec une applicabilité dans la recherche et les futures applications cliniques.

La majorité des scanners cliniques offrent un champ de vision axial (Axial Field of View; A-FOV) limité, entre 15 et 26 cm [4]. En imagerie statique, la couverture du corps entier est obtenue en combinant plusieurs positions du lit à différents emplacements axiaux pour étendre le champ de vision effectif [5], ou par un mouvement axial continu du lit (Continuous Bed Movement; CBM) [6]. De même, pour réaliser une imagerie dynamique sur l'ensemble du corps, des protocoles dynamique du corps entier (Dynamic Whole Body; DWB) ont été développés, qui utilisent de multiples passages répétés sur le corps entier [7–9]. Mais ces protocoles d'acquisition posent des défis qui proviennent des lacunes temporelles résultantes dans les

données dynamiques acquises de toute position de lit donnée. Ces écarts sont introduits à chaque position du lit par le temps consacré à l'imagerie d'autres positions du lit et par les retards du système de scanner dus au temps nécessaire pour déplacer le lit dans la direction axiale et préparer l'acquisition de la position suivante du lit. Mais cette acquisition résulte en une forte réduction à la fois des nombre de détections totaux collectés pour chaque position lit et de la fréquence d'échantillonnage temporel. En outre, l'acquisition d'informations sur les changements temporels rapides dans la phase initiale de l'étude dynamique est compromise, car ces changements ne sont pas échantillonnés de manière adéquate pour toutes les positions du lit. Par conséquent, les estimations des paramètres à partir d'acquisitions TEP dynamiques du corps entier sont potentiellement compromises par les limitations ci-dessus dans leur précision et leur exactitude. La génération d'images paramétriques à partir de données dynamiques nécessite l'ajustement du modèle dynamique d'intérêt sur les courbes d'activité temporelle (Time activity curve; TAC) pour chaque voxel de l'image. En raison de la mauvaise statistique et du bruit élevé associés aux mesures de TAC au niveau du voxel, qui sont encore dégradés par les protocoles d'acquisition DWB, les estimations d'images paramétriques peuvent être fortement erronés par le bruit et potentiellement biaisées. L'objectif principal de cette thèse était d'explorer l'optimisation de l'acquisition et les nouvelles stratégies de reconstruction pour améliorer les cartes paramétriques du corps entier.

Les contributions peuvent être séparées en trois parties. La première partie se concentre sur l'optimisation du protocole DWB sur un scanner clinique TEP/IRM, visant à réduire les écarts temporels des acquisitions DWB et à augmenter les comptes collectés ainsi que la fréquence d'échantillonnage. La deuxième partie se concentre sur l'utilisation d'algorithmes de reconstruction dynamique pour améliorer l'imagerie paramétrique de la TEP, en utilisant des données simulées et réelles. La troisième et dernière partie est consacrée à l'application des algorithmes de reconstruction dynamique évalués sur des données réelles d'une première étude pharmacocinétique chez l'homme appelée IsotoPK [10], afin de fournir une régularisation temporelle des cartes d'activité et de générer des cartes paramétriques pertinentes pour cette étude. Dans cette application à des données DWB réelles, des considérations supplémentaires ont été faites pour tenir compte des erreurs de modélisation dans la reconstruction en utilisant des modèles résiduels adaptatifs dans la boucle de reconstruction.

Contributions

TEP dynamique multi-lits pour le corps entier: Optimisation de l'acquisition

Dans ce chapitre, nous examinons les résultats des performances d'acquisition d'un protocole DWB mis en œuvre sur le scanner Signa TEP/IRM dans le cadre de l'étude pharmacocinétique IsotoPK [10], en termes

de délais et d'écart temporels qui en résultent. Nous décrivons ensuite le développement et la mise en œuvre d'un protocole expérimental entièrement automatisé pour l'imagerie DWB qui a été conçu dans le but de réduire les délais d'acquisition et de permettre une plus grande flexibilité sur l'acquisition. Cette protocole a été conçu dans le but de réduire ces délais en automatisant entièrement le processus d'acquisition et en enregistrant en continu les informations TEP dans un seul fichier en mode liste pour toutes les positions du lit pendant toute la durée de l'étude DWB. En utilisant une telle stratégie d'acquisition, les délais entre les positions du lit et les balayages WB ont été réduits au temps pris par le seul mouvement physique de la table du scanner. La performance du protocole d'acquisition expérimental nouvellement développé a été testée sur une étude de un primate non humain et les résultats ont été comparés au protocole utilisé dans l'étude IsotoPK.

En utilisant les informations temporelles des données TEP brutes IsotoPK extraites de 7 examens de sujets, les délais moyens de ce protocole DWB à 5 positions de lit ont fourni un délai intra-lit moyen de 5,69 s (95%CI : 5,63-5,75) et un délai moyen entre les balayages WB de 26,17 s (95%CI : 26,13-26,22).

Après des tests initiaux à l'aide de fantômes, le protocole DWB automatisé a été testé sur une étude Non-Human Primate (NHP) utilisant un nouveau traceur ^{18}F -Crizotinib. Le examen a été effectué avec l'utilisation de 3 positions de lit, pour un total de 28 passages de WB. La figure 1 montre les 260 premières secondes de la courbe de acquisition des données enregistrées en mode liste, avec les phases et les positions du lit superposées. Celles-ci montrent la phase initiale de lit unique dynamique (Dynamic Single Bed; DSB) qui a été conduite centrée sur le cerveau pendant une durée de 90 s, suivie par les premières acquisitions de passes WB de trois positions de lit. L'estimation des délais (écarts temporels) pour cette étude utilisant le protocole d'acquisition automatisé a été faite en utilisant les informations enregistre. Les résultats ont montré un délai moyen intra-lit de 3,77 s (95%CI : 3,62-3,91) et un délai moyen entre les balayages de 4,6 s (95%CI : 4,53-4,67). Pour faire une comparaison entre le protocole IsotoPK de 5 positions de lit et le protocole automatisé qui a été testé en utilisant 3 positions de lit, le temps de retard entre les balayages de cette étude a été estimé en utilisant une approximation à 7,66 s.

L'utilisation du protocole entièrement automatisé a permis de réduire considérablement les délais, tout en simplifiant l'acquisition des ensembles de données DWB par une automatisation complète. Ces réductions des délais peuvent se traduire par une amélioration des statistiques d'acquisition ainsi que par un balayage temporel plus rapide, ce qui peut être essentiel dans les premières phases de l'acquisition du DWB. De considérations supplémentaires sur les vitesses de table admissibles pour la sécurité et le confort des patients doivent être faites avant d'utiliser ce protocole sur des sujets humains.

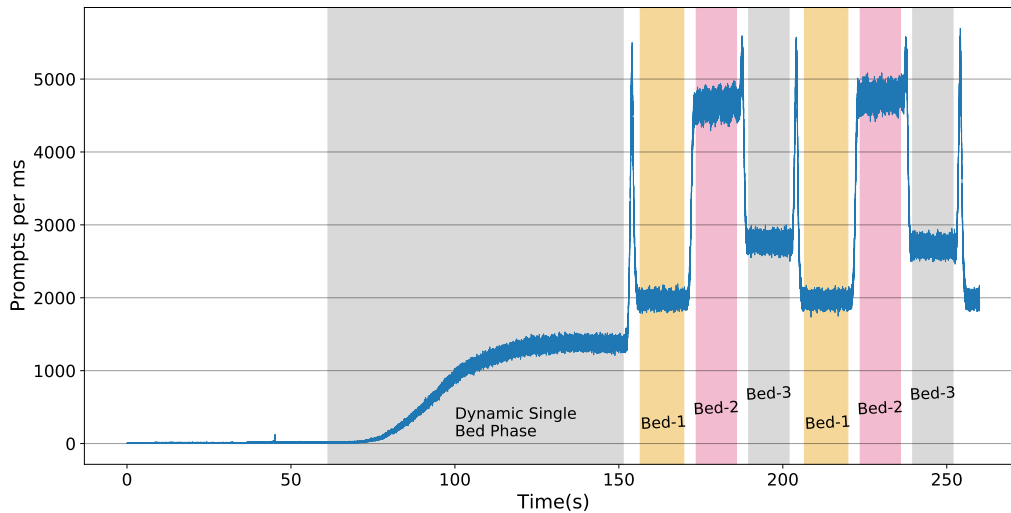


Figure 1: Courbe de tête (taux de détections en fonction du temps) de l'étude du primate acquis montrant les phases DSB et DWB de l'acquisition et les trois positions du lit DWB.

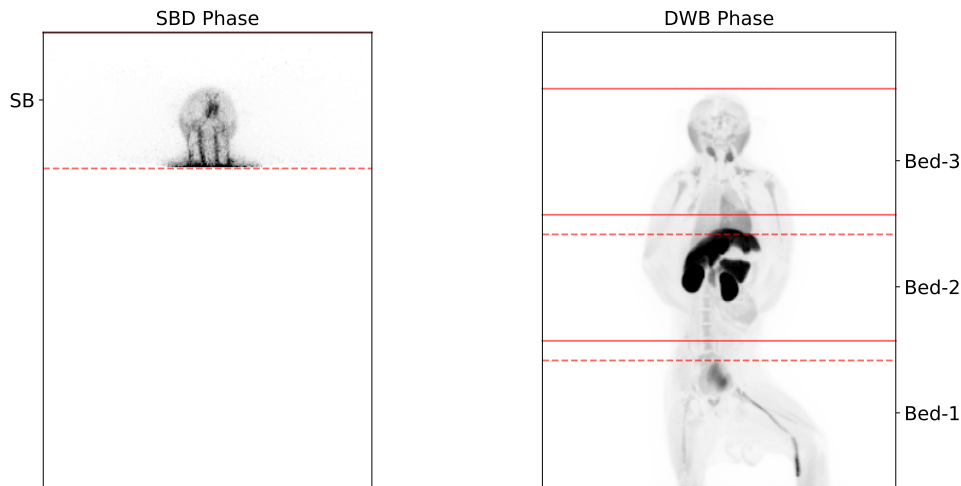


Figure 2: Vues de projection d'intensité maximale des images TEP reconstruites de l'étude primate, pour les deux phases de l'acquisition.

Reconstruction dynamique de données DWB: Une étude de simulation

La génération d'images paramétriques à partir de données dynamiques peut être un défi lorsqu'elle est appliquée à des données DWB. En raison de la mauvaise statistique et du bruit élevé associés aux mesures de TAC au niveau du voxel, en particulier pour les acquisitions DWB, les estimations d'images paramétriques peuvent être fortement erronées par le bruit et potentiellement biaisées. L'utilisation de la reconstruction dynamique directe a été proposée pour améliorer cette tâche en utilisant des modèles dynamiques directement dans la reconstruction. Ces techniques permettent une modélisation plus précise du bruit des données TEP brutes dans le processus de reconstruction et peuvent améliorer le bruit des images paramétriques et réduire le biais [11]. Dans ce chapitre, nous décrivons l'implémentation d'algorithmes de reconstruction dy-

namique au sein de la plateforme open-source de reconstruction entièrement quantitative CASToR [12], qui a été réalisée dans le cadre de ce projet. Nous évaluons ensuite les performances des algorithmes de reconstruction dynamique à l'aide de simulations pour l'imagerie DWB TEP au fluorodésoxyglucose ($[^{18}\text{F}]\text{FDG}$), pour différents modèles dynamiques et pour différents protocoles d'acquisition en DWB. Les simulations ont été réalisées à l'aide du fantôme cérébral numérique Zubal [13]. Les résultats ont finalement été démontrés dans une étude TEP dynamique réelle. L'évaluation a porté spécifiquement sur l'imagerie paramétrique Patlak K_i et l'utilisation du modèle Patlak Patlak1985 et de l'analyse spectrale Cunningham1993 pour la reconstruction dynamique. Le modèle d'analyse spectrale a été utilisé avec trois ensembles différents de nombres de fonctions de base (17, 9 et 6). Le modèle de Patlak n'est valable que pour les données après que les conditions d'état stationnaire sont atteintes ($t > t_{ss} \approx 15\text{min}$), alors que le modèle spectral peut s'adapter à toutes les données dynamiques. Afin de comparer plus étroitement les deux modèles pour la reconstruction 4D, des comparaisons ont été faites en utilisant le modèle spectral avec toutes les données dynamiques ainsi qu'avec les données dynamiques après t_{ss} (reconstructions marquées avec $t > t_{ss}$).

Les résultats de la comparaison entre la reconstruction dynamique (4D) et la reconstruction image par image (3D, suivie d'une modélisation cinétique post-reconstruction) ont été effectués pour deux régions du fantôme cérébral. Les comparaisons ont été effectuées en utilisant des mesures au niveau du VOI et du voxel (respectivement %Bias vs %CoV et %RMS Bias vs %RMS CoV). Ces résultats sont présentés dans la figure 3. Les résultats montrent que la reconstruction dynamique utilisant le modèle de Patlak (4D Patlak) sur les données DWB peut fournir des résultats proches de ceux des protocoles à lit unique sans lacunes temporelles dans leurs données. En outre, la reconstruction 4D Patlak a fourni une gamme plus courte de valeurs de biais avec des itérations croissantes par rapport à la reconstruction 3D. La reconstruction dynamique avec le modèle spectral (4D Spectral) a fourni des résultats encore meilleurs que la reconstruction Patlak 4D des données DWB et la reconstruction 3D des données dynamiques à lit unique. La reconstruction spectrale 4D, utilisant 9 fonctions de base, a permis d'obtenir un compromis optimal entre une faible variance/bruit et un faible biais. La reconstruction spectrale 4D utilisant des données $t > t_{ss}$ a donné lieu à un comportement similaire en termes de variance et de bruit à celui de la reconstruction Patlak 4D, avec des caractéristiques de biais légèrement inférieures sur certaines régions par rapport à la reconstruction Patlak.

Les résultats appliqués à l'ensemble de données réelles, qui ont été répertoriées pour émuler le cadrage et les écarts d'acquisition du DWB, ont montré que le rapport contraste/bruit (CNR) le plus élevé sur une tumeur dans les poumons a été obtenu par les reconstructions 4D Spectral, suivies par la reconstruction Patlak 4D. Les deux méthodes de reconstruction dynamique ont fourni un rapport contraste/bruit plus faible que la reconstruction 3D effectuée sur des données DWB ou des données dynamiques à lit unique sans lacunes.

Une évaluation du bruit paramétrique de l'image dans le foie a montré un comportement similaire pour toutes les reconstructions 4D, avec un bruit plus faible que la reconstruction 3D des mêmes données DWB mais plus élevé que la reconstruction 3D des données dynamiques à lit unique. Les images paramétriques K_i issues des reconstructions 3D et 4D des données réelles aux itérations avec des valeurs SD du foie correspondantes sont présentées dans la figure 5. En conclusion, nous avons montré que la reconstruction

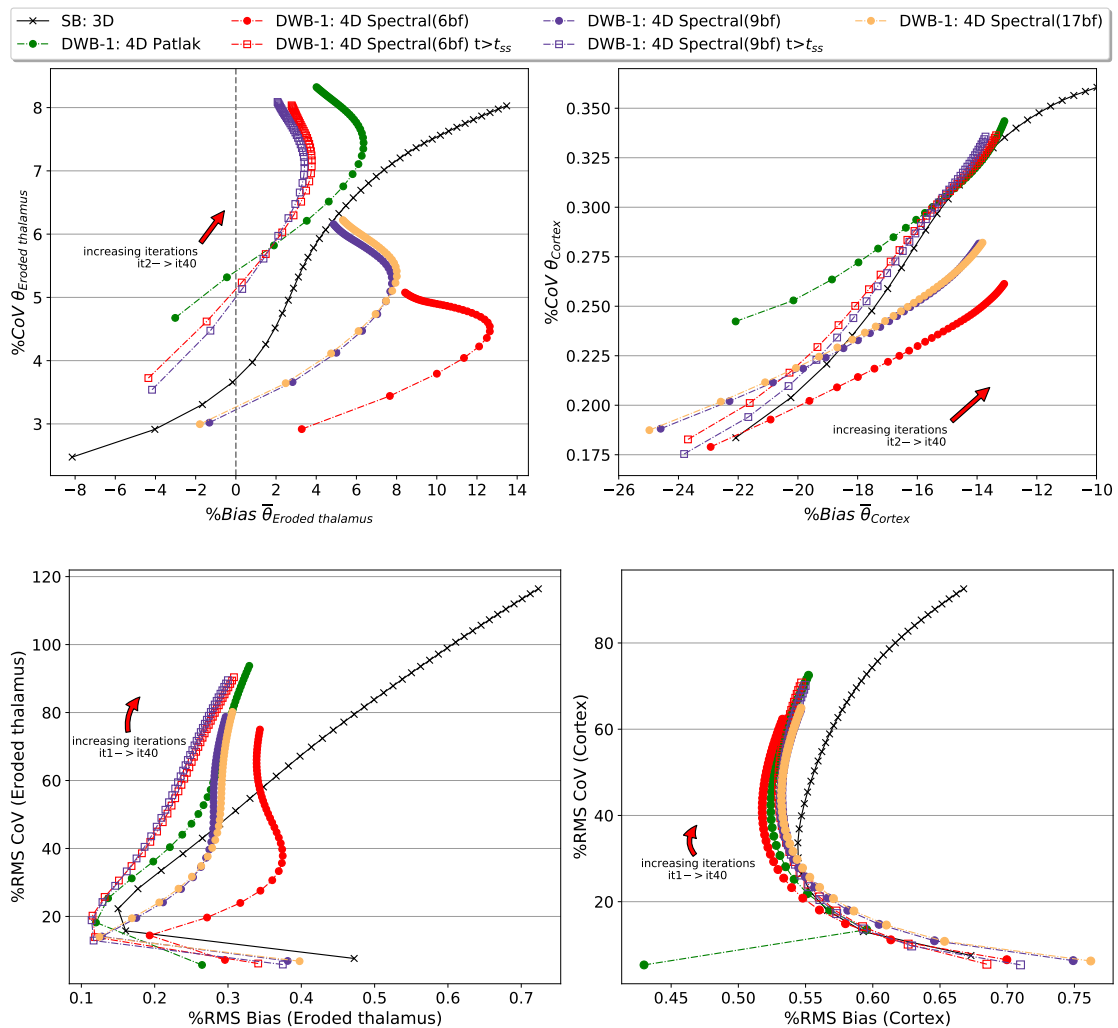


Figure 3: Simulation: Courbes de compromis entre le bruit et le biais du thalamus (gauche) et du cortex (droite) pour les reconstructions 4D des données du protocole DWB-1. Métriques basées sur les VOI (haut) et sur les voxels (bas).

dynamique 4D est nécessaire en imagerie paramétrique DWB pour obtenir une quantification précise et stable. Pour l'imagerie paramétrique FDG Patlak K_i , nous avons montré des résultats de reconstruction dynamique directe Patlak avec des valeurs de bruit et de biais comparables à l'imagerie paramétrique basée sur la reconstruction 3D à partir d'études dynamiques à lit unique. L'utilisation du modèle spectral dans la reconstruction a permis une meilleure utilisation des données dynamiques et une réduction supplémentaire

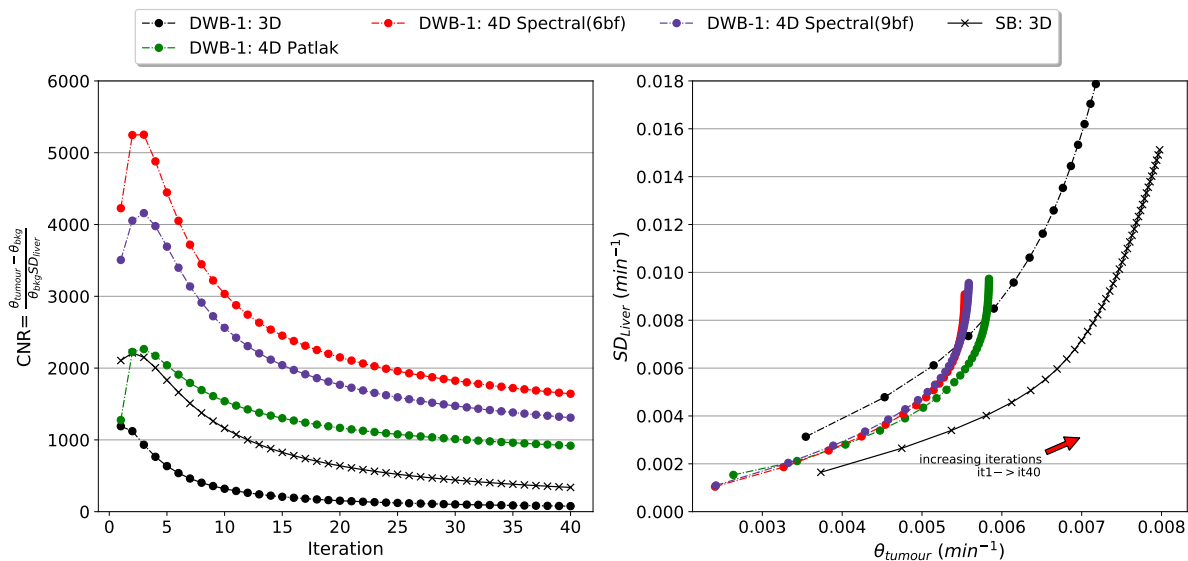


Figure 4: Données réelles: Rapport contraste/bruit (gauche) et SD du foie par rapport à la moyenne des VOI de la tumeur (droite) pour les reconstructions 3D et 4D.

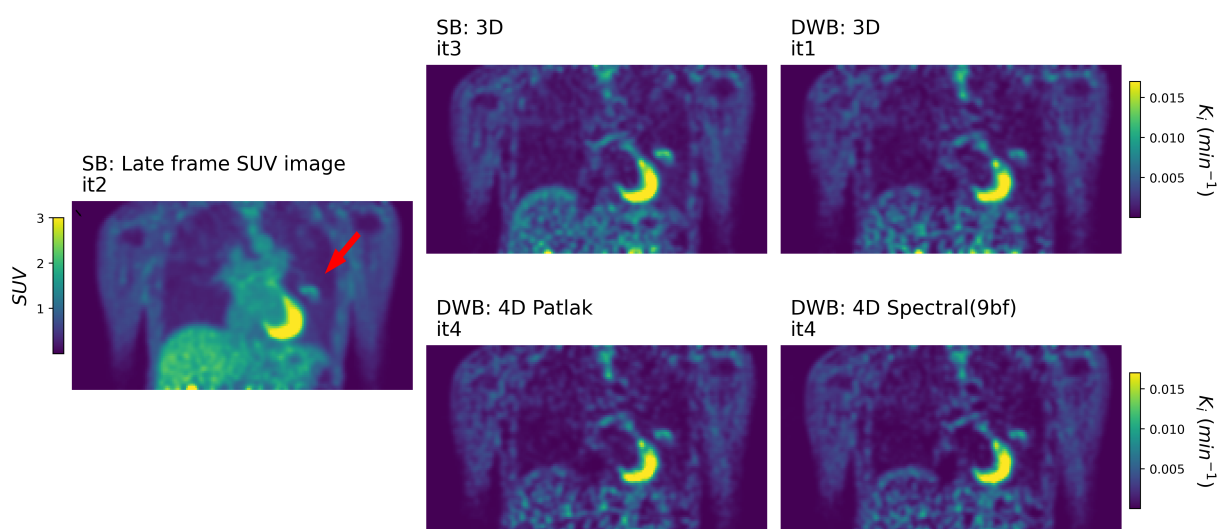


Figure 5: Données réelles: Les images paramétriques K_i (avec filtrage Gaussien à 5mm) de SB et DWB rejouent des ensembles de données provenant de reconstructions 3D et 4D à des valeurs SD appariées sur le foie.

du bruit par rapport à la reconstruction dynamique de Patlak. Dans l'ensemble, l'utilisation de la reconstruction dynamique 4D pour l'imagerie paramétrique DWB offre des propriétés souhaitables qui permettent la transition de les études dynamiques à lit unique et les pratiques courantes d'imagerie paramétrique par reconstruction 3D sans perte de qualité d'image et avec des avantages supplémentaires pour la précision des images paramétriques.

Reconstruction dynamique de données DWB: Application d'une étude pharmacocinétique réelle

Dans ce chapitre, nous décrivons la mise en œuvre des algorithmes de reconstruction dynamique développés précédemment dans un cadre de reconstruction dynamique directe multi-lits au sein de CASToR. Cette approche directe permet d'utiliser toutes les données TEP acquises avec des informations temporelles précises dans une seule boucle de reconstruction, tout en permettant l'utilisation de la reconstruction dynamique directe pour des protocoles d'acquisition DWB plus flexibles et complexes.

Le cadre développé a été appliqué sur des données DWB réelles, qui ont été acquises dans le cadre de l'étude pharmacocinétique IsotoPK [10]. Le protocole d'acquisition de cette étude commence par une acquisition dynamique à lit unique (Dynamic Single Bed; DSB) de 180 s centrée sur le foie, suivie d'une acquisition DWB de 15 passages WB, pour une durée totale d'une heure. L'étude est réalisée sur des volontaires sains, avec une injection d'un nouveau traceur [^{11}C]Glyburide, pour étudier la distribution et la fonction des transporteurs de solutés (SLC) dans la pharmacocinétique des médicaments. Deux scans sont réalisés par volontaire en un seul jour, respectivement sans et avec l'utilisation de l'inhibiteur (rifampicine), appelés scans *CTRL* et *RIF*. Des reconstructions dynamiques ont été réalisées avec le modèle spectral et ont été évaluées par rapport à une reconstruction 3D régulière utilisant les données de la courbe temps-activité (TAC) sur les volumes d'intérêt (VOI). Enfin, les reconstructions du modèle spectral ont été utilisées pour générer des images paramétriques K_1 . Comme les estimations de K_1 sont sensibles aux informations dynamiques initiales, qui, pour ce protocole, n'étaient disponibles que pour les emplacements couverts par l'acquisition DSB, les images paramétriques K_1 générées n'ont été utilisées que pour l'évaluation des VOI couverts par cette seule acquisition. En outre, la correction de la fraction du sang a été ignorée pour l'imagerie de K_1 afin d'éviter l'induction d'un bruit excessif par l'application de cette correction au niveau du voxel ; les images paramétriques estimées de K_1 de substitution (symbolisées par K_1^*) sont donc présentées.

Les résultats de l'analyse VOI, donnés dans la figure 6 pour le scan *CTRL*, ont montré une bonne concordance des TAC entre la reconstruction 3D et spectrale 4D. Les images paramétriques de K_1^* issues de la reconstruction spectrale 4D sont présentées dans la figure 7 pour les scans du même sujet, avec et sans injection de l'inhibiteur. En outre, nous présentons dans ce chapitre la mise en œuvre et les résultats des tests d'un algorithme de reconstruction dynamique innovant avec la modélisation résiduelle adaptative pour détecter et corriger toute écart du modèle dynamique. Ces sont particulièrement importantes pour la reconstruction dynamique, car le processus de mise à jour tomographique est lié au modèle dynamique et les erreurs d'ajustement du modèle dynamique peuvent se propager spatialement à d'autres régions. Dans l'étude IsotoPK, la principale erreur concernée était le processus de remplissage de la vessie qui était mal modélisé par le modèle spectral. Nos résultats utilisant la modélisation résiduelle adaptative

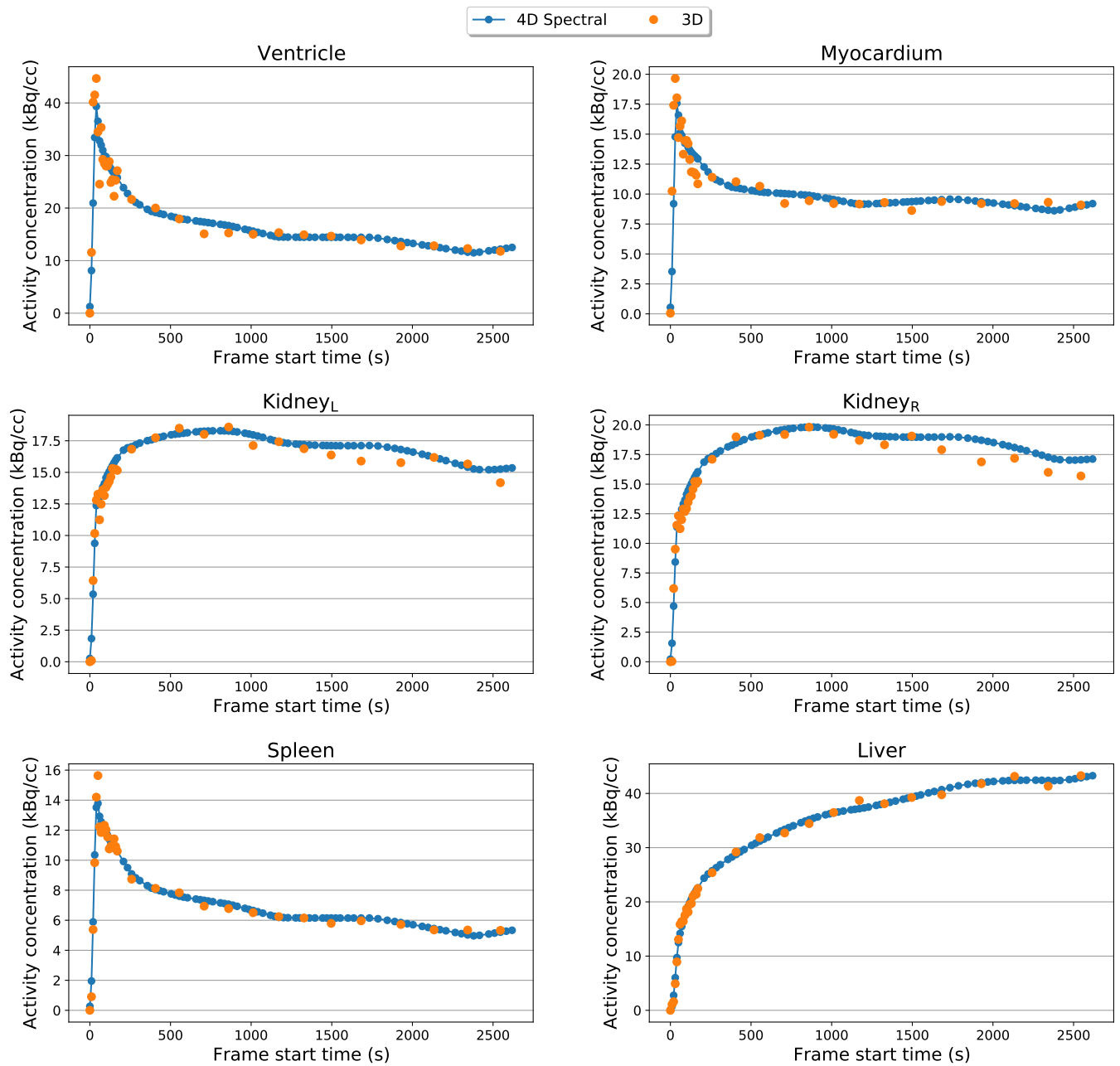


Figure 6: Courbes d'activité temporelle moyenne des VOI pour la reconstruction spectrale 3D et 4D. Régions VOI indiquées qui sont incluses dans l'acquisition DSB et DWB.

dans la reconstruction dynamique ont montré des améliorations significatives dans le TAC de la vessie, où l'algorithme adaptatif a réussi à détecter et à corriger le processus de remplissage, au prix d'un bruit d'image supplémentaire sur toutes les régions. Les résultats optimaux ont été obtenus avec une combinaison de filtrage spatial et temporel dans le traitement des données résiduelles avant la modélisation résiduelle, en termes de sélectivité de l'algorithme et de niveaux de bruit ajouté.

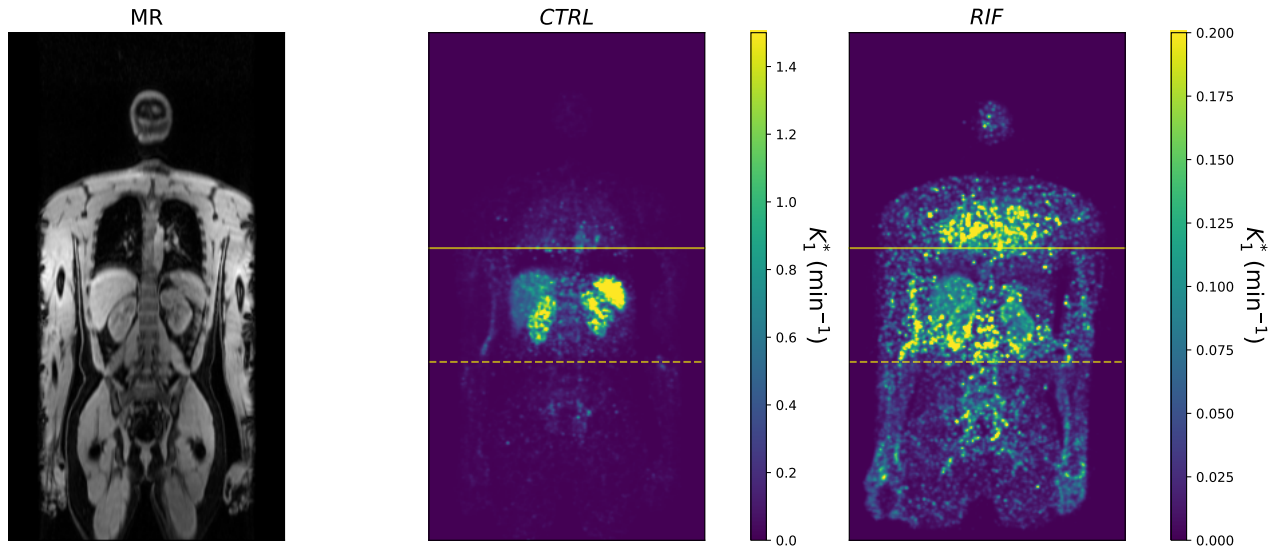


Figure 7: K_1 estimé à partir de la reconstruction spectrale 4D pour les régions VOI incluses dans les acquisitions DSB et DWB, présentées pour les balayages *CTRL* et *RIF*.

Conclusions et perspectives

L'imagerie TEP dynamique sur le corps entier a le potentiel d'augmenter la valeur de l'imagerie TEP, en permettant d'étendre au corps entier l'imagerie TEP et paramétrique entièrement quantitative. Dans le processus de transition des études dynamiques à lit unique aux études DWB à lits multiples, il y a une perte considérable de statistiques de données TEP et de fréquence d'échantillonnage. La reconstruction dynamique peut faciliter cette transition en compensant la perte de qualité de l'image et en offrant des avantages supplémentaires pour la précision des images paramétriques. Il est possible de réduire davantage le bruit de l'image en optimisant le protocole d'acquisition ou en utilisant des modes d'acquisition améliorés pour l'imagerie DWB, comme la acquisition CBM.

Nous avons montré avec succès qu'avec l'utilisation du modèle d'analyse spectrale, l'utilisation de toutes les données dynamiques dans une reconstruction unique et l'utilisation de la modélisation résiduelle adaptative, un algorithme générique de reconstruction dynamique peut être appliqué pour pratiquement tous les types d'acquisitions DWB. Cette reconstruction fournit une régularisation temporelle sur les estimations d'activité et permettant la génération de certaines images paramétriques lorsque celles-ci sont pertinentes pour l'étude.

Plusieurs aspects liés à l'estimation des types de mouvements complexes présentés pendant la durée typique d'une étude DWB, que ils doivent être pris en compte dans la reconstruction dynamique pour garantir une imagerie sans erreur et sans artefact. Récemment, avec le développement de nouveaux scanners à FOV étendu [14, 15] et de scanners corps total [16], il y a un regain d'intérêt pour résoudre ces problèmes

pour l'imagerie dynamique du corps entier. Bien que les scanners à A-FOV étendu puissent certainement bénéficier de l'estimation des images paramétriques de la DWB, en particulier celles sensibles à la cinétique rapide précoce après l'injection, leur disponibilité dans les environnements cliniques sera un sujet de préoccupation pendant au moins un certain temps. Les processus dynamiques plus lents peuvent encore être échantillonnés efficacement sur l'ensemble du corps avec les scanners actuels et les protocoles de DWB multi-lits, tels que ceux récemment introduits dans certains scanners commerciaux [17], qui peuvent être plus rentables et plus facilement accessibles dans les environnements cliniques. Nous nous attendons donc à ce que le regain d'intérêt pour l'imagerie paramétrique du corps entier et l'imagerie quantitative complète se traduise par des avancées qui bénéficieront à l'imagerie DWB pour les scanners de tous les A-FOV et pour différents protocoles d'acquisition.

Introduction

Positron Emission Tomography (PET) has grown over a period of multiple decades from a tool used infrequently and primarily limited to research applications into a clinical imaging tool that plays a major role in many clinical practices and applications. In combination with multiple available radiotracers, the compounds that enable PET imaging to target and gather information of function at the molecular level, PET can provide unique biomarker information. The non-invasive nature of PET imaging, in combination with its potential for fully quantitative and reliable reproducibility of biomarker information, are some very important aspects that make it desirable in the delivery of precision medicine. Precision medicine is defined as an approach for disease treatment and prevention that takes into account individual variability in genes, environment, and lifestyle for each person. PET can play a vital role towards wider adoption of precision medicine due to its potential in the delivery of unique biomarker information [3].

Engineering advancements over the last decades have led to the development of highly efficient PET systems and in the creation of hybrid imaging systems, notably the PET/CT and PET/MR systems. The clinical need for multi-modality information has led to the fast adoption of such hybrid systems in clinical practice, with “one-stop-shop” protocols providing multi-modality information in single imaging sessions. Finally, hybrid systems have enabled the use of imaging information in “synergy”, to provide new and superior information on the underlying function and anatomy [18].

Despite PET's great success in clinical integration and applicability, the use of the modality and the main focus of many years of development have been concentrated on static imaging and qualitative or semi-quantitative measures. These have been driven mainly by applications in oncology, where these measures have so far been deemed sufficient in clinical pathways of cancer patients. At the same time, the ability of PET to provide fully quantitative measures of the biological functions under study has been reserved for research orientated applications and developments of new tracers or study of human physiology. But recently, the increasing focus on precision medicine has led to renewed attention to PET's dynamic capabilities, for quantification of biologically relevant parameters by monitoring tracer kinetics and dynamic behaviour. These quantitative capabilities of PET are expected to be at the centre of future developments and clinical

research for the next decade [2, 19].

Problemata

The majority of the current clinical applications of PET can be found in oncology, where imaging information over the Whole Body (WB) is needed to detect and characterise the primary and metastatic disease. Whole body information is also desirable for many current and potential future applications of dynamic PET, which can result in fully quantitative measures and biomarkers information over the whole body. Beyond the use of such information for precision oncology, it can be used to study the kinetics of drugs distribution and function over the whole body. This information can be used, while considering the human body as a single system, in the study of interactions and signalling between organs of the body to investigate complex physiology and pathology interactions [2, 20].

A major limitation in the acquisition of the required PET data over the whole body is the limited axial field of view (A-FOV) of the majority of current clinical systems. The majority of the PET systems provide an axial coverage between 15 and 26 cm [4]. In practice, whole-body coverage is achieved using multiple bed positions at different axial locations to provide the desired axial coverage [5], or via continuous axial bed motion (CBM) during the acquisition [6]. Both acquisition strategies can be extended for Dynamic Whole Body (DWB) acquisition, by use of multiple repeated whole-body passes [7–9]. Recently these DWB protocols have been integrated within commercial PET systems [17]. These acquisition protocols pose challenges that arise from the resulting temporal gaps in the acquired dynamic data of any given bed position. These gaps are introduced at each bed position by the time spent on imaging other bed positions and by scanner system delays due to the time required to translate the bed in the axial direction and prepare for the acquisition of the next WB pass. The result is a sharp reduction in both total counts collected for each axial location as well as in temporal sampling frequency. Furthermore, acquisition of information from fast temporal changes in the early phase of the dynamic study is compromised, as those are not sampled adequately for all bed positions. Consequently, parameter estimates from dynamic whole-body PET acquisitions are potentially compromised by the above limitations in the acquisition, degrading their precision and accuracy.

Recently, scanners with increased A-FOV have been developed, offering increased sensitivity and substantially more or total-body coverage, that enables synchronous dynamic imaging of the whole body without the need of multiple bed positions and the associated issues with temporal gaps [14–16]. These systems are currently found in very few pilot PET centres around the world and are not widely adopted in clinics yet. Since the first Total-Body scanner came online there has been an increased focus in the research for clinical applications of such systems, one of which is the use for dynamic whole-body imaging. As such the

research interest in this field is expected to increase in the next years, with a particular focus on clinical utility as well as practical aspects of ease-of-use and cost-effectiveness.

Challenges and Contributions

PET dynamic data can be used to extract kinetic parameters over regions of interest or on the voxel level, with the latter being used to create parametric images of the applied dynamic model. Parametric images can provide information that is helpful in identifying and separating out different regions that exhibit different dynamic behaviour, without imposing predefined Volumes Of Interest (VOIs) in the analysis [21]. One of the major challenges in dynamic whole-body acquisitions using multiple whole-body passes is the estimation of accurate parametric images. Generation of parametric images from dynamic data requires fitting of the dynamic model of interest on time activity curves (TAC) for every voxel in the image. But due to the poor statistics and high noise associated with TAC measurements at the voxel level, which are further degraded by DWB acquisition protocols, parametric image estimates can be heavily corrupted by noise and potentially biased. The main objective of this thesis was to explore acquisition optimization and novel reconstruction strategies for the improvement of whole-body parametric maps. The contributions can be separated into two major parts. The first part A) is focused on optimization of the DWB protocol on a clinical PET/MR scanner, aiming at the reduction of temporal gaps in the DWB acquisition and increase of collected counts as well as an increase of sampling frequency. The second part B) is focused on the improvement in the use of acquired DWB PET data by exploiting dynamic reconstruction algorithms. As part of this PhD project, various dynamic reconstruction algorithms were implemented in the open-source reconstruction platform CASToR, for use with simulated and real data acquired from clinical scanners. An innovative approach for direct multi-bed dynamic reconstruction was developed and applied on real DWB data, for the direct reconstruction of parametric images and temporal regularisation of the reconstructed activity image data.

HYBRID-ITN

This PhD project was funded and conducted within the Healthcare Years for Bright Researchers for Imaging Data (HYBRID) Innovative Training Network (ITN). This is an industrial and academic ITN, funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 764458. The aim of the HYBRID group is to advance and fully exploit the potential of integrated, dual-modality and multi-parametric imaging offered by multi-modality hybrid imaging. Quantitative and parametric imaging is at the centre of focus of the group.

The main challenges that were addressed by the group define the three main work packages of the programme:

- WP2: Data collection

The aim of the data collection group is to address challenges of multi-modality data acquisition and image reconstruction for the reliable formation of parametric and multi-parametric images.

- WP3: Data processing

The aim of the data processing group is to explore and improve on methods of extracting information using multi-parametric imaging and multiple parameters.

- WP4: Clinical translation

The aim of this group is to explore integration techniques of multi-parametric imaging into clinical use-case scenarios.

This PhD project was conducted as part of the data collection group WP2 (project WP2.4). The planned direction of the project was defined towards expanding computation and use of fully-quantitative parametric maps in PET to whole-body datasets. Specifically, the direction of the project was set towards the development of clinically viable schemes for parametric whole-body PET/MR imaging for improved characterisation of oncological diseases throughout the body. The carried out project focused on general methodological advancements for whole-body parametric imaging, with applications on real data focusing on whole-body pharmacological studies rather than clinical studies in oncology due to the limited availability of clinical whole-body data.

Specific tasks and goals have been pre-defined by the ITN, to be delivered throughout the project in the form of reports of deliverables and milestones. Those are not included in the thesis manuscript explicitly but many of them form part of the contributions.

Secondments between the partner organisations were also planned within the HYBRID network. The aim of secondments is for the participating PhD students to learn from practices in other organisation and engage in multi-centre research projects. Two academic and one industrial secondment was planned for each student. In this project, secondments were planned with the University Medical Center Groningen (UMCG), the Medical University of Vienna (MUW) and with General Electric Healthcare (GEHC). Additionally, the secondment of a student from King's College London (KCL) was organised to take place in our centre. The secondment with the student from KCL and the secondment to MUW resulted in collaboration projects, whose work has resulted in two publications. These are attached at the end of this manuscript in the **Secondary Contributions** section.

- GEHC: Waukesha, WI (3 weeks)

The secondment was planned at the main factory facility which hosts the research and development team of GE's PET/MR systems. The purpose of the secondment was to conduct research for the

development of a fully automated dynamic whole-body acquisition protocol for the Signa PET/MR system. In addition this secondment served as an experience of research and development in the industrial setup.

- GEHC: Zürich (1 week)

The secondment with GE also took part at the University hospital of Zürich, where research and testing is performed for clinical applications of dynamic PET imaging, in order to get an insight into the clinical implementation of dynamic PET protocols.

- UMCG (2 weeks)

This secondment was planned in order to gain experience in PET kinetic modelling for research studies and explore uses of analysis methods that could be used for this PhD project.

- MUW (2 weeks)

The initial purpose of this secondment was to make use of advanced reconstruction techniques developed for this PhD project to a cohort of epilepsy dynamic PET dataset at MUW for generation of parametric images. Due to the pandemic, the majority of the secondment was conducted remotely. The collaboration project was slightly adapted to be performed by distance and focused more on motion correction aspects for dynamic brain PET.

Apart from the secondments, the HYBRID network conducted many meetings (approximately twice a year) where all the ITN partners would come together and discuss progress. These meetings served substantially in exchange of ideas and guidance on individual research projects as well as in forming of collaborations.

Organization of the manuscript

The manuscript is organised into two major parts. **Part I** outlines the methodologies involved in this project that are necessary for the understanding of the work carried out in this project. It is separated into four chapters which cover PET physics, pharmacokinetics, PET image reconstruction theory and implementations in custom software respectively. **Part II** of the manuscript provides the contributions made in this thesis in the form of four chapters.

Chapter 5 describes the development of a custom fully-automated protocol for dynamic whole body imaging on the Signa PET/MR and shows results from the use of this protocol on a NHP scan.

Chapter 6 describes the development and implementation of dynamic reconstruction methods within an open-source reconstruction software, which were subsequently used in this project, for dynamic single bed studies. The rest of the chapter outlines in detail an extensive simulation study conducted for the evaluation

of the developed reconstruction methods for DWB Patlak parametric imaging. This simulation study was presented at the **IEEE/MIC** 2019 conference and submitted for publication to the **Physics in Medicine & Biology** journal.

Chapter 7 presents the development of a direct multi-bed dynamic reconstruction method, as an extension of the developments presented in chapter 6 for use with all dynamic bed data from DWB studies. In this chapter we present the application of this direct multi-bed reconstruction method to dynamic whole body data from a first in man pharmacological study conducted at our centre. The results of this application in the pharmacological study were presented at the **European Association of Nuclear Medicine** 2020 conference.

Chapter 8 presents work conducted for the application of an adaptive modelling method for dynamic reconstruction and its application on whole body dynamic data from the pharmacological study presented in the previous chapter. The results of the application were presented at the **IEEE/MIC** 2020 conference.

A Conclusions and Prospects section is provided at the end of **Part II**, summarising the contributions in the context of the aims of this PhD project and of clinical utility of findings. Future prospects and aspects that need to be addressed further as also discussed.

Appendixes with supplementary material relating to the presented work are also provided.

Secondary contributions made in collaboration projects as part of the ITN programme are detailed at the end of the manuscript in the **Secondary Contributions** section.

Part I

Theory and Methods

Chapter 1

Positron Emission Tomography

This section covers aspects of the main principles of Positron Emission Tomography (PET) and serves as a brief introduction to the notions that are necessary for the description of the work carried out in this thesis. It is not an exhaustive review of the processes involved in PET imaging. Readers can find more basic principles explained in detail in the textbooks which are frequently referenced in this chapter.

1.1 Historical Perspective

The main principles of a PET imaging system were developed and demonstrated with a working scanner prototype in the late 1970s by Ter-Pogossian et al. [22] and Phelps et al. [23]. The main concept of their prototype, which forms the basis of PET devices, was the placement of detectors in a circular formation around the imaged object and the detection of annihilation photon pairs which serves as "Electronic" collimation. This principle of "Electronic" collimation makes PET imaging superior to single photon based imaging devices still until today as it does not require a physical collimator which considerably reduces the sensitivity, as in Single-photon Emission Computed Tomography (SPECT) imaging systems. Early PET systems were limited due to the cost and engineering limitations to an axial coverage of a few axial planes and were mostly used in brain imaging. Development of scanner models with a larger diameter and larger axial Field of View (FOV) enabled use for imaging of other organs than the brain [24]. The expanded FOV along with the capability of achieving whole-body coverage by use of shifted axial acquisitions [25] (multiple axial bed positions to achieve whole-body coverage) have established the use of PET in oncology [26] and driven many more technological developments towards higher sensitivity for improved small lesion detectability and reduction of scan time [27].

1.2 Fundamental physics of PET

1.2.1 Positron emission

As its name suggests, PET is an imaging method based on positron emission. Positron emission is a spontaneous process that happens as part of the β^+ decay process of radionuclides. Radionuclides are comprised of atoms with excess energy that decay to stable forms via routes that result in the emission of radiation. The rate at which a radionuclide undergoes decay depends on its characteristic half-life $T_{1/2}$. This is defined as the time taken for half of the nuclei of a specific radionuclide to decay. The rate of decay at any time t is defined as the activity $A(t)$, measured in Becquerels (Bq), which changes over time according to

$$A(t) = A_0 e^{-\lambda t}, \quad (1.1)$$

where A_0 is the activity at reference time $t_0 = 0$ and λ is the decay constant, for which

$$\lambda = \frac{\ln(2)}{T_{1/2}}. \quad (1.2)$$

The β^+ decay process results in the emission of a positron (e^+) particle and a neutrino (ν). The positron is given part of the excess radioisotope energy in the form of kinetic energy, which when emitted within a material is gradually lost from continuous interactions with other atoms of the material until the positron approaches close to a rest. During this period the positron follows a tortuous random path. The positron range can be defined for a sufficiently large number of emissions as either the FWHM or the mean of the distribution of distances between the emission and annihilation positions. The positron range value will depend on the positrons energy spectrum and the interacting material properties. After most of its kinetic energy has been expended, the positron rapidly interacts with an electron and annihilates. This interaction results in the conversion of the two particles into two photons of 511 keV which are emitted in almost opposite directions ($\sim 180^\circ$). Due to the non-zero kinetic energy during the annihilation, the excess energy results in a small acollinearity of the photon pair. For *in vivo* [^{18}F]-Fluorodeoxyglucose (FDG) imaging, a common radiolabeled tracer used in PET oncology applications, it has been shown that the FWHM acollinearity is approximately 0.54° [28]. A list of positron emitting radionuclides which are commonly used in PET imaging is given in table 1.1 along with relevant characteristics for PET imaging.

1.2.2 Interactions with matter

The mean range of positrons from commonly used PET radionuclides is in the order of a few millimetres within tissue and almost all positrons are annihilated within the body. On the other hand, the 511 keV photons

Table 1.1: Commonly used radioisotopes and their relevant characteristics for PET imaging [29].

Radionuclide	Half-life	e^+ maximum energy (MeV)	Mean range in water (mm)
^{15}O	2 min	1.732	3.0
^{13}N	10.0 min	1.199	1.8
^{11}C	20.4 min	0.96	1.2
^{18}F	110 min	0.634	0.6
^{68}Ga	67.8 min	1.899	2.9
^{64}Cu	12.7 h	0.653	0.7
^{89}Zr	78.4 h	0.902	1.3

have fewer chances of interacting within the body and a fraction of them will exit the imaged object without interacting.

The two most probable interactions for photons of 511 keV in tissue are photoelectric absorption and Compton scattering. In photoelectric absorption, the photon is completely absorbed while interacting with an atomic electron of the inner shell, to which it provides all of its energy. In Compton scattering, the photon interacts with an atomic electron of an outer shell, to which it passes part of its energy. This scattering process results in a change of direction and reduction of the energy of the original photon, while the loosely bound electron is ejected from the interacting atom. Between the two processes, the Compton effect is the dominant interaction for 511 keV photons in tissue. Elastic scattering (Rayleigh scattering) is another interacting process in which no loss of energy occurs and the direction of the incident photon is changed by a relatively small angle. This interaction is more dominant in lower energies than 511 keV photons.

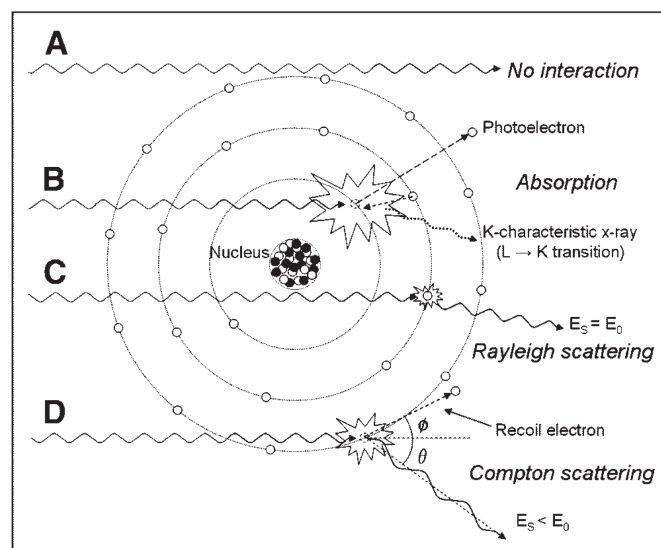


Figure 1.1: Illustration of the described interactions. (A) No interaction resulting in transmission of photon. (B) Photoelectric absorption from inner shell electron, resulting in its ejection and followed by an inner electron transition and characteristic X-Ray emission. (C) Elastic (Rayleigh) scattering conserving the energy of the photons but resulting in small angle change in direction. (D) Compton scattering with outer shell electron resulting to change of energy and direction of incident photon. Adapted from *Seibert et al.* [30].

1.2.3 Attenuation

Knowledge of the probabilities for the interaction of 511 keV photons in a material can be used to calculate a precise attenuation factor that can be applied at the macroscopic level. Given a well collimated photon beam of intensity I_0 , the intensity I_x at depth x within the material (along the direction of the beam) will be reduced due to interactions with the material according to Beer-Lambert's law

$$I_x = I_0 e^{-\mu x}, \quad (1.3)$$

where μ is the linear attenuation coefficient (in cm^{-1}). This factor accounts for all possible interactions, whether absorption or scattering, and its value depends on the material properties and the energy of the photons. In water its value for 511 keV photons is 0.096 cm^{-1} [31].

1.3 PET Systems

1.3.1 PET Detectors

The goal of a PET imaging system is to stop and detect the annihilation photon pairs and record information that can be used to estimate the annihilation event's position. The basic component for the detection of annihilation gammas is the scintillation crystal. These are inorganic crystals that emit light (lower energy photons) upon interaction with the gammas. The amount of produced light is proportional to the energy deposited by the gamma interactions and can be used to deduce energy information of the interaction. Photosensitive detectors are coupled with the crystals to capture the produced light and output an electronic signal that can be digitally registered. Traditionally Photomultiplier Tubes (PMTs) are used in most PET systems, while some more recent systems make use of Silicon Photomultipliers (SiPMs). Depending on their mode of operation SiPMs can allow for better efficiency and response speed and can be used in conditions where PMTs could not, such as within the MR field of PET-MR hybrid systems. More details on SiPM integration in PET/MR are given in section 1.4.2. The most common configuration of the PET detectors is within a block or module configuration, where a smaller number of photosensitive detectors to crystals is used. An example of a single crystal block to 4 PMTs is shown in figure 1.2 for PMT based scanners. The crystals are partially cut into segments to reduce lateral dispersion of light and improve localisation of detection by the PMTs. In the example of figure 1.2 the crystal is cut in a 6×6 configuration.

The blocks or modules are placed in ring configurations that provide full 360° of coverage in the transaxial direction. Multiple rings are often placed adjacent to each other to increase axial coverage and solid angle coverage which provides increased detection sensitivity.

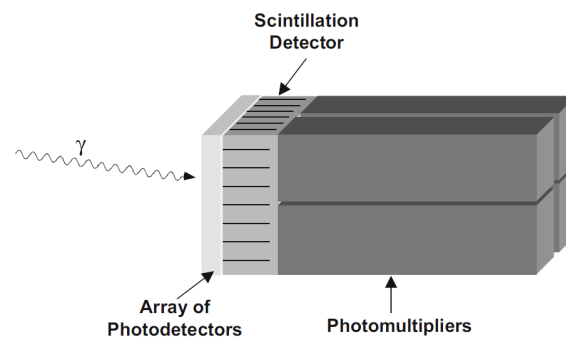


Figure 1.2: Example illustration of PMT based block detector [1] (Reproduced with permission).

1.3.2 PET Data coincidence sorting

Individual events recorded by the detectors are called *single* events. In PET, detection of annihilation events requires the detection of both annihilation generated photons. To identify these photons, the detection system makes use of "coincidence detection". Pairs of single events detected within a predefined timing window are assumed to be photons originating from a single annihilation which are defined as *prompt coincidence events*. The line connecting the two detectors that record the coincident event is defined as the Line of Response (LOR).

Improved timing resolution of detector systems has enabled for further information of the annihilation point to be made by capturing the detector arrival difference of the two annihilation photons. This difference can help localise the point on the LOR where the annihilation took place, within some range of uncertainty defined by the detector timing resolution. This capability of PET is referred to as *time-of-flight* (TOF). This information, collected for each coincidence event, can then be used within the image reconstruction process for improved results, as it will be shortly described in chapter 3.

Unfortunately not all coincidence events recorded within the coincidence window will always be originating from the same annihilation event and be detected without interacting within the body. Apart from true coincidences, they could also be one of the following listed type of events. Some of these type of events are illustrated in figure 1.3.

- **Random event**

As the rate of single events increases the chances of photons originating from different annihilation events being detected within the coincidence timing window are also increasing. In this case, the system will record coincidence events that are not correlated. These events are referred to as random events. The rate of random events is directly proportional to the size of the timing window and to the square of the activity in the scanner. These events are uncorrelated to the imaged object and hence

degrade the acquired data and subsequently image quality and quantification. The expected rate of random coincidences can be estimated using the rates of single events or using delayed coincidence windows. These estimations are then pre-processed and subsequently applied as corrections in the image reconstruction process.

- **Scatter events**

As described scattering of the annihilation gammas results in changes to its energy and direction of travel. Subsequent detection of scattered gammas results in mispositioned LORs that also degrade the data, image quality and quantification. Because scattered gammas have lower energy than 511 keV, they can be rejected by applying a low energy threshold in the detectors. But due to energy resolution limitations, this threshold is set low enough to best avoid rejection of true coincidence events while still filtering a reasonable amount of scattered events. To correct for the remaining events that are being recorded as true coincidences, special scatter simulation algorithms are employed to estimate the amount of scatter coincidences in the data and account for it during the image reconstruction process [32, 33].

- **Multiple events**

Multiple single events (more than two) can be recorded within the coincidence timing window in which case they are referred to as multiple events. As these cannot be used to resolve LORs, they are either rejected completely or in some cases processed further to deduce which pair of single events are more likely to be true coincidences, using techniques that vary between scanner models and manufacturers.

- **Delayed event**

As described above, an estimation of randoms can be made using an additional detection channel to capture coincidences with a delay of several times the duration of the coincidence window. These events are considered uncorrelated and serve as a direct measurement of randoms. Specific variance reduction techniques are then applied on these randoms estimations before being used as corrections in reconstruction, to avoid inducing additional noise in the data [1].

- **True event**

A true event is a coincidence detection of photons originating from a single annihilation event, which have not undergone any interaction prior to their detection.

- **Prompt event**

True, random and scatter events that meet the acceptance criteria for coincidence detection are indistinguishable at the time of detection and recorded as valid coincidence events. They are referred to as prompt events. These are pre-corrected or used directly in the reconstruction process along with the

corrections, depending on the use of either analytical or statistical reconstruction methods respectively.

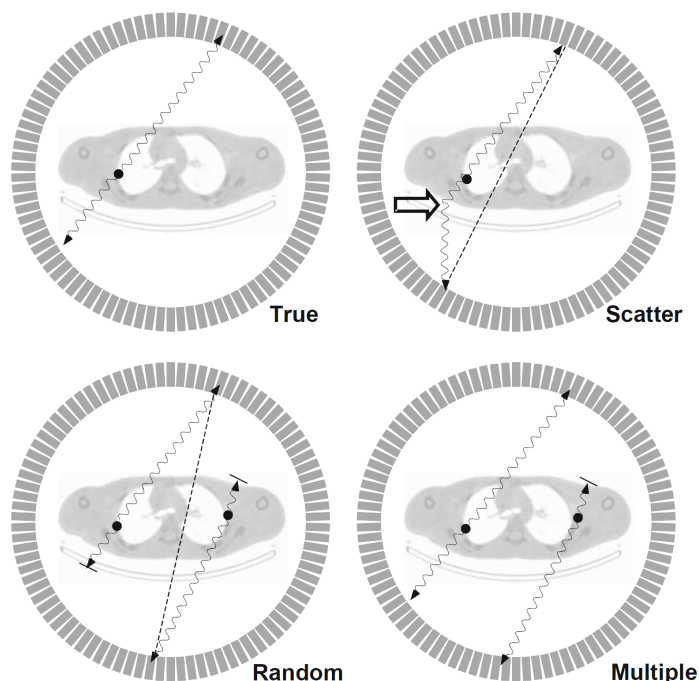


Figure 1.3: Representation of different types of detected coincidence events. Adapted from Bailey *et al.* [1] (Reproduced with permission).

1.3.3 PET acquisition

As described the ring formation of PET detectors is the dominant geometry used in PET systems. Using multiple rings results in the increase of Axial Field of View (A-FOV), solid angle coverage and possible combinations of detectors meaning a higher number of LORs. But early multi ring systems were making use of 2D acquisition, where only direct and cross-plane ring coincidences were allowed. This was enforced using tungsten septa between rings, as seen in figure 1.4.

With evolving detector and electronics technology, 3D acquisition became possible and is now the standard acquisition mode. 3D acquisition offers the same data as 2D acquisition and also includes all the oblique LORs data resulting in an increase of sensitivity (4 to 6 times) [34]. The use of oblique views leads to non-uniform sensitivity profiles in the axial direction due to the higher number of LORs closer to the centre of the A-FOV, with the maximum sensitivity at the centre and a minimum at the edges of the A-FOV. A comparison between the 2D and 3D sensitivity profiles is shown as an example in figure 1.5. In addition to more coincidence events, the higher sensitivity and acceptance of single events result in an increase of randoms and scatter events, which in addition may now be originating from activity outside the A-FOV of the system.

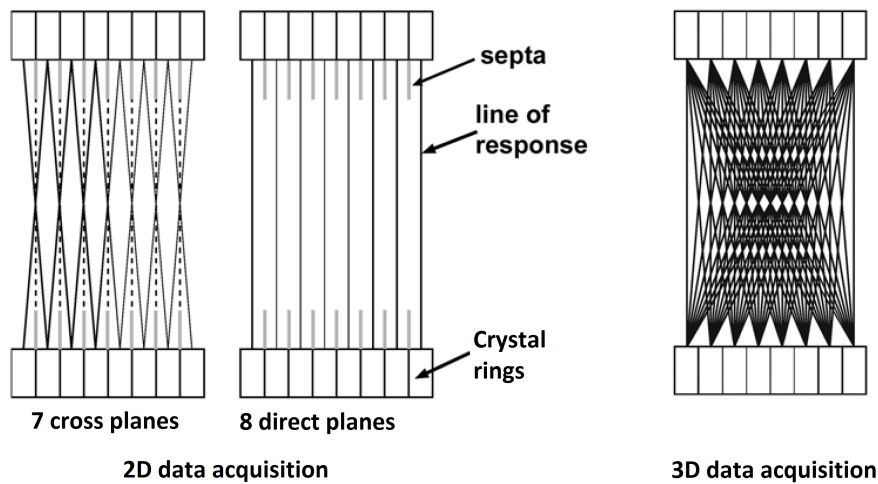


Figure 1.4: Example illustration of LORs for 2D acquisition mode using direct and cross planes (left) and 3D acquisition mode (right) for an 8 ring scanner with 15 axial slices. Adapted from Cherry S. and Magnus D. [35] (Reproduced with permission).

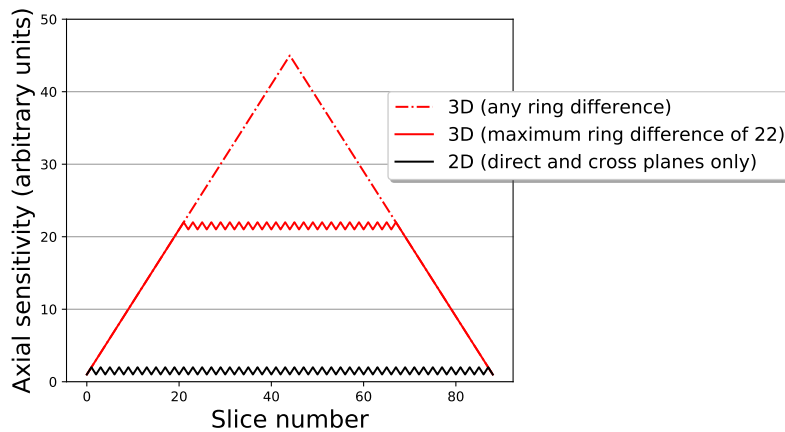


Figure 1.5: Example of 2D and 3D axial sensitivity profiles, with and without maximum ring difference limits, for a scanner with 45 crystal rings which provide 45 direct and 44 cross-planes.

In 3D mode the maximum angle of events accepted in the axial direction can sometimes be limited by enforcing a maximum ring difference permitted LORs. This results in a uniform axial sensitivity profile at a central region of the A-FOV, as seen in figure 1.5.

1.3.4 Storage of PET coincidence events

The recorded coincidence data are stored digitally to allow post processing and reconstruction of image data. The different methods for storing the data can result in different storage requirements, allow or not allow for specific event information to be stored and even necessitate different reconstruction techniques.

- **List Mode**

In the simplest form coincidence events can be stored in a binary file as a stream of events by the order

of their detection. This format follows naturally the detection process and allows for multiple detector information to be included in each event. A time tag is normally included in the data stream every millisecond. The minimum information recorded per event is the detector pair IDs. Any additional information such as time-of-flight, detection energy, etc. can also be included with each event. For time-of-flight the data can include exact arrival time differences, to make best use of the information in post processing or reconstruction methods. The use of list-mode files is practical for dynamic studies as they naturally include all dynamic information and can take less storage space than the other alternative formats described below. List-mode data can be binned into the formats described below before reconstruction or used directly with list-mode reconstruction algorithms.

- **Histogram**

Coincidence events per detector pair (LOR) can be summed together and stored into a single entry. The total number of entries will be equal to the total number of detector pairs. These entries make up a histogram, where effectively all the events have been histogrammed into the detector pairs. No timing information is preserved and hence multiple histograms are required if data are recorded dynamically, in a predefined temporal binning. This format can result in smaller files for static imaging compared to list-mode, but in the case of dynamic imaging it frequently results in a much larger total size of files as multiple detector pair entries are empty (zero) for some time frames. Furthermore, if time-of-flight information is also available, separate histograms need to be created for each time-of-flight bin (discretization of the TOF resolution), which further increases the zero entries and storage requirements. Compression is possible in both axial and transaxial direction of the data, which is referred to as axial compression (or span) and angular compression (or mashing) respectively [34]. These are employed by some scanner manufacturers to counteract the increasing size of histograms from increasing scanner resolution and better TOF resolution. The compression strength is chosen as a trade-off of file size and degrading image quality properties [36].

- **Sinogram**

Sinograms are representations of the data in projections through the process of projection using a transformation such as the Radon or X-Ray transform [37]. Each pixel of the sinogram represents the integral of events over a specific line through the image space. The name "sinogram" comes from the fact that a point source (off-centred) is represented as a sine wave in the sinogram. The use of sinograms is inherited from other tomographic imaging methods where data are acquired as projections. Sinograms are used with analytical reconstruction methods, shortly described in chapter 3, which require the projection space to be fully and uniformly sampled.

As in this project we did not make use of analytical reconstruction algorithms, we have not described the

formation and use of sinograms in detail. In the project, we made use of both real data from clinical PET scanners and simulated data from analytical simulations. For real data we made use of the list-mode data format, to reduce file size and allow for flexibility in the treatment of the data, while for simulations we used the histogram data format as we were limited to that by the nature of analytical simulations. It is important to note that clinical PET systems are performing reconstructions using histograms or sinograms and although they can record data in list-mode format, they always re-bin the data to histograms or sinograms before performing a reconstruction. By contrast in this project, we made use of list-mode reconstruction algorithms when using list-mode datasets.

1.3.5 PET Corrections and Quantification

PET has always been used as a quantitative imaging method, providing image values that relate to radioactivity concentration. This is an important requirement for semi-quantitative and quantitative interpretations of the imaged data, with quantitative measures being at the foreground on this thesis project. But accurate quantification of images requires corrections that need to be considered before and during the reconstruction process. The main corrections needed for quantifiable PET are outlined here.

- **Randoms correction**

As discussed previously, random events in the data are estimated using delayed coincidence detection or by measurements of single event rates between detectors. For most clinical scanner manufacturers and for list-mode data these are normally provided in the same stream of data, with delay events recorded similarly to prompts and with single event rates recorded for every predefined time interval (for example every second) for each detector or detector block. Similarly, for histogram data, a separate histogram of random events is provided. A histogram per frame (time bin) is required for multiple frame datasets, for randoms as well as for prompt events. In the reconstruction software used in this projects, CASToR [12], the corrections are provided for each event LOR or histogram bin within the raw dataset file. Furthermore, randoms corrections in CASToR are provided in rates (s^{-1}) which is a more natural format to use with list-mode data reconstruction and dynamic datasets.

- **Scatter correction**

As described previously, a certain amount of the annihilation gammas will scatter with the atoms of the travelling medium via Compton scattering, which results in changes of energy and direction of the gammas. Even after the energy filtering applied on the detectors, an amount of those scattered gammas will be detected and recorded as coincidence events that degrade the PET data and affect image quality and quantification. The most commonly used approach to account for scatter in clinical scanners is the use of the Single Scatter Simulation algorithm [32] to estimate scatter. These simulations

are based on an initial activity distribution estimate from the uncorrected PET data and knowledge of the probability of scattering. Scatter estimates, similar to random estimates, are then used as additive corrections within statistical reconstruction methods. Again, in CASToR these are provided as rates (s^{-1}).

- **Normalisation**

Sensitivity between LORs will differ due to detector and geometric efficiencies effects. Normalisation coefficients for each LOR are estimated using measurements and modelling of the normalisation components and are subsequently used in reconstruction to correct for these efficiencies.

- **Dead-time correction**

After every detection event, a certain amount of time is required for sub-systems involved in the detection to become ready for detection again and so interaction events occurring during that recovery time will not be registered. As the number of interactions increases at higher imaged activities, the proportion of events not registered is also increasing. The result is a non-linear system response for different levels of imaged activities. This effect is corrected using dead-time correction which is applied by the use of lookup tables that relate single rates to dead-time factors in addition to real-time dead-time monitoring measurements.

- **Attenuation correction**

Absorption or scatter interactions within the body results in loss of gammas detection. Even if only one of the two annihilation gammas is lost the result is a non registered event. The probability of attenuation depends on the total probability of interaction within a LOR and is independent of the annihilation position within that line. This enables the estimation of attenuation factors for each LOR within the body by use of transmission measurements, either with radioactive sources or X-rays sources. For these measurements earlier scanners made use of positron or single gamma sources to estimate attenuation while most modern clinical systems make use of Computed Tomography (CT) or Magnetic Resonance (MR) scans to estimate attenuation factors.

- **Calibration Factor**

Subsequently, after all other corrections have been applied there is a need for a global calibration factor to relate the estimated number of true events to activity concentration. PET systems are calibrated against a reference source to obtain such factors.

- **Decay correction**

Finally, measurements need to be corrected for decay of the imaged radionuclide for the duration of the acquisition and for decay-correction to a reference time. For static imaging, the reference time is

chosen to be the imaging start time, while for dynamic acquisitions the reference time is commonly chosen to be the time of tracer injection.

1.4 Hybrid PET Systems

1.4.1 PET-CT

As described above attenuation correction is essential for quantitative PET imaging. Early PET systems made use of external radioactive sources to acquire a transmission scan. Some of the drawbacks of these methods were that transmission scans would contribute to an increase of image noise on PET images and that transmission scan acquisition was increasing the total duration of the examination. As PET imaging became more frequently used in clinical applications, the need for fusion of PET images with CT images became apparent, firstly for the clinical value by complementary PET functional images to CT anatomical images and secondly for aiding in attenuation correction and anatomical localisation. These needs led to the development of the first hybrid PET systems, with the first PET/CT system being introduced in the late 1990s [38]. The first PET/CT was able to acquire a whole body PET/CT scan, using multiple bed positions as it will be described later in this chapter, within an hour with precisely co-registered CT and PET images that were acquired close in time [39]. The CT scan was used in PET attenuation correction via scaling of attenuation coefficients (μ) to account for the energy difference between CT X-rays and annihilation photons [31]. PET/CT eliminated the need for radioactive source transmission scans and the problems with excessive noise associated with these relatively poor quality transmission images.

1.4.2 PET-MR

MRI provides anatomical images with higher soft-tissue contrast than CT imaging. The option of different acquisitions sequences can allow for different types of soft-tissue contrast, which can also extend to dynamic and parametric MR imaging applications [18] and also to functional MRI [40]. The fusion of PET and MR was technically challenging due to interference between the two systems [41]. Initial PET and MR clinical workflows and systems made use of separate PET and MR or PET/CT and MR scanners to scan the patient using a single bed to transfer the patient from one scanner to the other and minimise patient misalignment [42, 43].

The use of PMT based detectors for synchronous PET/MR imaging was only possible using long optical fibres that shifted the detection of events by the PMTs at a safe distance away from the centre of the magnetic field [44, 45]. Later advancements in PET detector technology allowed for Avalanche photodiodes (APD) and silicon photomultipliers (SiPM) based detectors, which led to the development of PET inserts [40]

for MR and the development of fully integrated PET-MR systems that perform synchronous acquisitions [46–48]. There are currently two PET/MR integrated systems by commercial manufacturers, the Siemens mMR and the GE Signa. In this project, we relied on access and real PET data from a GE Signa PET/MR that is available in our centre. But we also made use of Siemens mMR data in a collaboration project with the Medical University of Vienna that is described in the Secondary Contributions section at the end of this manuscript.

The Signa PET/MR scanner was designed based on an existing 3 Tesla MR scanner (3T MR750w MR scanner) that was modified to accommodate the PET detector ring. The ring comprises of 28 transverse modules (seen in figure 1.6) with 720 scintillator crystals per module. Those are coupled with SiPM detector modules, which are capable of capturing TOF information. A schematic of the modules and their integration in the system ring is shown in figure 1.6. The PET ring configuration results to 45 crystal rings which provide a total of 89 slices and an A-FOV coverage of approximately 25 cm with a slice thickness of 2.78 mm. Details on the system characteristics and evaluation of performance can be found in the work of Grant *et al* [47]. It is interesting to note that the latest GE PET/CT systems make use of similar detector configuration and type which provide similar performance for PET imaging [49].

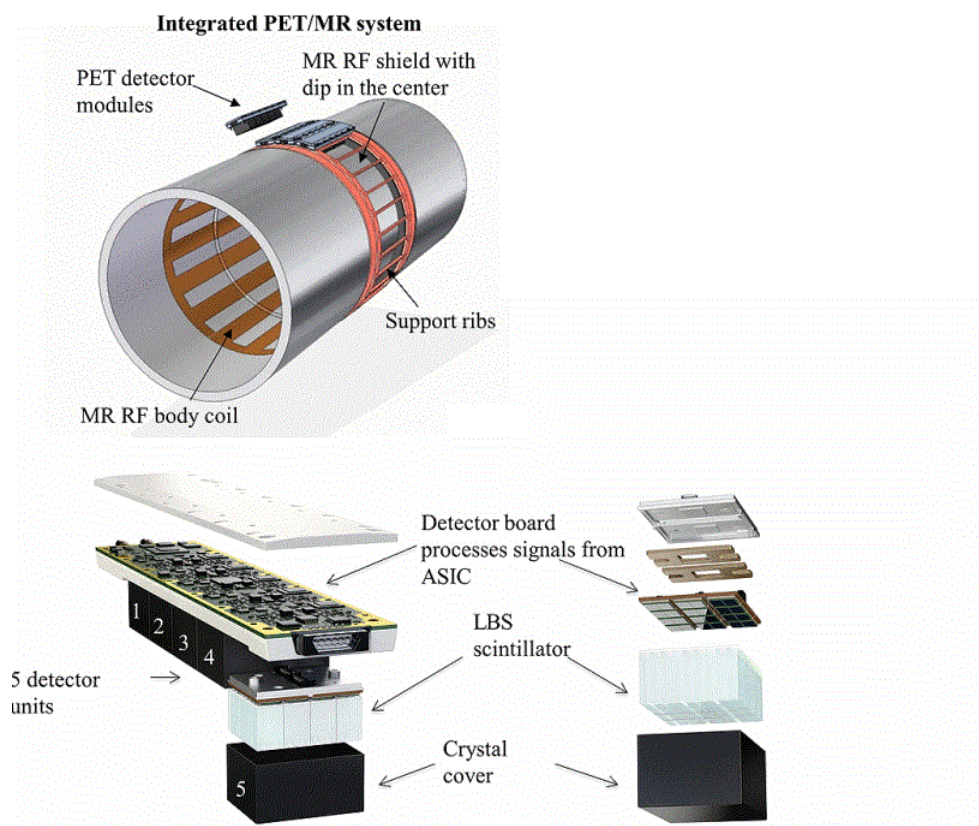


Figure 1.6: Schematic of the GE Signa hybrid PET-MR system, comprising of detector module units (bottom) in a ring formation within the MR RF body coil (top) [48].

1.5 Whole Body PET: Static Imaging

For many clinical applications, as for example in oncology, PET imaging over the whole body is essential for the detection and characterisation of primary and metastatic disease. Developments in PET detectors technology and reduction of production costs have resulted in increasing axial length of PET scanners using additional detector rings, with currently widespread clinical models offering between 15 to 26 cm of axial coverage [4]. In practice for static imaging whole-body coverage is achieved using multiple bed positions. The first suggestion and optimization work in extending the effective A-FOV of PET scans using multiple bed positions was made by Dahlbom *et al.* [25]. This work was made on PET systems operated in 2D mode, where a bed displacement of approximately equal to the system's A-FOV was used to increase the acquisition's effective A-FOV. As systems became capable of acquiring in 3D mode, offering increased sensitivity but resulting in axial varying sensitivity profiles, different strategies were needed for multi-bed acquisitions. The two methods suggested and developed are the *Step and Shoot* (SS) [5] and the *Continuous Bed Motion* (CBM) [6] acquisition methods.

1.5.1 Step and Shoot

The SS method makes use of multiple bed positions that are partially overlapped in the axial direction to increase the sensitivity of the acquisition at the edges of adjacent beds, by combining data of adjacent beds over the overlapping region as shown in figure 1.7. One way of combining the multi-bed datasets is to reconstruct each bed individually, displace the reconstructed images according to their axial location and combine them using weighted averaging [5]. This method has prevailed in clinical PET systems that use the SS acquisition method, as it does not require additional considerations in the reconstruction process of each bed and the combination of bed images can be performed post-reconstruction. Alternatively, the axial displacement of each bed raw dataset can be performed during the projection and back-projection process in iterative reconstruction, which then directly results in the reconstruction of the whole-body image [50]. Use of the overlap data in iterative reconstruction can potentially result in improved noise characteristics at the overlapping regions, as the full sampled statistics over these regions are combined prior to each image update [50, 51]. The axial sensitivity profile for the Signa PET-MR system is shown in figure 1.7. The system makes use of all (44) ring differences in the acquisition and reconstructions, which results in the shown axial sensitivity profile. Using this profile, multi-bed acquisition resulting in a uniform axial sensitivity profile requires overlap of 44 slices ($\sim 50\%$ of A-FOV). The amount of overlap used depends on the needs for uniformity in axial sensitivity and reconstructed image noise. This in term will also depend on the used reconstruction type and the activity distribution of the imaged subject [5]. For standard clinical scanning at the Signa PET-MR an overlap of $\sim 27\%$ is used by default, to balance between sensitivity uniformity and

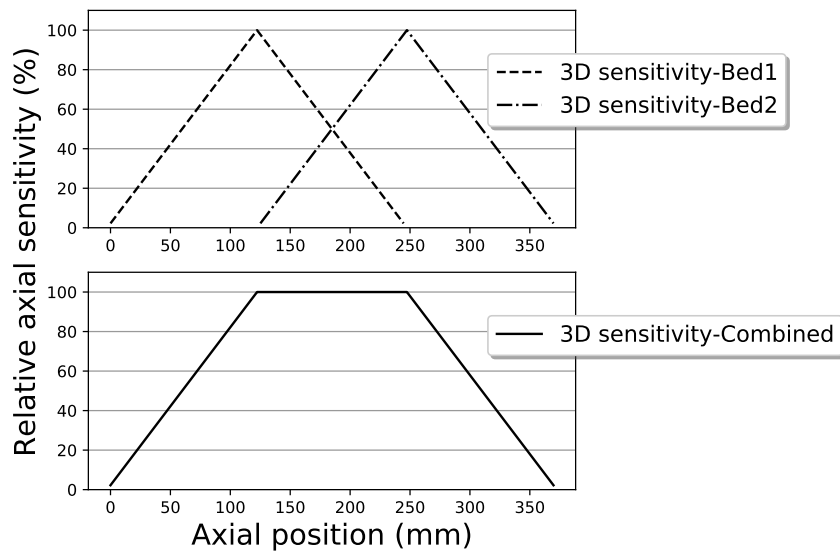


Figure 1.7: Relative axial sensitivity of individual beds (top) and combined sensitivity profile (bottom) for approximately 50% overlap for the Signa PET/MR.

examination time for standard WB examinations. The trade-off is made between the effective A-FOV and the total acquisition time, with the latest being of practical importance for patient comfort and high throughput. In addition, the acquisition time per bed is also an important parameter that affects this trade-off. For example, newer and higher sensitivity scanners can enable shorter scanning per bed for the same image quality, which allows for increased overlapping and improved axial sensitivity uniformity at the same total scan time. Examples of three overlapping options and the provided coverage for the Signa PET/MR are shown in figure 1.8 and 1.9 figure respectively. Many clinical WB protocols actually require imaging of approximately half the length of the body, from head to thighs, which can be accommodated with 5 or 6 bed positions on the Signa PET/MR. When full body coverage is required the number of beds is increased to 9 or 10.

1.5.2 Continuous Bed Motion

Continuous Bed Motion was proposed as an extension of step and shoot acquisition performed with small steps, to provide uniform axial sensitivity profiles [52, 53]. In clinical CBM acquisition protocols, the bed positional information is stored in list-mode during the examination and the data are sorted after or during the examination in histograms or sinograms (referred as "chunks") before reconstruction. The velocity of the bed movement can be adjusted depending on the amount of desired collected statistics, similar to the acquisition time per bed in SS acquisitions. In recent systems, the bed velocity can also be varied within an examination according to the needs and distribution of the imaged activity [6]. Beyond the potential technical gains, CBM protocols have also been shown to aid in patient comfort during examination [54].

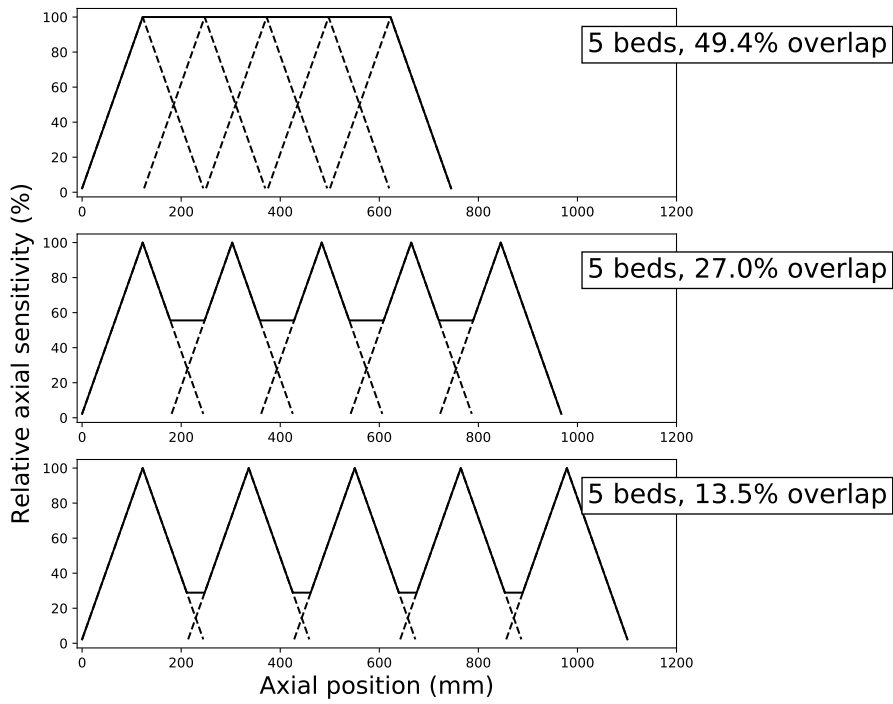


Figure 1.8: Relative axial sensitivity of 5 bed positions with decreasing overlap for the Signa PET/MR.

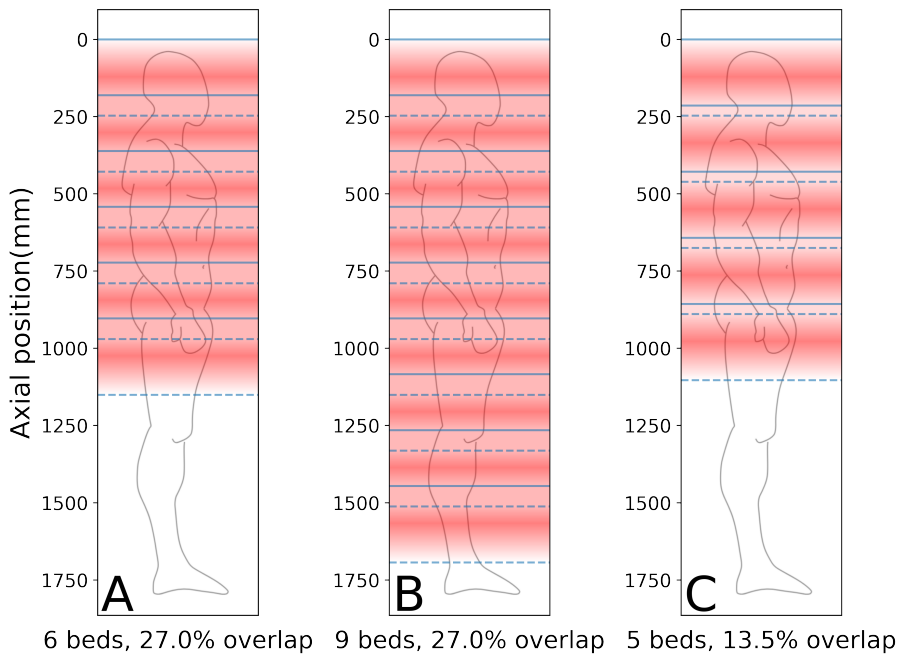


Figure 1.9: Combinations of overlap and number of bed positions for static (A&B) and dynamic whole-body imaging(C). Relative axial sensitivity is shown in shades of red, with bed start (——) and end (-----) positions.

1.6 Whole Body PET: Dynamic Imaging

As outlined in the introduction, clinical and research applications can benefit from DWB PET information. In clinical applications, DWB data can be used to construct fully quantitative parametric images for diagnosis and response monitoring of disease and pathology over the whole body. In research, DWB information can enable studying of the whole body organism and interactions between different tissues, organs or compartments [2, 20].

Although recent advancements in PET have led to the development of PET/CT systems with increased A-FOV, with approximately half [14, 15] or even total-body axial coverage [16], the majority of clinical PET systems in use are limited in the range from 15 to 26 cm [4]. Based on the same principles and methods used in static WB PET imaging, DWB protocols have been developed with the use of repeating whole-body passes (often referred to as "sweeps"). These protocols can be implemented using SS acquisition, as proposed in the original work on multi-bed DWB protocols by Karakatsanis *et al.* [7, 8], or as later proposed using CBM [17, 55]. Such protocols are nowadays implemented in commercial PET/CT systems [17] and it has been shown that their use in clinical practice is feasible [56, 57]. Their uses in clinical imaging is an ongoing active area of research.

The transition from single-bed to multi-bed dynamic acquisition poses some considerable limitations in acquisition counts and sampling frequency. The immediate effect of the transition is the introduction of temporal gaps in the acquired data of any given bed position. These are introduced at each bed position by the time spent on imaging other bed positions and by scanner system delays due to the time required to move the bed to the next position and prepare for the next acquisition. These gaps cause a significant reduction in the sensitivity of the acquisition, with fewer total counts collected for each axial location when compared to single bed dynamic acquisitions. Furthermore, estimation of fast temporal changes in tracer uptake is compromised as the early time points of the acquisition are not fully sampled for all beds. Finally, the established clinical protocols that make use of image derived input function (IDIF) to ease integration in clinical practice further sacrifice imaging time in the study's early phase, which is spent in acquiring fast frames over a single bed location, during a Dynamic Single Bed (DSB) phase, centred over the heart and the aorta [8, 17]. These limitations pose considerable problems on consequent parameter estimation and to a greater extent in parametric imaging performed using data from these protocols over the whole-body. These issues are addressed further in **Part II** of this thesis manuscript.

1.7 Advancements on extended A-FOV PET systems

Longer axial coverage has been a desirable characteristic for PET imaging systems, but limitations in technology and costs made it possible only during recent years. As described in recent review articles, earlier attempts to make scanners beyond the 15-26 cm of A-FOV were successful but at the time only for prototypes and limited by cost and hardware capabilities [4, 58]. Recently the EXPLORER consortium led to the development of scanners with 70 cm and 194 cm A-FOV [14, 59]. The adopted term for scanners that can encompass the whole-body is *Total-body* (TB) PET. More recently, a 106cm A-FOV PET-CT scanner was made commercially available by Siemens [15].

The increase in A-FOV offers many potential benefits for clinical and research applications [20]. Many of the direct clinical applications of such systems are envisioned for standard of care imaging using considerably lesser injected activity, improved image quality and detection limits of lesions, faster throughput etc. Early imaging applications have shown considerable potential towards these aspirations [60, 61]. Beyond standard of care, many research opportunities arise from the availability of high sensitivity combined with synchronous imaging of the whole body. Particular for dynamic imaging over the whole-body early applications have shown the feasibility of whole-body parametric imaging [62–64], study of fast kinetics including joint estimations of input function [65, 66] as well as whole-body parametric imaging with much lesser injected activity [67]. Comparisons on methodology and challenges for DWB imaging using regular scanners and extended A-FOV scanners are discussed further in the discussion and conclusion sections of this manuscript.

Chapter 2

Pharmacokinetics

PET makes use of positron-emitting radionuclides for the study of biochemical and physiological processes *in vivo*. The molecules of interest for the processes under study are labelled with a radionuclide and then introduced in the body. The PET imaging system provides information about the distribution of the labelled molecules *in vivo* over time and can be used to deduce information about the underlying process kinetics.

2.1 Principles of pharmacokinetic modelling

Pharmacokinetics refers to the study of absorption, distribution, metabolism and excretion of drugs in living systems. The study of pharmacokinetics is based on measurements of the concentration of drugs and their metabolites in tissues over time. Pharmacokinetic models describe the transport and binding rates of tracer from local concentration differences across boundaries, that can be either physical (such as a membrane or an organ outline) or conceptual boundaries as for example between bound and unbound tracer. These boundaries define separate compartments with distinct activity concentration which form the basis of pharmacokinetic models, also referred to as compartmental models.

The three key assumptions underlying compartmental modelling are:

- The concentration of the PET tracer is not high enough to influence the physiological processes and endogenous molecular interactions under study.
- That all physiological processes and interactions are in constant state for the duration of the PET study.
- The assumption that tracer concentration is instantly uniform in all compartments of the model.

By common convention in pharmacokinetic modelling, the first compartment is the arterial plasma pool from where the tracer distributes to tissues. The concentration of tracer in the arterial plasma $C_P(t)$ over time t is measured or deduced from population studies and applied to the model, as an input function that powers the system. If the tracer is metabolised during the study, this process needs to be modelled using metabolite measurements. Only the concentration of parent tracer can be used as input function in quantitative analysis of the tracer kinetics. By convention in dynamic PET studies conducted under a single session, the time point $t_0 = 0$ is set to be the tracer injection time.

Compartmental models behave according to a set of first-order ordinary differential equations, which means that the change of concentration in one compartment is a linear function of the concentrations of all compartments. This linearity establishes that the measured tissue activity concentration will be the convolution of the input function with the impulse response function (IRF) of the system, which is described by the compartmental model and its parameters. As such the tissue activity concentration $C_T(t)$ can be modelled as

$$C_T(t) = C_P(t) * \text{IRF}(t), \quad (2.1)$$

where $*$ is the convolution operator. In this thesis, the convolution operation always denotes convolution in the time domain, from 0 to infinity with

$$C_P(t) * \text{IRF}(t) = \int_0^\infty C_P(\tau) \text{IRF}(t - \tau) d\tau. \quad (2.2)$$

When a measurement of activity concentration is made with PET, the measurement will include the underlying tissue activity and activity from the intravascular blood in this tissue. The proportion of tissue volume occupied by intravascular blood V_B is commonly referred to as blood fraction. The measured activity concentration C_{PET} can be expressed as

$$C_{PET}(t) = (1 - V_B)C_T(t) + V_B C_B(t), \quad (2.3)$$

where C_B is the total blood activity concentration. Measurements of the arterial plasma to total blood ratio can be made to relate between $C_B(t)$ and $C_P(t)$. For the tracers of interest in this PhD project, the ratio of the two concentrations is assumed to be constant with time and to be $C_B(t) = rC_P(t)$.

2.2 One-tissue compartment model

As the simplest model the one-tissue compartment model (1TCM) can be described using two constant rates for the input and output of tracer from the tissue, K_1 and k_2 respectively, as seen in figure 2.1.

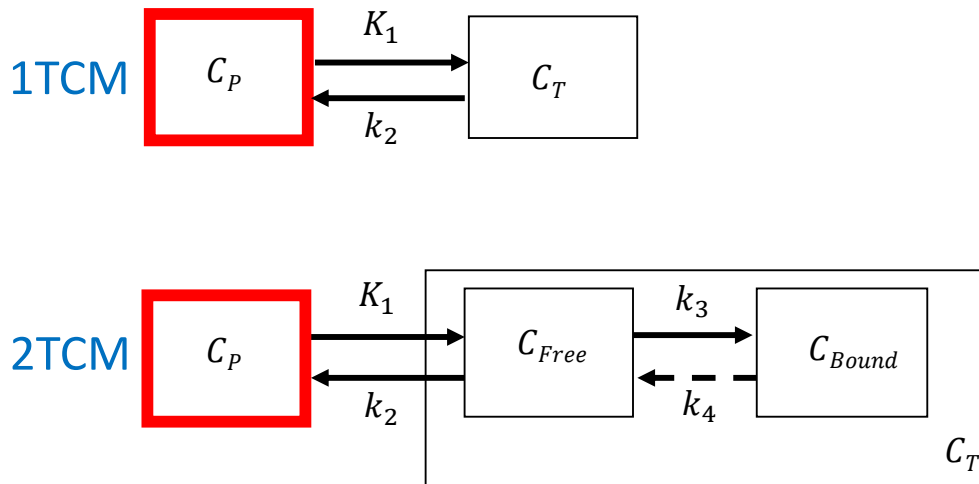


Figure 2.1: Representation of compartments and exchanges rates for 1TCM (top) and 2TCM (bottom)

The rate of change of the activity concentration in tissue C_T will depend on the metabolite corrected arterial plasma input function C_P and the activity concentration in tissue, described by the differential equation

$$\frac{dC_T(t)}{dt} = K_1 C_P(t) - k_2 C_T(t). \quad (2.4)$$

By applying the Laplace transform on equation 2.4, we have

$$s\bar{C}_T - C_T(0) = K_1 \bar{C}_P - k_2 \bar{C}_T, \quad (2.5)$$

where \bar{C}_T and \bar{C}_P are the transforms of C_T and C_P respectively. With $C_T(0) = 0$, this relationship can be solved for \bar{C}_T providing

$$\bar{C}_T = \frac{K_1}{s + k_2} \bar{C}_P. \quad (2.6)$$

The inverse transform of equation 2.6 provides

$$C_T(t) = K_1 e^{-k_2 t} * C_P(t). \quad (2.7)$$

Equation 2.7 is the solution of the differential equation 2.4, which becomes equation 2.8 for the PET measurement that includes the fractional blood volume.

$$C_{PET}(t) = (K_1 e^{-k_2 t} * C_P(t)) (1 - V_B) + C_B(t) V_B \quad (2.8)$$

2.3 Two-tissue compartment model

The two-tissue compartment model (2TCM) is a commonly used model as it describes the behaviour of ^{18}F -Fluorodeoxyglucose (^{18}F -FDG), which is commonly used tracer in clinical and research PET protocols. The separation into two tissue compartments is made to distinguish between free and trapped (bound) tracer, represented as $C_{Free}(t)$ and $C_{Bound}(t)$ respectively, with the trapping caused by the tracer being metabolised in the cells by mitochondria. The set of differential equations describing the 2TCM is shown in equations 2.9.

$$\frac{d}{dt}C_{Free}(t) = K_1C_P(t) - (k_2 + k_3)C_{Free}(t) + k_4C_{Bound}(t) \quad (2.9a)$$

$$\frac{d}{dt}C_{Bound}(t) = k_3C_{Free}(t) - k_4C_{Bound}(t) \quad (2.9b)$$

The pathway of tracer from the trapped to the free state, via the process of dephosphorylation, is commonly considered negligible for the duration of common PET studies. With the assumption of $k_4 = 0$ the two differential equations in 2.9 simplify to the system 2.10.

$$\frac{d}{dt}C_{Free}(t) = K_1C_P(t) - (k_2 + k_3)C_{Free}(t) \quad (2.10a)$$

$$\frac{d}{dt}C_{Bound}(t) = k_3C_{Free}(t) \quad (2.10b)$$

Similarly to the 1TCM, the Laplace transform can be used to solve this system and result in equation 2.11.

$$C_T(t) = C_{Free}(t) + C_{Bound}(t) = K_1 \left(e^{-(k_2+k_3)t} + \frac{k_3}{k_2 + k_3} (1 - e^{-(k_2+k_3)t}) \right) * C_P(t) \quad (2.11)$$

The parameters K_1 , k_2 and k_3 , which are referred to as micro-parameters, can be estimated by fitting equation 2.11 on measured Time Activity Curve (TAC) data. A parameter of interest for clinical studies is the influx rate constant K_i , given by equation 2.12. This is considered as a macro-parameter of the system and can be understood as the proportion of flux K_1 that results in trapped tracer.

$$K_i = \frac{K_1 k_3}{k_2 + k_3}. \quad (2.12)$$

The influx of FDG is proportional to the influx of glucose, also referred as the glucose metabolic rate MR_{glu} . The proportionality constant is called the lumped constant LC and along with the concentration of blood glucose C_P^{glu} can be used to express

$$\text{MR}_{glu} = K_i \left(\frac{C_P^{glu}}{LC} \right) \quad (2.13)$$

2.4 Gjedde-Patlak linearisation method

Direction estimation of model micro-parameters, such as those of equation 2.11, requires non-linear fitting optimization procedures. These are commonly time consuming and their estimations are heavily susceptible to noise. For parametric imaging, where the model estimation has to be performed for every voxel of the image, estimation of micro-parameters is commonly avoided due to the poor statistics and high noise associated with TAC measurements at the voxel level. Linearisation methods allow for transformation of the measured data, to enable use of linear least-square fitting procedures for estimation of model macro-parameters, under certain assumptions. Furthermore, these methods reduce the number of parameters to be estimated, thus reducing the variability of estimates and sensitivity to noise.

With the assumption of irreversible tracer behaviour the Gjedde-Patlak method has been developed, described by Gjedde [68] and Patlak *et al.* [69]. The proposed transformation is

$$\frac{C_T(t)}{C_P(t)} = K_i \frac{\int_0^t C_P(\tau) d\tau}{C_P(t)} + V_\alpha, \quad t > t_{ss}, \quad (2.14)$$

where K_i is the steady state trapping rate and V_α the apparent volume of distribution. An example of the transformation applied on a 2TCM TAC is shown in figure 2.2.

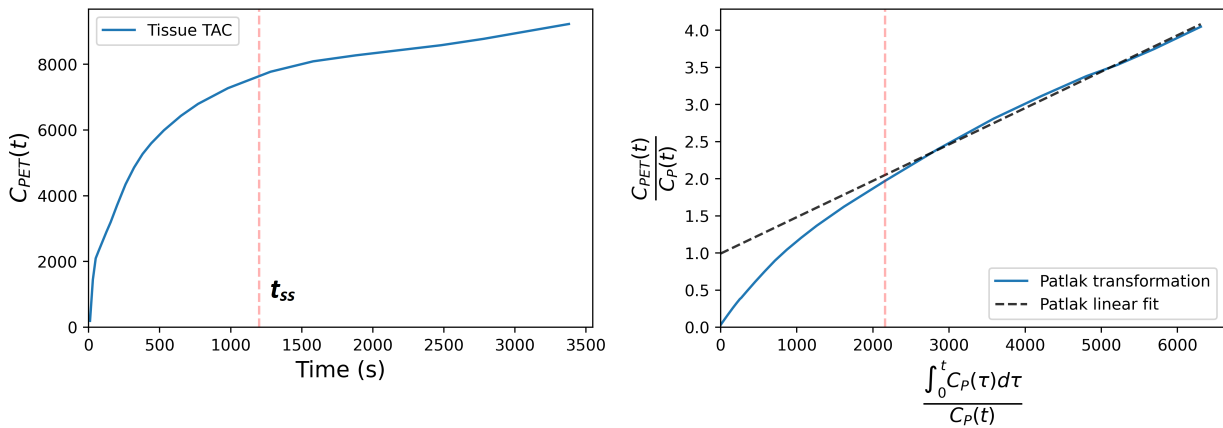


Figure 2.2: 2TCM example TAC (left) and its Patlak transformation and linear fit (right)

The transformation is valid for time points t after steady state conditions are achieved at time t_{ss} , as shown in the example plot above. Steady state conditions are achieved when the reversible compartments are in steady-state equilibrium with the plasma blood compartment.

The Gjedde-Patlak linearisation method, referred to simpler as *Patlak model*, is commonly used with the 2TCM model for FDG, under the assumption of $k_4 = 0$. In this case, the Patlak model parameters can be

related to micro-parameters using equation 2.12 and

$$V_\alpha = \frac{K_1 k_2}{(k_2 + k_3)^2}. \quad (2.15)$$

With the assumption of $C_B(t) = rC_P(t)$, we can substitute equation 2.14 into equation 2.3 and describe the observed activity $C_{PET}(t)$ using the Patlak model as

$$\frac{C_{PET}(t)}{C_P(t)} = \underbrace{(1 - V_B)K_i}_{\theta_1} \frac{\int_0^t C_P(\tau) d\tau}{C_P(t)} + \underbrace{(V_\alpha(1 - V_B) + rV_B)}_{\theta_2}, \quad (2.16)$$

where the Patlak slope θ_1 and the Patlak intercept θ_2 are the model parameters that can be estimated from TAC measurements of $C_{PET}(t)$. A limitation in the use of the Patlak model using equation 2.16 is that V_B is not necessarily known a priori and Patlak analysis can not distinguish between K_i and $(1 - V_B)$. In many applications, V_B is assumed to be small (≤ 0.05) and neglected, but it can be a cause for systematic errors. In the applications of the Patlak model in this project, we will refer to the slope θ_1 as the Patlak K_i value, which is the value of interest that is commonly used in practice with Patlak analysis.

2.5 Spectral analysis method

The Spectral analysis method was originally introduced by Cunningham et al. [70]. The method is based on the general form of the solutions of compartmental models and describes the generic behaviour of any compartmental system as a positively weighted sum of decaying exponential functions with decay rates β which describe the exchange between compartments, convolved with an input function.

The spectral analysis model for $C_T(t)$ can be expressed using M functions as

$$C_T(t) = \sum_{b=0}^{M-1} \phi_b e^{-\beta_b t} * C_P(t), \quad (2.17)$$

where ϕ_b are the model coefficients (constrained to positive values) for the exponential functions with decay rates β_b that describe the exchange between compartments.

The advantage of this methodology is that it can be used to fit on TAC data, with few assumptions on the underlying kinetics. Additionally, it can be used to deduce information of the underlying kinetics using the basis pursuit strategy proposed by Gunn *et al.* [71]. Macro-parameters of the underlying model can also be deduced using the spectral analysis fitted model. Tracer delivery to tissue K_1 can be estimated directly with

$$K_1 = \sum_{b=0}^{M-1} \phi_b. \quad (2.18)$$

For reversible kinetics, the parameters can be used to deduce the volume of distribution V_D as

$$V_D = \sum_{b=0}^{M-1} \frac{\phi_b}{\beta_b}. \quad (2.19)$$

For irreversible kinetics, a parameter of the model is used to account for the trapping rate K_i . In this work we use parameter ϕ_0 to describe irreversible trapping, with its respective exponential decay rate set to zero $\beta_0 = 0$. With this assumption the model becomes

$$C_T(t) = \phi_0 * C_P(t) + \sum_{b=1}^{M-1} \phi_b e^{-\beta_b t} * C_P(t), \quad (2.20)$$

for which $K_i = \phi_0$.

Finally, to model the observed activity $C_{PET}(t)$ using the spectral analysis model, we can substitute equation 2.17 into equation 2.3 and assume again that $C_B(t) = rC_P(t)$ to get

$$C_{PET}(t) = (1 - V_B) \sum_{b=0}^{M-1} \phi_b e^{-\beta_b t} * C_P(t) + rV_B C_P(t). \quad (2.21)$$

If we account for the parameter $(1 - V_B)$ into the weights ϕ_b , the equation can be written in short as

$$C_{PET}(t) = \sum_{b=0}^M \phi_b e^{-\beta_b t} * C_P(t), \quad (2.22)$$

for which $\beta_M \rightarrow \infty$ and $\phi_M = rV_B$. When fitted on measured $C_{PET}(t)$ data, the spectral model in equation 2.22 can be used to deduce K_1 , and either V_D or K_i respectively for reversible or irreversible tracers behaviour, using

$$K_1 = \frac{\sum_{b=0}^{M-1} \phi_b}{1 - V_B} \quad (2.23a)$$

$$V_D = \sum_{b=0}^{M-1} \frac{\phi_b}{\beta_b (1 - V_B)} \quad (2.23b)$$

$$K_i = \frac{\phi_0}{1 - V_B}. \quad (2.23c)$$

2.5.1 Choice of spectral rates

On equation 2.22 the spectral rates $\beta_1 \dots \beta_{M-1}$ are used to describe the exchange between compartments. These are set to cover the range of expected underlying kinetics and are commonly logarithmically spaced within that range [71]. As a rule of thumb, the lower limit of the range can be set to $\beta_1 = 1/(3T_{end})$ where T_{end} is the total time of the PET study, and the upper limit of the range can be set to $\beta_{M-1} = 3/T_{in}$ where T_{in} is the duration of the first frame of the study [72].

In spectral analysis, the number of the spectral parameters used is empirically set in the 10^2 order of magnitude. This relatively large number allows for clear separation of the underlying exchange rates, for deduction of models of the underlying behaviour. For use with dynamic reconstruction a smaller number of parameters is used, ideally less than the number of time bins (frames) of the data, which is still adequate to model the PET measurements while maintaining low image noise.

2.6 IsotoPK pharmacological study

Traditionally it has been assumed that passive diffusion is the main mechanism controlling drug delivery to tissues. But it is now recognised that the presence of membrane transporters at blood-tissue interfaces suggests that transporters also play an important role in drug pharmacokinetics. DWB imaging studies can play an important role in the study of transporter distribution and function in regards to drug delivery to tissues over the body [73]. To this purpose, a novel PET tracer has been developed using Glyburide (glibenclamide, GLB) labelled with ^{11}C . Glyburide is a drug used for treatment of diabetes and targets many transporters of the Solute Carrier O (SLCO) family [74, 75]. Preliminary pre-clinical studies have indicated that these transporters are expressed mainly in the liver and the kidneys [74].

A first in man study, named *IsotoPK*, was designed and is being conducted in our centre for the study of the distribution of these transporters in healthy volunteers [10]. The study is conducted on the Signa PET/MR, using a Dynamic Whole Body (DWB) acquisition protocol, with two acquisitions per volunteer to study the distribution without and with the administration of an inhibitor substance prior to PET imaging. Arterial blood samples for deduction of an input function and metabolite analysis are collected manually during the duration of each scan.

Data from this study are presented in chapter 7, showing examples of distribution of the tracer on an example volunteer. The use of the data in this project was made with a focus on methodological aspects for whole-body parametric imaging, but the developed methodology will be used in the future after all volunteer data have been collected to evaluate its findings. Initial results on three volunteers have shown that Glyburide

is very slowly metabolised and therefore did not require metabolites to be accounted for in PET analysis, since their impact on PET quantification would be minimal. Findings also showed strong binding of tracer with plasma ($\geq 90\%$). Predominant uptake of the tracer was seen in the liver and also the kidneys. Lower uptake was observed in the spleen, the aorta wall and the pancreas. At all other tissues, no strong tracer uptake was seen. Data coming from this protocol were used in this thesis. The IsotoPK study was the first DWB protocol to be conducted on the Signa PET/MR.

2.6.1 PET analysis in the liver

One of the unique characteristics of the liver, in regards to pharmacokinetic modelling, is that it is supplied with blood via two routes. The hepatic artery (HA) accounts for approximately 25% of the blood supply in the liver, while the portal vein (PV) accounts for the rest 75% [76]. The portal vein delivers blood that has been filtered mainly by the gastrointestinal tract, a process that alters the characteristics of the portal vein input function. Studies on pigs and non-invasive studies on humans have produced methods to model the PV input function as a dispersion of the arterial input function [77], which can be modelled using

$$C_{PV}(t) = k_g e^{-k_g t} * C_P(t). \quad (2.24)$$

With knowledge of the k_g dispersion value and ratio between PV and HA input, the liver input function $C_H(t)$ can be then modelled as

$$C_H(t) = 0.75 \cdot C_{PV}(t) + 0.25 \cdot C_P(t). \quad (2.25)$$

An toy example demonstration of the two components of $C_H(t)$ is shown in figure 2.3.

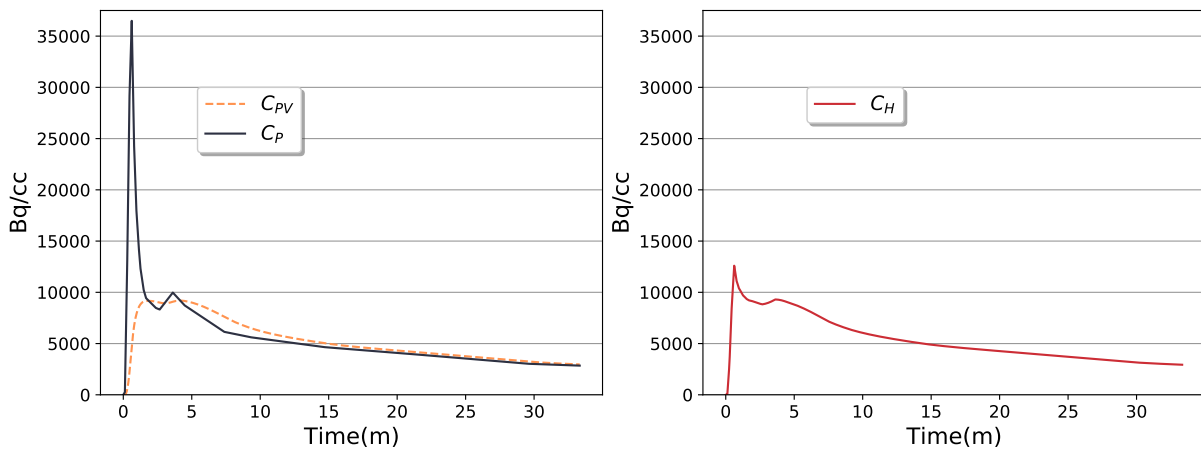


Figure 2.3: Example measured arterial input function $C_P(t)$ and modelled PV input function (using $k_g=0.5 \text{ min}^{-1}$ [77]) (left). Combination of arterial and PV input function to provide $C_H(t)$, assuming a 25/75 ratio (right).

The use of imaging information for non-invasive estimation of the portal vein input function and their effects in pharmacokinetic model estimates over the liver is an active area of research [78–80] with no standardised and widely accepted practices established yet. Further interest and research into DWB imaging is expected to address these issues for accurate WB parametric imaging that accurately accounts for the linear dual input model.

Chapter 3

PET image reconstruction

Image reconstruction is necessary to produce images of activity distribution from the acquired tomographic measurements. Reconstruction algorithms used for this process can be categorised as either analytical or statistical reconstruction methods. Analytical reconstruction methods seek to invert the transformation that links the image to the data domain, using linear analytic approaches. These methods treat the measured LOR data as line integrals over image space and necessitate corrections to be applied on projection data prior to reconstruction, in order to result in valid and quantitatively accurate images. Traditionally the most commonly used analytical reconstruction method is *Filtered Back Projection* which is described very briefly in this chapter. Statistical reconstruction methods are derived from statistical formulations of the detection process and allow for the use of complex system models that include various effects of the acquisition process. These methods result in non-linear formulations of the reconstruction problem which require iterative optimisation methods to reach a solution. The solution sought is a set of image parameters (that describe the activity distribution) that best describes the acquired tomographic data. In this thesis project, we made exclusive use of statistical reconstruction methods due to their ability to incorporate complex system models, including the use of dynamic models which was crucial for the aims of this thesis.

3.1 Projection and back-projection process

Coincidence detection of annihilation photons in PET leads naturally to a line-integral model where the number of coincidence events of an LOR is approximately linearly proportional to the integral of tracer density along the volume joining the two detectors. The projection process can be written as

$$\mathbf{y} = \text{proj}\{\boldsymbol{\lambda}\}, \quad (3.1)$$

where λ is the continuous distribution of radiotracer and y the continuous projection data (or else sinogram data). The 2D projection operation is also known as the Radon transform [81, 82] and translates from the image to the projection data domain. Projections in 3D can be made using the X-ray transform or extension of the Radon transform [37]. The projection's dual operation is back-projection, which translates from the data domain to the image domain.

3.1.1 Image representation

In practice, the spatio-temporal radiotracer distribution is described using a model with a finite number of parameters. The most common choice in common practice is the use of equally sized non-overlapping voxels that cover the useful FOV. Their use can also extend to the temporal domain with a set of voxels describing the FOV for each non overlapping temporal bin. In this case, the sets of voxels per temporal bin are considered temporally independent. If for a moment we consider only the spatial domain and static imaging, we can model the spatial radiotracer distribution λ with an n_j number of voxels of intensity λ_j . For the linear model case, the set of functions describing the distribution are referred to as *spatial basis functions*. From here on we will be using the λ symbol to refer to the n_j dimension vector of λ_j voxel weights that describe the spatial activity distribution as

$$\lambda = \{\lambda_j | j = 1, \dots, n_j\}. \quad (3.2)$$

If we now consider the temporal domain of the activity distribution as well, we can define a set of n_t independent temporal bins (frames). Later in this chapter, we will show how dynamic models can be used to describe the behaviour of voxel values across the temporal domain, but traditional reconstruction treats frames as independent static datasets. In this case, the activity distribution of each frame t can be written as

$$\lambda_t = \{\lambda_{tj} | j = 1, \dots, n_j\}. \quad (3.3)$$

3.1.2 Projection & Analytical reconstruction

Forward projection of image to data space can be treated by summing contributions of voxels across each LOR. The geometrical projection matrix X can be defined, with elements X_{ij} to describe the contribution of each voxel j in each LOR bin i . As the projection is a computationally costly process in practice, different methods have been proposed that balance between accuracy and consistency and computing requirements. Some of these methods, which are also implemented in the CASToR reconstruction software, are listed below with a short description.

- **Siddon projector** [83]: Weights the contribution of a voxel to a given LOR by the length of the LOR that intersects the voxel.
- **Distance driven** [84]: An optimised method for calculating weights by mapping pixel boundaries and detector boundaries for each projection to a common axis .
- **Joseph** [85]: Estimates contribution of voxels to LOR based on linear interpolation and their distance from the LOR.
- **Multi-Siddon** [86]: Uses multiple lines from the faces of the detectors in each LOR to approximate the volume intersected between the two detectors and the voxel.

Similarly, back-projectors using the same methods operation assign to voxels in the FOV the contribution from each LOR bin. Analytical reconstruction methods seek to estimate an image by inversion of the forward-projection process, by accounting for contributions from all LORs in image space. This results in analytical algorithms, including the most widely used algorithm of *Filtered Back Projection* (FBP). But while analytical reconstructions are linear processes and computationally fast, accuracy is limited by the simplistic assumptions of the line integral model, ignoring many degrading effects such as positron range, variations in response across LORs etc. In addition, these methods do not account for the statistical properties of the detection process in the data. Finally, the FBP algorithm seeks to solve an ill-posed problem meaning that small changes in the data can result in largely disproportional effects on the reconstructed image. As the projection data include stochastic noise from the detection process, without regularisation the reconstruction suffers from artefacts. In practice, smooth low pass filters like the Hann apodization filter are applied in the reconstruction process to reduce the strength of these artefacts at the cost of degraded spatial resolution. The sub-optimal trade-off between strength of artefacts and spatial resolution can be adjusted by changing the filter's cut-off frequency.

3.2 Formulation of the system model

The analytical reconstruction methods are based on the idealised description of the scanning process using the line integral model. But in fact, there are many effects that should ideally be considered in the scanning system model. For example the statistical nature of the detection process, positron range and detection resolution effects, the detection of scattered and random events as well as the discrete nature of the detection and scanner geometries that do not result in complete sampling. But as the scanning model complexity is increased, analytic expressions that seek to inverse the scanning process are not feasible. For this reason, iterative algorithms are employed, which seek a solution by optimising an objective function that expresses some distance between the measured data and the modelled data from an image estimate.

We can define the system model using an $n_i \times n_j$ system matrix P . Each element P_{ij} of the matrix is the probability of detection by voxel j to data bin i . As discussed, many effects can be included in this matrix elements which will be outlined below. By contrast, scatter effects can be hard to implement in the system matrix and random effects are non-linear effects that cannot be modelled linearly. As such the scatter and random events are considered to be known for each detector bin and included as an additive background b_i for each data bin i in the system model.

The model of the data at bin i from an image λ can be written as a sum over voxels of the probability of detection in this bin

$$\hat{y}_i = \sum_{j=1}^{n_j} P_{ij} \lambda_j + b_i, \quad (3.4)$$

where \hat{y}_i is the modelled data mean.

The system matrix can be decomposed to the individual contributing components as separate sparse matrices and vectors

$$\hat{y}_i = n_i a_i \sum_{j=1}^{n_j} X_{ij} \sum_{k=1}^{n_j} H_{jk} \lambda_k + b_i, \quad (3.5)$$

where

- n_i are the normalisation factors for each LOR bin
- a_i are the attenuation factors for each LOR bin
- X_{ij} is the geometrical projection matrix entry
- H_{jk} is the resolution modelling matrix entry, applied as a convolution in image space to account for different effects impacting resolution (positron range, detector size, etc.)
- b_i the background events for each LOR bin.

Resolution modelling can be applied on both data and image space of the system model, but in practice is applied on one of the two domains [87]. In the CASToR reconstruction software that was used in this project, resolution modelling is implemented in image space as written in the above expression.

If Time of Flight (TOF) measurements are available, the additional information regarding the probability of the annihilation event along the LOR can be incorporated in the model. TOF weights are assumed to be independent of the other system matrix elements and thus act as an additional multiplication factor. Depending on the type of TOF information, the weights can either be quantized (for each TOF bin) or expressed as a continuous function. More details on both options and the implementation of TOF reconstruction can be found in the work of Filipović *et al.* [88].

3.3 Formulation of the objective function

We can consider the total number of events in each projection bin to be modelled as a random sample from a Poisson distribution. According to the probability mass function, the conditional probability or likelihood function for \hat{y}_i given the measured data y_i will be

$$p(y_i|\hat{y}_i) = L(\hat{y}_i|y_i) = e^{-\hat{y}_i} \frac{\hat{y}_i^{y_i}}{y_i!}. \quad (3.6)$$

With the assumption that measurements of counts in each bin are independent random processes, the likelihood of the data over all bins will be

$$p(\mathbf{y}|\hat{\mathbf{y}}) = L(\hat{\mathbf{y}}|\mathbf{y}) = \prod_i^{n_i} e^{-\hat{y}_i} \frac{\hat{y}_i^{y_i}}{y_i!}. \quad (3.7)$$

By substituting the system model equation 3.4 in equation 3.7, we can write an expression of likelihood of the image λ given the measured data \mathbf{y}

$$L(\lambda|\mathbf{y}) = \prod_i^{n_i} e^{-(\sum_{j=1}^{n_j} P_{ij}\lambda_j + b_i)} \frac{(\sum_{j=1}^{n_j} P_{ij}\lambda_j + b_i)^{y_i}}{y_i!}. \quad (3.8)$$

This expression can be used as the objective function in the optimisation process of seeking the most likely (ML) estimate of λ from a measurement \mathbf{y} . It is more convenient to take the expression of the log likelihood and since the log function is monotonic the log likelihood can be used to arrive to the same ML estimate.

The log likelihood expression is

$$\ln L(\lambda|\mathbf{y}) = \sum_{i=1}^{n_i} \left[y_i \ln \left(\sum_{j=1}^{n_j} P_{ij}\lambda_j + b_i \right) - \sum_{j=1}^{n_j} P_{ij}\lambda_j - b_i - \ln(y_i!) \right]. \quad (3.9)$$

3.4 Maximum Likelihood - Expectation Maximisation

Equation 3.9 of the Poisson log-likelihood will be used to arrive to the maximum likelihood estimate image λ , which will be noted as λ^{ML} , that maximises the likelihood of the modelled data given the measured data \mathbf{y}

$$\lambda^{ML} = \arg \max_{\lambda} (\ln L(\lambda|\mathbf{y})). \quad (3.10)$$

The second partial derivative of the log-likelihood to λ can be shown to be negative semidefinite to all allowed images and thus the log-likelihood function is a concave function. This means that a found local maximum

through the optimisation process will be the global maximum of the function.

Seeking to solve equation 3.9 to find analytically the maximum likelihood image λ^{ML} , using the Kuhn-Tucker conditions we arrive to its first partial derivative to λ_j and seek to solve by setting it to be equal to zero.

$$\frac{\partial \ln L(\lambda | \mathbf{y})}{\partial \lambda_j} = \sum_{i=1}^{n_i} \left[y_i \frac{\sum_{j=1}^{n_j} P_{ij}}{\sum_{j=1}^{n_j} P_{ij} \lambda_j + b_i} - \sum_{j=1}^{n_j} P_{ij} \right] = 0, \quad (3.11)$$

but this expression has no closed form solution. The arrival to this expression shows the need for iterative methods to seek the λ^{ML} solution.

The most common algorithm used for this problem is the Expectation Maximisation (EM) algorithm that was first applied on statistical PET reconstruction by two key works by Shepp and Vardi [89] and Lange and Carson [90]. In these works the solution is derived through the introduction of the "complete data" concept [91].

Let \mathbf{z} be the complete data random dataset of $x_{ij} + g_i$ values which describes the exact number of emissions from voxel j and the background data g_i that contribute to the measurement at projection bin i , with the many-to-one mapping $y_i = \sum_{j=1}^{n_j} x_{ij} + g_i$. The complete dataset is unknown, but the conditional expectation of the complete data can be expressed using an image estimate (a guess) noted as $\lambda^{(k)}$ and the measured data \mathbf{y} as

$$\hat{x}_{ij}(\lambda^{(k)}, y_i) = y_i \frac{P_{ij} \lambda_j^{(k)}}{\sum_{d=1}^{n_j} P_{id} \lambda_d^{(k)} + b_i}, \quad (3.12)$$

$$\hat{g}_i(\lambda^{(k)}, y_i) = y_i \frac{b_i}{\sum_{d=1}^{n_j} P_{id} \lambda_d^{(k)} + b_i}. \quad (3.13)$$

The complete dataset follows a Poisson distribution, with its log-likelihood being

$$\ln L(\lambda | \mathbf{z}) = \sum_{i=1}^{n_i} \left[\sum_{j=1}^{n_j} (x_{ij} \ln(P_{ij} \lambda_j) - P_{ij} \lambda_j) + g_i \ln(b_i) - b_i \right], \quad (3.14)$$

where parameters not related to its optimisation to λ have been dropped. If we replace the expectation of the complete data using equations 3.12 and 3.13 we can then seek to maximise this likelihood function to obtain the ML image estimate of the expected complete data. By using the first derivative of this expression and setting to zero we arrive at a closed form solution

$$\lambda_j^{(k+1)} = \frac{\lambda_j^{(k)}}{\sum_{i=1}^{n_i} P_{ij}} \sum_{i=1}^{n_i} P_{ij} \frac{y_i}{\sum_{d=1}^{n_j} P_{id} \lambda_d^{(k)} + b_i}, \quad (3.15)$$

that provides a new estimate $\lambda^{(k+1)}$. This single update equation combines the two steps of the optimisation

process. First, given an image estimate $\lambda^{(k)}$ the expectation of the complete data is estimated. Then, the log-likelihood of the expectation of the complete data is maximised. This iterative process results in monotonic increase of the original log-likelihood function. As the original log-likelihood is concave, the process will result in convergence to the global maximum. This process is the Maximum Likelihood Expectation Maximisation (MLEM) algorithm.

The use of the conditional expectation of the data is an example of the general concept of optimisation transfer, where the construction of surrogate functions is made to be used with a simpler optimisation process, that leads to optimisation of the main function as well. One advantage of this algorithm is that an update over all voxels of the image can be made with a single pass over the data. The disadvantage is that it results in very slow convergence speeds. To accelerate convergence the Ordered Subsets Expectation Maximisation (OSEM) algorithm is used in most practices, which makes use of subsets of the data at each update step (each subset) to reduce computing time for each image update.

3.5 Dynamic reconstruction

Soon after the proposition of the EM algorithm for iterative PET reconstruction by Shepp and Vardi [89] and Lange and Carson [90], the former group proposed an extension of the EM algorithm to update parameters of a dynamic model and a version of the update algorithm that iterates through the whole of dynamic PET data in each iteration [92]. Dynamic PET data are traditionally divided among many time bins (frames) resulting in limited counts in each frame. Independent reconstruction of each frame dataset and post-reconstruction kinetic modelling results in noisy and potentially biased parameter estimates. Furthermore, the noise in each frame image estimate is spatially correlated and is hard to be accounted for in the post-reconstruction modelling. The use of a dynamic reconstruction approach that updates over parameters using all the dynamic PET raw data offers the advantages of accurate noise modelling of the raw data and accurate system modelling directly in the process of the dynamic model parameter estimation. Unfortunately, one major disadvantage of this approach was very slow convergence properties making it difficult for use in practice and the topic was not researched further at that time [92].

More than 10 years later the approach was revisited by Matthews *et al* [93] where it was combined with linear models. As it will be shown in this chapter the MLEM algorithm can be easily extended to parametric space with the use of linear dynamic models. On their application, the benefits in reducing parametric image noise were seen, at the cost of very slow convergence speeds. For use with linear models, attempts to accelerate convergence were made by use of OSEM [94] and computing acceleration and compression techniques [95]. In the case of dynamic reconstruction with OSEM it was shown that the algorithm exhibits

the common OSEM problem of limit-cycles, for which a decreasing subsets scheme was used to eliminate this effect [96].

It was not until the work of two groups in 2010, Wang *et al* [97] and Matthews *et al* [98], that allowed for practical and more widespread use of dynamic reconstruction. Their methods, based on principles of optimisation transfer by Lange [99], decouple the dynamic reconstruction process to an EM update over all data and to a ML problem in image space. The first step iterates through the tomographic data and updates the activity estimate images, while the second step simply updates the dynamic model parameters using the updated activity images. With the second step being much faster, multiple dynamic model updates can be conducted for each update over data which results in acceleration of overall convergence. Results were demonstrated by Wang *et al* [97] for EM and Preconditioned Conjugate Gradient (PCG) based optimisations using linear models. While that work was limited to linear dynamic models, the work by Matthews *et al* [98] generalised on the optimisation of the image space ML problem by the use of an equivalence to a weighted least-square minimisation problem. This formulation allowed for use of existing Least Squares (LS) optimisation algorithms, that are commonly used for post-reconstruction model fitting, to be used in 4D reconstruction for linear and non-linear models. The disadvantage of this approach is that the resulting formulation is not strictly concave and thus does not guarantee monotonic convergence to a global maximum. Nevertheless, convergence behaviour has been observed in practice with different weighting schemes [100, 101].

The use of non-linear models within dynamic reconstruction has shown clear benefits in precision and accuracy [100, 102, 103] but are more sensitive to initialisation and reconstruction parameters and could lead to unpredictable behaviour.

3.5.1 Dynamic data and models

As described in chapter 2, dynamic data are used to seek parameters of kinetic models for the understanding of underlying molecular processes. Similarly to the image data, the projection data are binned temporally into y_{ti} for each projection bin i at frame t for a total number of number of n_t frames. The data of each frame can then be written as

$$\mathbf{y}_t = \{y_{ti} | i = 1, \dots, n_i\}. \quad (3.16)$$

Conventionally the data of each frame are reconstructed as individual static datasets and the resulting images are used for post-reconstruction modelling. When the parameters sought are calculated at the voxel level, the result is a set of parameters for each voxel in the FOV, which are referred to as parametric maps.

If we assume an example dynamic model that describes the dynamic behaviour of the radiotracer distribution

with n_p number of p parameters, then the set of parameters for each voxel j can be expressed as

$$\boldsymbol{\theta}_j = \{\theta_{pj} | p = 1, \dots, n_p\}. \quad (3.17)$$

These can be used to model the activity behaviour at each time frame t according to

$$\lambda_{tj} = f_t(\boldsymbol{\theta}_j), \quad (3.18)$$

where $f()$ is the function of the dynamic model that estimates radiotracer activity values over n_t time frames given a set of n_p model parameters. Assuming that the dynamic model is the same for all voxels in the image space, we can write for short

$$\boldsymbol{\lambda} = f(\boldsymbol{\theta}), \quad (3.19)$$

with the complete set of parametric maps and spatio-temporal images being respectively

$$\boldsymbol{\theta} = \{\theta_{pj} | p = 1, \dots, n_p; j = 1, \dots, n_j\}, \quad (3.20)$$

$$\boldsymbol{\lambda} = \{\lambda_{tj} | t = 1, \dots, n_t; j = 1, \dots, n_j\}. \quad (3.21)$$

The dynamic model $f()$ can be either linear or non-linear to the set of parameters p .

3.5.2 Dynamic reconstruction - Nested optimisation

The log likelihood expression for dynamic data and the dynamic model becomes

$$\ln L(\boldsymbol{\theta} | \mathbf{y}) = \sum_{t=1}^{n_t} \sum_{i=1}^{n_i} \left[y_{ti} \ln \left(\sum_{j=1}^{n_j} P_{ij} f_{tj}(\boldsymbol{\theta}) + b_{ti} \right) - \sum_{j=1}^{n_j} P_{ij} f_{tj}(\boldsymbol{\theta}) - b_{ti} - \ln(y_{ti}!) \right], \quad (3.22)$$

where now the additive corrections vector b is used for the known corrections on each frame t and data bin i . Here we have assumed that the system matrix P does not depend on time frame t . Similar to 3.12 and 3.13, the conditional expectation of the complete data can be written using the generic dynamic model $f()$ as

$$\hat{x}_{tij}(\boldsymbol{\theta}^{(k)}, y_{ti}) = y_{ti} \frac{P_{ij} f_{tj}(\boldsymbol{\theta}^{(k)})}{\sum_{d=1}^{n_j} P_{id} f_{td}(\boldsymbol{\theta}^{(k)}) + b_{ti}}, \quad (3.23)$$

$$\hat{g}_{ti}(\boldsymbol{\theta}^{(k)}, y_{ti}) = y_{ti} \frac{b_{ti}}{\sum_{d=1}^{n_j} P_{id} f_{td}(\boldsymbol{\theta}^{(k)}) + b_{ti}}. \quad (3.24)$$

The complete log-likelihood function can then be formed, using the above expected complete data and maximised to get an update of the $\theta^{(k)}$ estimate. By dropping terms that do not contribute to the optimisation we result in

$$\theta^{(k+1)} = \arg \max_{\theta} (\ln L(\theta | \hat{z})) = \sum_{t=1}^{n_t} \sum_{b=1}^{n_j} \left[\sum_{i=1}^{n_i} P_{ib} \right] \left[-f_{tb}(\theta_b) + \ln(P_{ib} f_{tb}(\theta_b)) \frac{\sum_{i=1}^{n_i} \hat{x}_{tib}}{\sum_{i=1}^{n_i} P_{ib}} \right]. \quad (3.25)$$

The last part of the expression is equivalent to an EM update over all tomographic data as

$$\frac{\sum_{i=1}^{n_i} \hat{x}_{tib}}{\sum_{i=1}^{n_i} P_{ib}} = \frac{f_{tb}(\theta^{(k)})}{\sum_{i=1}^{n_i} P_{ib}} \sum_{i=1}^{n_i} P_{ib} \frac{y_{ti}}{\sum_{d=1}^{n_j} P_{id} f_{td}(\theta^{(k)}) + b_{ti}}. \quad (3.26)$$

This set of images can be referred to as the EM update image

$$f_{tb}^{(EM)}(\theta^{(k)}) = \frac{f_{tb}(\theta^{(k)})}{\sum_{i=1}^{n_i} P_{ib}} \sum_{i=1}^{n_i} P_{ib} \frac{y_{ti}}{\sum_{d=1}^{n_j} P_{id} f_{td}(\theta^{(k)}) + b_{ti}}. \quad (3.27)$$

By substituting the equation 3.27 in the log-likelihood maximisation we have

$$\theta^{(k+1)} = \arg \max_{\theta} \sum_{t=1}^{n_t} \sum_{b=1}^{n_j} \left[\sum_{i=1}^{n_i} P_{ib} \right] \left[-f_{tb}(\theta) + \ln(f_{tb}(\theta)) f_{tb}^{(EM)}(\theta^{(k)}) \right]. \quad (3.28)$$

Equations 3.27 and 3.28 form the two step process of nested optimisation. An update over PET raw data for each voxel and each time frame is performed using 3.27, followed by an image based optimisation of the dynamic model parameters for each voxel using equation 3.28. It is important to note that the model fitting process of equation 3.28 can be performed independently for each voxel.

3.5.3 Linear dynamic models - direct 4D reconstruction

As described in chapter 2, many dynamic models utilised in practice for parametric imaging are linear models. These can be expressed in the form of matrices, which effectively are a set of temporal basis functions of the dynamic model. The modeled activity using a linear model of n_p number of parameters is

$$\lambda_{tj} = f_t(\theta_j) = \sum_{p=1}^{n_p} B_{tp} \theta_{pj}. \quad (3.29)$$

In this particular case of linear dynamic models it is straightforward to incorporate the model in the MLEM update equation 3.15 as

$$\theta_{pj}^{(k+1)} = \frac{\theta_{pj}^{(k)}}{\sum_{t=1}^{n_t} B_{tp} \sum_{i=1}^{n_i} P_{ij}} \sum_{t=1}^{n_t} B_{tp} \sum_{i=1}^{n_i} P_{ij} \frac{y_{ti}}{\sum_{d=1}^{n_j} P_{id} \sum_{q=1}^{n_p} B_{tq} \theta_{qd}^{(k)} + b_{ti}}. \quad (3.30)$$

Unfortunately, this simple form of the dynamic reconstruction problem using linear models suffers from very slow convergence speeds, as found previously [92, 93]. Strategies to improve the convergence speed are still being investigated [104], as this direct reconstruction approach can be beneficial in applications of list-mode level motion correction and other potential applications.

3.5.4 Linear dynamic models - Nested EM

To accelerate convergence of dynamic reconstruction using linear models the nested optimization framework can be utilised. By substituting the linear model equation 3.29 into equation 3.28 we have

$$\boldsymbol{\theta}^{(k+1)} = \arg \max_{\boldsymbol{\theta}} \sum_{t=1}^{n_t} \sum_{b=1}^{n_j} \left[\sum_{i=1}^{n_i} P_{ib} \right] \left[- \sum_{p=1}^{n_p} B_{tp} \theta_{pb} + \ln \left(\sum_{p=1}^{n_p} B_{tp} \theta_{pb} \right) f_{tb}^{(EM)}(\boldsymbol{\theta}^{(k)}) \right]. \quad (3.31)$$

This expression can be optimised for each voxel independently as

$$\theta_j^{(k+1)} = \arg \max_{\theta_j} \sum_{t=1}^{n_t} \left[\sum_{i=1}^{n_i} P_{ij} \right] \left[- \sum_{p=1}^{n_p} B_{tp} \theta_{pj} + \ln \left(\sum_{p=1}^{n_p} B_{tp} \theta_{pj} \right) f_{tj}^{(EM)}(\boldsymbol{\theta}^{(k)}) \right]. \quad (3.32)$$

As we have assumed that the system matrix P does not depend on time, the sensitivity term $[\sum_{i=1}^{n_i} P_{ij}]$ can be dropped from this optimisation. The right parenthesis of this voxel-wise optimisation expression is similar to the log-likelihood from the static reconstruction problem in equation 3.9, with different parameters and data being optimised. This function can be optimised using a similar MLEM update solution that is now applied over image space for the estimation of the model parameters

$$\theta_{pj}^{(k+1)} = \frac{\theta_{pj}^{(k)}}{\sum_{t=1}^{n_t} B_{tp}} \sum_{t=1}^{n_t} B_{tp} \frac{f_{tj}^{(EM)}(\boldsymbol{\theta}^{(k)})}{\sum_{q=1}^{n_p} B_{tq} \theta_{qj}^{(k)}}. \quad (3.33)$$

This results in a nested optimisation framework for linear models using equation 3.27 for updating over tomographic data and equation 3.33 for the dynamic model update resulting in updated parametric images. In this project, in all applications of dynamic reconstruction, we made use of linear models within the nested optimisation framework.

Chapter 4

CASToR

CASToR stands for Customizable and Advanced Software for Tomographic Reconstruction and is an open-source fully quantitative reconstruction platform that has been developed within a collaboration project, partly financed by France Life Imaging (FLI). It is available on the website of the collaboration project (<https://castor-project.org/>). This PhD project relied heavily on the use of CASToR for developing and performing reconstructions, on both simulated and real patient data. The work conducted in this project resulted in the development and evaluation of new functionalities, which are now part of the released public version 3.1.1. These are described in detail in chapter 6.

In this chapter, we provide a short introduction to the functionalities and innovative reconstruction methods provided in CASToR that play an important role in the work performed in this PhD project. Further information, instructions and examples on the use of CASToR can be found at the website of the collaboration project (<https://castor-project.org/>). The platform is developed using the C and C++ programming languages and supports PET, SPECT and CT imaging. In this short description, the focus is on PET reconstruction for static and dynamic imaging. A more detailed description of all the functionalities of CASToR can be found on the official website and the official publication by Merlin *et al.*[12].

The main philosophy behind the design of the platform is genericity and abstraction. The code architecture is divided into main components which manage global tasks. These are named "managers" and handle tasks such as reading datafiles, handling reconstruction dynamic aspects, managing the scanner geometry, computing a projection, etc. Each "manager" component is utilising abstract classes which include a representation of all the desired functionalities, required by the component, as virtual functions. The final step is to implement these virtual functions using a specific implementation as a specific class. Using this strategy, generic code of basic functionalities is implemented only once while specific classes require coding of only

the basic functionalities that are specific to the implementation. This allows for the development of specific classes with a minimal amount of coding, that can be used as plug-ins to the existing generic architecture. An example of this design is shown in figure 4.1, with the *oProjectorManager* as the main component, the *vProjector* as the virtual class which includes all the generic functionalities of a projector, and finally the projector implementations which include code that calculates a projection using a specific implementation. Template classes are also provided for instructing how new implementations, of projectors in this example, can be made.

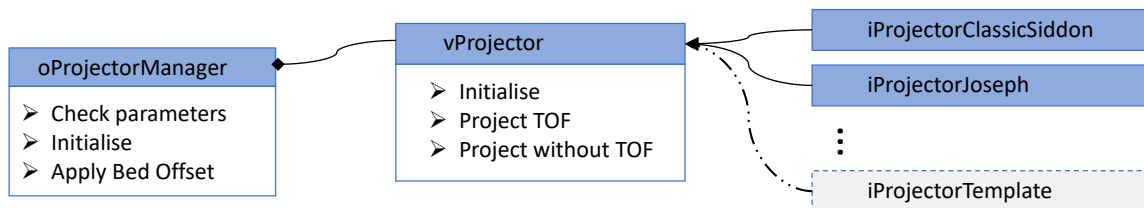


Figure 4.1: Example of CASToR abstraction design for the projection component.

4.1 Datafile

Data are provided in CASToR in the form of a CASToR datafile, which is based on a generic data description that is identical for both list-mode and histogram data. A "CASToR event" is either a list-mode event or a histogram bin. The minimum information required for each CASToR event of the datafile are a time-stamp, pair of detector IDs and number of events. Additional information can also be provided per event such as scatter and random corrections, normalisation factors, TOF, gating information, etc.

List-mode data maintain the exact timing information of each event. This is advantageous in the reconstruction of dynamic datasets, as the choice of the desired frames for reconstruction is made within CASToR, during reconstruction and using the framing selected by the input of reconstruction parameters. This of course is limited in the case of real data by the corrections used in the reconstruction, which are pre-computed using a specific framing definition prior to construction of the CASToR datafile.

Histograms are by definition events that have been histogrammed for a specific time range. All events of a CASToR histogram datafile have the same timestamp which is the timestamp of the first time point of the histogrammed data. Thus dynamic data need to be pre-processed into individual histograms, one histogram per dynamic frame, using a predefined framing definition. Multiple histograms from a dynamic dataset can be concatenated together into a single file before used in CASToR for dynamic reconstruction. In this case, reconstructions can be performed using the concatenated file and solely with the framing definition used

to create the histograms. Use of other framing definitions would require re-processing of the data before providing them into CASToR for reconstruction.

In this project, when possible, the use of list-mode datafiles was preferred due to the offered flexibility. List-mode datafiles were used for reconstructions of real PET datasets, while histograms were used for reconstructions of simulated datasets (from analytical simulations).

Real Data Corrections

Although in simulations it is relatively easy to get an estimate of corrections, these are harder to obtain for real data. Various estimation methods, as outlined in chapter 1, are employed by scanner manufacturers to generate corrections that are necessary for quantitatively accurate reconstruction. CASToR does not provide any functionalities for estimation of corrections. These must be pre-computed and included in the construction process of the castor datafile.

In this project we made use of real data from GE and Siemens PET systems. Both manufacturers provide offline processing tools (*GE-PET toolbox* for GE systems and *E7 tools* for Siemens systems) for reconstruction, which permit the extraction of corrections. These tools were used in this project for generation of all the corrections, when using real data in our evaluations.

4.2 Geometry

A generic description of the geometry of an imaging system in CASToR allows for the definition of any PET system. Individual detector elements are defined by 3D Cartesian coordinates and an orientation vector. These are pre-computed and input as look-up tables, or are computed by CASToR using a system definition similar to that used for GATE simulations [105].

In this project the geometries of the Signa PET/MR and Siemens mMR PET/MR scanners were used, for which lookup tables are provided with the current version of CASToR (Version 3.1).

4.3 Dynamic aspects

The use of generic functions and generic datafile definition allows for the reconstruction to be performed by a single implementation of an iterative algorithm. The main steps performed within this iterative algorithm are shown in algorithm 1.

The platform is designed to handle three temporal levels of binning. It makes temporal binning for dynamic

frames and binning in two levels of gating (for example cardiac and respiratory motions).

Algorithm 1: CASToR core iterative loop

```

for  $i \leftarrow 1$  to nb of iterations do
  for  $j \leftarrow 1$  to nb of subsets do
    index start ← current subset;
    index step ← number of subsets;
    Perform Image-based Convolution (forward step);
    // loop over bed positions
    for  $s \leftarrow 1$  to nb of beds do
      // Parallel loop
      for  $e \leftarrow$  index start to nb events step index step do
        Get Event corresponding to e;
        if Deformation required for e then
          Perform Image-Based Deformation(forward step);
        end
        // apply axial offset for bed
        Apply bed offset;
        // Recover system matrix elements associated with this event
        Compute/load the system matrix elements associated to this Event;
        // Compute the update term associated to the optimization algorithm
        Compute the forward model;
        Compute the update term(s) to be back-projected;
        Back-project update term(s);
      end
    end
    Perform Image-based Convolution (backward step);
    Perform Image-Based Deformation (backward step);
    Update image according to the optimization algorithm;
    // Make use of a dynamic model with nested optimisation
    if Nested use of Dynamic model then
      Estimate/Fit dynamic model ;
      Estimate image from fitted dynamic model ;
    end
  end
end

```

4.3.1 Motion correction and image deformation

Image based deformations can be performed within the iterative loop, over gate bins or sub-frames defined by involuntary motion, that can counteract effects of motion in the data while still using all data (without the need of rejection or individual reconstructions per gate). Unfortunately, with the current version of CASToR the available implemented deformations are limited to rigid deformation. Although this deformation can be adequate for brain imaging, it is not suitable for modelling elastic motion that is commonly found in whole body studies. Owing to this limitation at this time, no motion correction was considered in the reconstructions and evaluations performed in this project.

4.3.2 Dynamic reconstruction

Multi-frame reconstruction of individual frames can be performed within CASToR with a single execution. The framing details can be provided in the reconstruction input. For each event, a dynamic switch function is used to identify to which frame the data belongs. Image update is performed accordingly to each respective frame image.

The dynamic series of images is stored in CASToR using a set of temporal basis functions and images of basis coefficients, similar to the description in equation 3.29. In the case of individual frame reconstructions, the set of basis is an identity matrix and the coefficient images are the frame images. For dynamic reconstructions using a dynamic model, the model derived basis functions can be used directly in CASToR, in which case the image update terms directly update the parametric images. But as discussed previously in section 3.5, dynamic reconstruction can be performed more efficiently when using optimisation transfer principles and nested optimisation for the dynamic model fitting. This functionality was developed in CASToR, as part of the developments made during this PhD project. Details of the implementation are provided in chapter 6.

4.4 Multi-bed reconstruction

With the generic description of the geometry implemented in CASToR, system matrix elements related to each detection event are computed on-the-fly, by projecting a ray through image space, or they are read from a pre-computed system matrix. The on-the-fly computation allows for additional flexibility, which has been used to enable direct multi-bed reconstruction. As described in section 1.5.1, multi-bed Step and Shoot (SS) acquisitions make use of overlapping beds to increase the sensitivity at the edges of each bed's FOV. The raw PET data for a static WB acquisition comprise of a total number of n_s datasets, one for each bed position s . We can represent each bed's raw PET dataset as

$$\mathbf{y}_s = \left\{ y_{si}, i = 1, \dots, n_i \right\}. \quad (4.1)$$

By incorporating the offset of each bed position in the projection operation, equation 3.15 can be re-written for direct reconstruction of the whole acquisition effective FOV, using all acquired raw data, as

$$\lambda_j^{(k+1)} = \frac{\lambda_j^{(k)}}{\sum_{s=1}^{n_s} \sum_{i=1}^{n_i} P_{sij}} \sum_{s=1}^{n_s} \sum_{i=1}^{n_i} P_{sij} \frac{y_{si}}{\sum_{d=1}^{n_j} P_{sid} \lambda_d^{(k)} + b_{si}}, \quad (4.2)$$

where now the image λ has the dimensions of the whole effective FOV, and the additive correction terms

b_{si} is provided for each respective bed position s .

Direct reconstruction of multi-bed data, which combines data from overlapping acquisitions within the iterative reconstruction loop, improves the statistics of the overlapping region that are available for each iteration. It has been shown that this technique can result in improved contrast to noise ratios at the overlapping regions, for specific levels of acquisition statistics [50].

This method has been implemented in CASToR by making use of an additional loop over bed positions and an "Apply bed offset" function, as seen in the CASToR iterative algorithm 1, which applies the bed offset to the projector for the events of each bed [51].

Part II

Contributions

Chapter 5

Multi-bed Dynamic Whole-Body PET: Acquisition Optimization

5.1 Introduction

In PET imaging one of the needs in many clinical and research applications is the acquisition of information over the whole body. Moreover, dynamic information over the whole body can allow for research applications of PET, such as in pharmacokinetics, to expand to the whole body and enable potential future clinical applications. But an important limitation of DWB protocols in scanners with limited A-FOV is the result of temporal gaps in the acquired data of any given bed position. In practice for scanners that have no in-built DWB protocols, such as the Signa PET/MR, a large fraction of the temporal gaps in DWB protocols can be attributed to a greater extent to system processes that are launched automatically between WB sweeps rather than to time taken to move the bed between bed positions. These processes include the transfer of raw data files and reconstructions performed during scanning. Reducing these system delays is therefore of prime importance for reducing temporal gaps in the data.

In this chapter, we review results of acquisition performance for a DWB protocol implemented on the Signa PET/MR scanner as part of the IsotoPK pharmacokinetic study [10]. A short introduction on the design of the protocol using current scanner features is provided, with additional details on the protocol and data processing of this protocol's data provided in Appendix A. We then describe the implementation of an experimental fully-automated protocol for DWB acquisitions on the Signa PET/MR, that was designed with the aim of reducing acquisition delays and allowing for greater flexibility in the selection of bed positions. The development of this protocol was conducted in collaboration with GE Healthcare, as part of this PhD project

(which was also a milestone within HYBRID). Finally, we present results from the use of the experimental acquisition protocol on a Non-Human Primate (NHP) study and compare against the standard DWB protocol used in the IsotoPK study using data from fourteen volunteer scans.

5.2 Methods & Results

5.2.1 Design of IsotoPK DWB protocol on the Signa PET/MR

Prior to commencing this PhD project and in perpetration for the IsotoPK study, a DWB protocol was designed on the GE Signa PET/MR scanner. The desired axial coverage was achieved using 5 bed positions and a reduced overlap, as shown in diagram (C) of figure 1.9. The relatively small overlap (half compared to routine clinical protocols) was selected to reduce the number of beds and subsequently the acquisition temporal gaps. The study design was limited to a total duration of 1 hour from injection and includes an initial dynamic single bed (DSB) phase centred over the liver, where the highest expression of the transporters under study was expected. The DSB position was imaged for 3 minutes from injection, prior to the start of DWB acquisition. Because the system has no in-built protocols for DWB imaging, a custom protocol had to be made using a sequence of static WB acquisitions. Each WB pass had to be individually pre-planned, which resulted in hard-coded bed positions (identical positions for all subjects, relevant to a reference mark). Each volunteer positioning was made using a chest-landmark, with no further adjustments of the protocol being possible for the optimum arrangement of the bed positions, relative to each patient's size.

For the design of the framing used in the IsotoPK DWB protocol, the following empirical metric has been taken under consideration. We define the Delays-to-Acquisition ratio (DAR) as the ratio of total delays to acquisition time for every WB sweep, using the relationship

$$\text{DAR}(n_s) = \frac{dl_{bed} \cdot (n_s - 1) + dl_{Sweep}^{(n_s)}}{t_{duration} \cdot n_s}, \quad (5.1)$$

where n_s is the number of beds in the acquisition, $t_{duration}$ is the frame duration for a single bed of the WB sweep, dl_{bed} the delays between adjacent beds and $dl_{Sweep}^{(n_s)}$ the delay between WB sweeps (for a DWB protocol of n_s bed positions). This relationship is based on the assumption that all beds in a WB sweep have the same frame duration. First estimations of the delay times for the Signa PET/MR had shown a delay of approximately 6 seconds between adjacent bed positions and 20 seconds between WB sweeps. Using this information, the framing sequence shown in table 5.1 was chosen with the shortest frame duration set to 20 seconds in order to maintain a DAR below 50% at the early phases of the DWB study.

The MR sequences required for attenuation correction (MRACs) were performed prior to injection and dur-

Table 5.1: Framing of IsotoPK DWB protocol.

Phase ID	Description	Frame Duration (s)	Number of frames per bed position	DAR
1	DSB	10	18	N/A
2	DWB	20	9	44%
3	DWB	30	8	29%
4	DWB	40	2	22%

ing the DWB protocol acquisition. The first MRAC sequence at each bed location lasted approximately 35 seconds (conducted prior to injection), with subsequent scans over the same locations lasting approximately 21 seconds per bed. This difference in time requirements between initial and subsequent MRAC sequences is caused by the MR shimming sequences that are performed before MR imaging. At first, shimming is conducted in full to optimise MR homogeneity, while only a faster shimming update is conducted on subsequent scans of the same bed positions. MRAC acquisitions were not repeated for all WB sweeps of the DWB protocol, to allow for staff entry in the room for blood sampling which is required for the derivation of the input function and metabolite analysis.

The acquired DWB data were initially reconstructed at the system console. Then, as part of this PhD project, the raw data were retrospectively exported for offline processing and reconstruction with CASToR, using an automated pipeline which is described in Appendix A.

5.2.2 Results from IsotoPK study

The result beds positions of the DWB protocol can be seen in figures 5.1 and 5.2 for the included fourteen studies from the IsotoPK protocol. Using the timing information of the extracted raw PET data, the average delay times per imaged subject were estimated, shown in the form of box-plots for dl_{bed} in figure 5.3 and for $dl_{Sweep}^{(5)}$ in figure 5.4.

It is noteworthy that with the accumulation of experience in using the PET/MR system for performing the DWB protocol, the delays between sweeps were reduced considerably, which can be seen by comparing the most recent examinations against the first. This can be attributed in part to improved preparation of the PET/MR system before performing the protocol (ex. reboot of the system prior to study, etc.). Before this practice was established, as the system software has not been designed for acquiring multiple whole-body passes many system crashes had been experienced using this custom protocol. These have caused losses of acquisition time (which has not been included in this evaluation) and also resulted in differences in the number of WB passes per subject. Secondly, in part, the reduction in delays can be attributed to improved staff training on the use of the protocol and awareness of common problems. For the 3 more recent subject

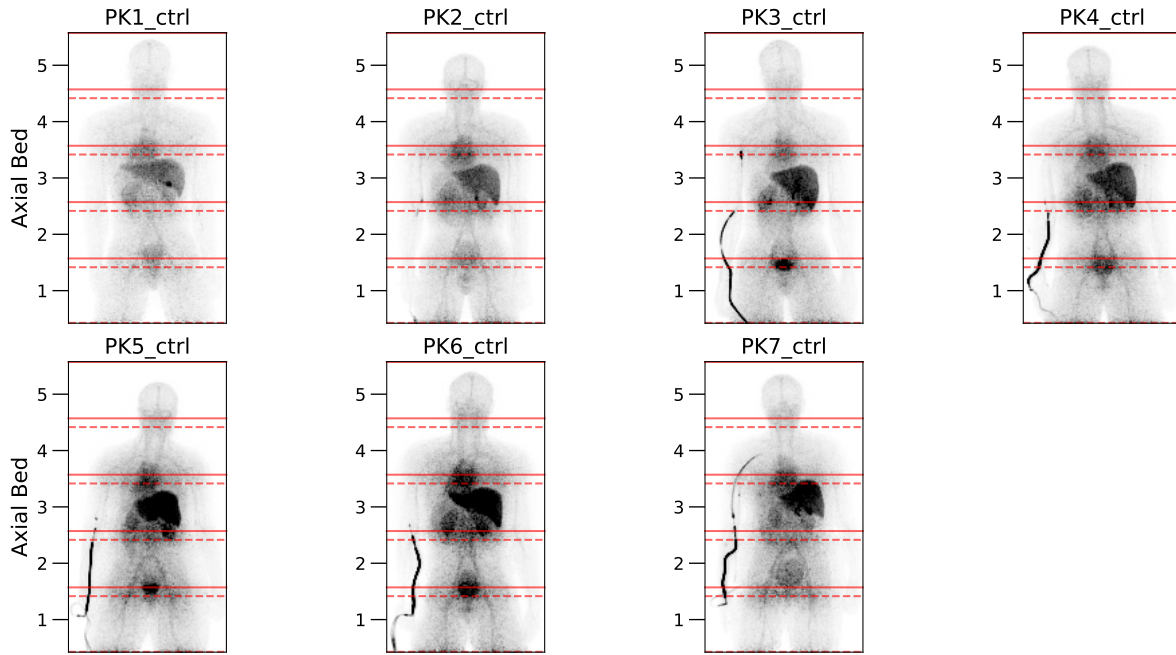


Figure 5.1: Coronal MIP projections of 7 volunteer control DWB scans with overlay of axial bed start (—) and end (-----) location.

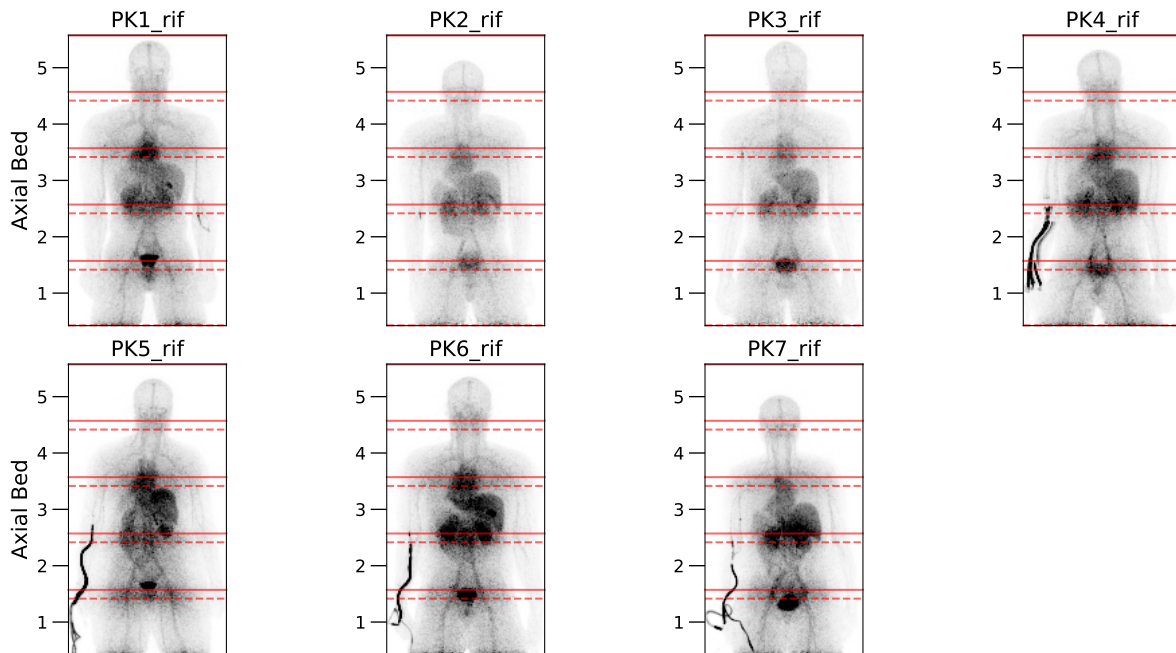


Figure 5.2: Coronal MIP projections of 7 volunteer rif DWB scans with overlay of axial bed start (—) and end (-----) location.

examinations the average intra-bed delay time dl_{bed} was 5.69 s (95%CI: 5.63, 5.75) and the average delay time between sweeps $dl_{Sweep}^{(5)}$ was 26.17 s (95%CI: 26.13, 26.22). This measured average $dl_{Sweep}^{(5)}$ value is slightly higher than the value considered in the design of the protocol. With these average measurements, the DAR for the WB sweeps of beds with 20 s frame duration becomes approximately 49%.

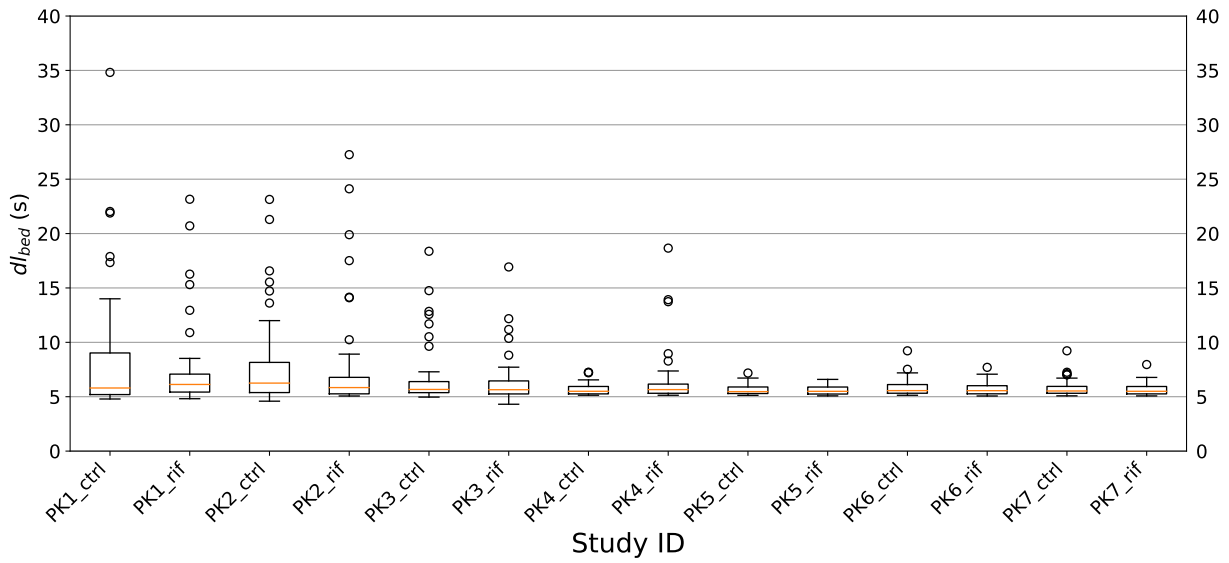


Figure 5.3: Box plots of intra-bed delays dl_{bed} of the IsotoPK DWB protocol used in practice.

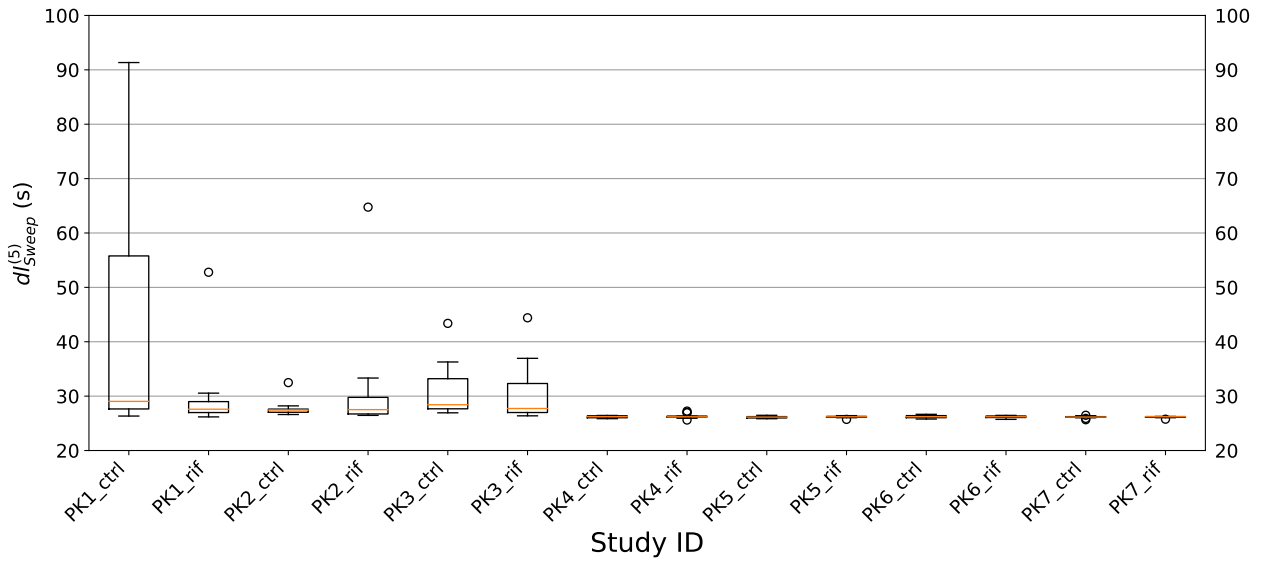


Figure 5.4: Box plots of delay between WB Sweeps dl_{Sweep} of the IsotoPK DWB protocol used in practice.

5.2.3 Design of a fully-automated DWB protocol on the Signa PET/MR

Part of this PhD project was allocated for the development of a fully automated DWB protocol on the Signa PET/MR. The main requirement for the envisioned protocol was to allow for continuous capture of PET data during DWB acquisition, into a single list-mode file for all bed positions and WB sweeps. Then the data would be processed after the acquisition, split into individual data for each bed position and reconstructed with the correct bed positional information. Using such an acquisition strategy, the delays between bed

positions and WB sweeps could be brought down to the time taken by the physical motion of the scanner table alone.

Towards this goal a three week secondment was planned at factory facilities of GE healthcare (Waukesha, Wisconsin, USA). There with help of the PET/MR team it was made possible to exploit in-build factory tools of the Signa PET/MR for the purposes of DWB automation. The two key tools necessary were:

- **Table Emulation**

This tool allows for disassociation of the table position between the MR and PET systems. It is the key tool that allows for the PET system to acquire continuously, while the MR system governs table motion. A disadvantage of this functionality is that once table emulation is enabled MR acquisitions cannot be performed.

- **Table Motion**

This tool commands the MR system to execute movements of the scanner bed. It can be used to drive the bed to a target location at a desired speed.

The automated DWB protocol was implemented as a Python class because the Python programming language is available on the PET/MR system's console and allowed for easy integration of the system tools with our custom made routines, all under a common system clock for accurate timing of bed movements and registration of events. The protocol was named "Auto-IsotoPK", but despite its name is a generic DWB protocol that is not limited to the IsotoPK pharmacokinetic study. It allows for an optional DSB scan to be acquired before starting the DWB acquisition. The protocol also allows for any number of beds to be used for DWB acquisition, with custom positioning of the beds for each examination using an initial MR scout image. Because MR acquisitions cannot be performed after *Table Emulation* is enabled, all bed position MRACs must be acquired before the PET examination and used for all WB sweeps of the study. A short Standard Operating Procedure (SOP) on the operation of the protocol is given in Appendix A.

After the procedure is completed, the whole PET study is stored as a single list-mode file, but without bed positional information. The precise timing information of the acquired bed positions is saved in a separate log file, which is used for post-processing the data and separation of the bed positions before reconstruction.

5.2.4 Results from NHP study

After initial tests using phantoms, the automated DWB protocol was tested on an actual pre-clinical DWB study. A macaque was scanned under full sedation with a novel [¹⁸F]Crizotinib tracer. Crizotinib is an anti-cancer drug used in the therapy of Non-Small-Cell Lung Carcinoma (NSCLC). The DWB study was

conducted to examine the tracer uptake in the brain as well as uptake and excretion from other organs. The macaque was injected with 185 MBq of the novel tracer. Directly after injection an initial DSB scan was conducted, centred over the brain for a duration of 90 s, followed by DWB acquisition of three bed positions. The study was planned for an approximate total duration of one hour. A total of 28 WB sweeps were fitted in the study, with the framing of 3×10 s, 5×20 s, 5×30 s, 5×45 s, 10×60 s for each of the three bed positions.

Acquisition of the required MRACs was performed prior to injection, at the planned bed positions shown in figure 5.5. In this acquisition, only the body coil of the PET-MR system was used, which is optimised for use with the human body size. Their use resulted in sub-optimal quality of MR images and generated attenuation maps. The attenuation maps were edited manually before being used for PET data reconstruction.

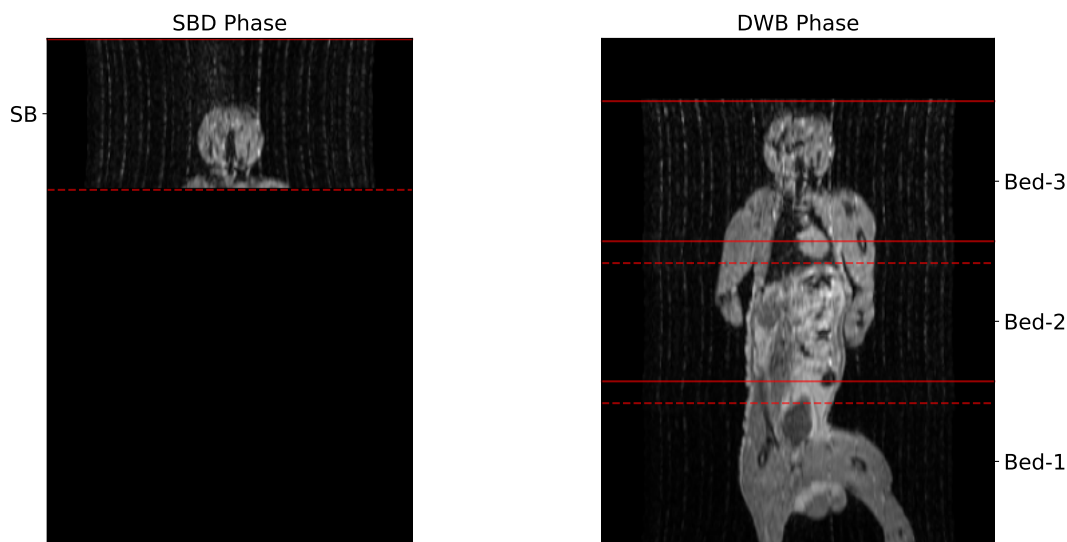


Figure 5.5: MRAC acquisitions of NHP study showing the planned bed positions of the two acquisition phases, with overlay of axial bed start (——) and end (-----) location.

The complete study dataset was recorded in a single list-mode file, of which the head curve (curve of prompts rate with time) can be seen in figure 5.6. By overlaying the recorded timing information over this curve, the two phases of the acquisition (DSB and DWB), as well as the three bed position of the DWB acquisition, can be distinguished. The initial 260 seconds of the recorded list-data's head curve with the overlaid phases and bed positions are shown in figure 5.7.

Using the timing information recorded in the acquisition log file, the data were split into four individual bed position datasets (one from DSB and three from DWB) and were processed with the GE-PET toolbox as individual single bed dynamic studies, to generate corrections necessary for reconstructions using CASToR. The list-mode data along with the generated corrections were then converted into the CASToR data-file format for subsequent reconstruction tests. A coronal Maximum Intensity Projection (MIP) view of 3D recon-

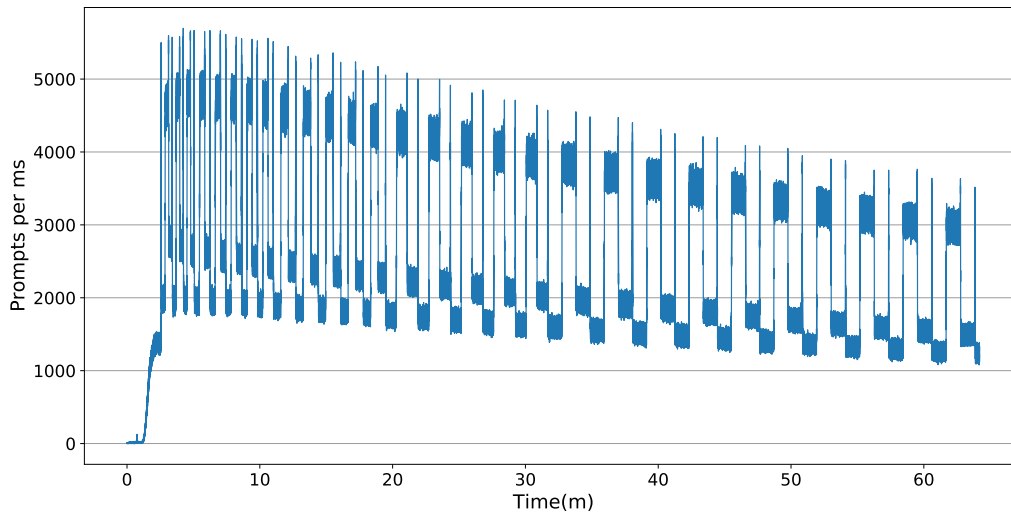


Figure 5.6: Head curve (prompts rate against time) of the acquired NHP study data in a single list-mode file using the fully-automated protocol.

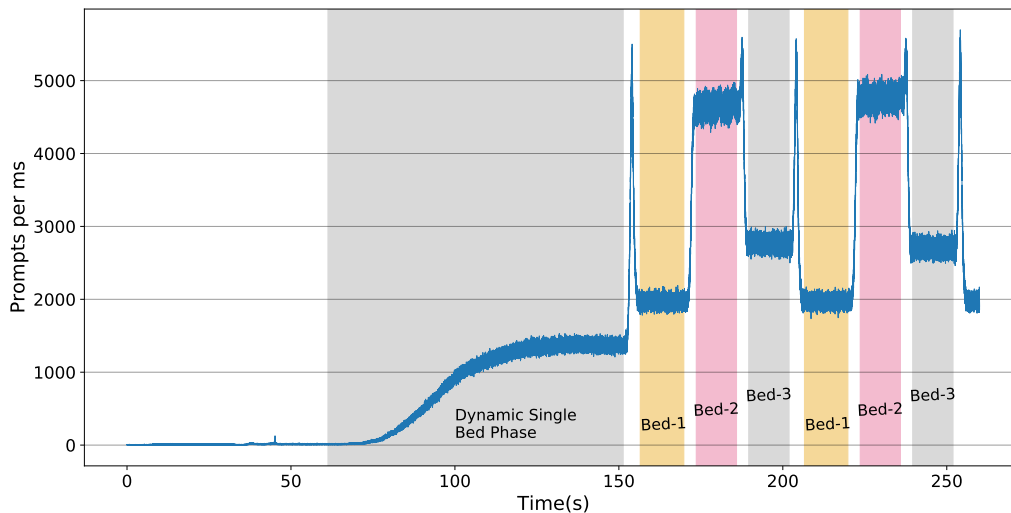


Figure 5.7: Head curve (prompts rate against time) of the acquired NHP study showing the DSB and DWB phases of the acquisition and the three DWB bed positions.

structions (averaged across all dynamic frames) is shown in figure 5.8.

An Image Derived Input Function (IDIF) was estimated from the reconstructed PET data. A right carotid Volume Of Interest (VOI), that was visible on both phases of the acquisition, and a left ventricle VOI on the Bed-3 position were used for the estimation. Both VOIs provided similar blood activity values for the DWB phase and were averaged to produce the final IDIF, shown in figure 5.9. This test showed that extraction of an IDIF, using multiple VOIs on both phases of the acquisition was possible and in good agreement between the used VOIs. Finally, an estimation of the delays (time gaps) for this single NHP study using the automated acquisition protocol was made using log timing information. The results showed an average intra-bed delay time dl_{bed} of 3.77 s (95%CI: 3.62, 3.91) and an average delay time between sweeps $dl_{Sweep}^{(3)}$

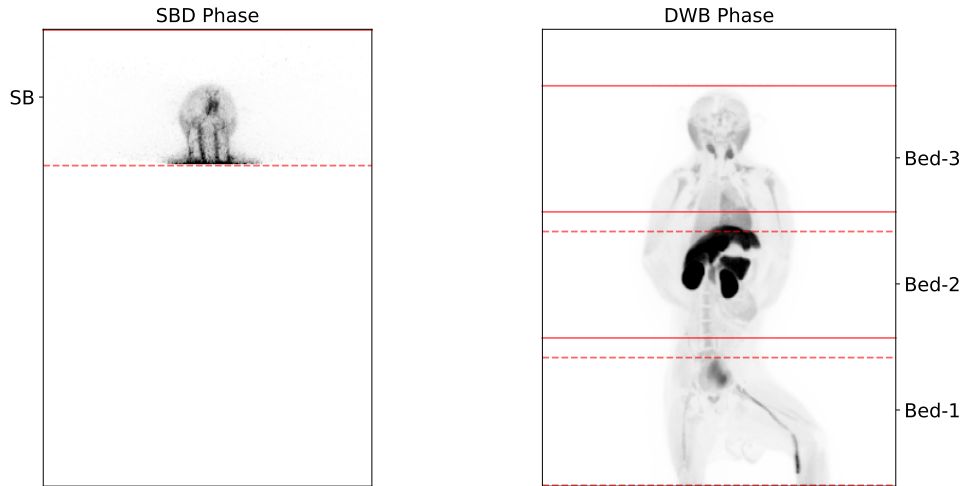


Figure 5.8: Coronal MIP views of the NHP study's reconstructed PET images, for the two phases of the acquisition, with overlay of axial bed start (—) and end (-----) location.

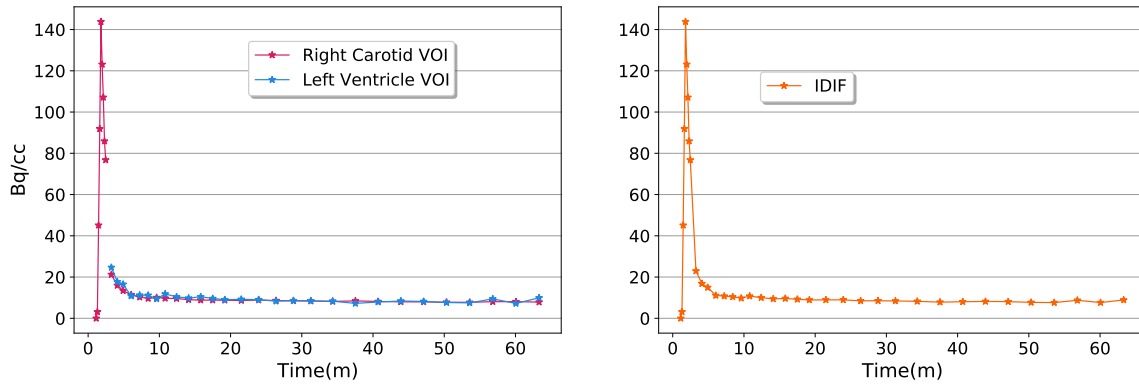


Figure 5.9: NHP study's image derived input function using information from multiple bed positions.

of 4.6 s (95%CI: 4.53, 4.67).

5.3 Comparison of protocols

The design and implementation of the fully-automated DWB protocol was made with the intentions of reducing delay times, compared to the custom implementation of a DWB protocol for the IsotoPK study. Before direct comparison of the protocols, the measured delay times between WB sweeps need to be adjusted to account for the difference in the number of bed positions between the two assessed protocols. Assuming a linear relationship between delays due to bed motion and the number of beds, the following relationship can be expressed

$$dl_{Sweep}^{(5)} = \frac{5}{3} dl_{Sweep}^{(3)}, \quad (5.2)$$

where now $dl_{Sweep}^{(5)}$ is the assumed delay between sweeps that would be achieved by the fully automated protocol for DWB imaging of 5 bed positions. It is expected that this value is an overestimation of the delays that would be achieved by the fully-automated protocol as the delays due to bed motion include an acceleration and deceleration phase that impacts shorter bed movements greater than longer movements. Using the measurements from the NHP study, the estimated $dl_{Sweep}^{(5)}$ that could be achieved is 7.66 s. Using this value we can estimate that the DAR for 20 s frames can be reduced from 49% to approximately 22.7%, by use of the fully automated protocol instead of the current IsotoPK DWB protocol. Furthermore, using the reduced $dl_{Sweep}^{(5)}$ delays a DAR of approximately 45.5% can be achieved for 10 s frames, allowing for more frequent sampling in the early phases of DWB acquisition without significantly compromising the quantity of acquired statistics.

Additionally, besides the reduced acquisition gaps, the fully automated protocol allows for more flexibility in the arrangement of bed positions for DWB imaging. By contrast, the hard-set bed positions of the IsotoPK DWB protocol do not always allow for optimum use of the effective A-FOV in each examination, as seen for example in examination PK2 in figures 5.1 and 5.2. In some cases, a lesser number of bed positions might be adequate and preferable as it would lead to a substantial increase of sampling frequency per bed.

5.4 Discussion

As seen by the reduction of acquisition delay times and reduction of DAR for short frame duration, the implementation of the fully-automated DWB protocol allows for improved DWB imaging with reduced acquisition temporal gaps. This gain can be used towards improving acquisition statistics by reducing the DAR ratio and towards a higher sampling frequency of early frames. A limitation in this assessment is that the comparisons were based on the empirical metric of DAR, without relating directly to the final kinetic analysis performed on the data and produced parametric images. In practice, faster sampling could also be achieved with larger acquisition gaps at the cost of reduced acquisition statistics and vice versa with higher statistics achieved at the cost of reduced sampling frequency. These trade-offs are expected to affect mostly kinetic estimations that are sensitive to fast dynamic information shortly after injection. Ideally, the DWB acquisition protocol should be optimised for the expected kinetics under study and the parameters of interest. Nevertheless, towards this optimisation, the developed fully-automated protocol can allow for greater variability in the available trade-off options of acquisition statistics vs. sampling frequency of early frames. Another aspect where fast sampling can be beneficial is for the derivation of the IDIF from DWB data. Given the fast initial sampling that can be achieved using a fully-automated protocol, it is possible to reduce the initial DSB acquisition duration or potentially remove it completely while still sampling frequently enough for an estima-

tion of the IDIF. In the NHP application presented in this chapter we showed that it is possible to combine IDIFs from multiple VOIs and from both DSB and DWB phases, without need for an identical bed position between the two acquisition phases. This flexibility can also allow flexibility in the DSB position placement over the WB scan, without compromising the derivation of the IDIF.

Additionally, another consideration that needs to be accounted for concerning fast sampling of early frames is the acquisition of MRAC sequences. For the Signa PET/MR the fastest MRAC sequence is performed in approximately 21 seconds (including preparation sequences) and as such shorter PET frames would have to be conducted without MRACs. In the IsotoPK DWB protocol, multiple MRACs are acquired in order to best account for any potential subject motion in the attenuation correction used for each WB pass. Their use can also be potentially expanded to the investigation of motion correction techniques. But if motion can be assumed to be small and negligible, then multiple MRACs would not be required and shorter PET frames can be acquired using MRACs acquired prior to injection.

In this evaluation, a practical limitation that has not been considered is safety limits on table movement that are needed to avoid undesirable effects from electromagnetic induction on patients/volunteers, which are caused by the fast movement of the bed within the MR field. For the tests conducted on the NHP, these limits have not been considered. These limits are expected to reduce the speed that would be permissible for human subjects, in compliance also with patient comfort requirements, and thus reduce to some degree the potential gains from the use of the fully automated DWB protocol.

In our tests we have considered only the use of S&S acquisition in the implementation and optimisation of DWB protocols. In a previous study on DWB protocols utilising CBM acquisition, advantages favouring the use CBM acquisition for DWB protocols were seen [55]. Beyond the aspects of reduced acquisition delays, CBM offers other benefits such as uniform axial sensitivity of acquisition, flexibility in sampling frequency by adjustments in table speed within each WB sweep, improved patient comfort, etc. Overall, use of CBM naturally overcomes many of the limitations posed by the use of multi-bed DWB protocols and S&S acquisition. Additionally, CBM protocols can also allow for bi-directional motion that eliminates delays between WB sweeps. These acquisition modes, their effects on acquisition gaps and result parametric image quality were considered further in the simulation study presented in chapter 6. Using the fully automated protocol and the developed tools we were able to emulate a CBM acquisition for the NHP study, by selecting a relatively slow table speeds and recording PET data continuously. But normalization and quantitative reconstruction of the acquired CBM datasets is a demanding, task as previously described [6], and thus quantitative reconstruction of these data was not considered further in this PhD project.

Overall the implementation of this fully automated protocol serves as proof of concept for flexible bed position placement and selection of frames duration, being limited only by the bed speed of the GE Signa

PET/MR and not by software or other system components. This protocol is a significant improvement from the currently used DWB protocol of the IsotoPK study. As the system has not been designed with DWB capabilities, the current DWB protocol involves manual planning of each WB sweep, multiple delays in data transfers and individual WB sweep reconstructions, etc.

However, the automated method does not allow for bed positional information to be recorded in the raw data and necessitate ad-hoc techniques to record bed positions and bed movements in separate files. These limitations necessitate custom processing steps to be performed after acquisition and prior to reconstruction, to allow for accurate and quantitative reconstruction of the acquired data. Furthermore, the current implementation of the automated protocol does not allow for MRI to be acquired during PET acquisition. Although a mixed acquisition using the automated protocol and the current implemented DWB protocol could allow for MR in the acquisition, it would further increase complexity and risk of system failures.

Due to the discussed limitations of the automated protocol and the considerations for safety, it was not used for subsequent DWB acquisitions within the IsotoPK study and was not considered further in the context of this thesis. It served only as a proof of concept for future developments.

5.5 Conclusion

A fully automated DWB protocol was developed on the GE Signa PET/MR as a proof of concept for fully automated and flexible acquisition of DWB imaging, recorded on a single list-mode file for the whole study. Data using this protocol were successfully acquired, processed and reconstructed in a test NHP study. Use of the protocol allowed for considerable reduction of delay times, enabling faster sampling without loss of PET data statistics. Thanks to the automated protocol, the minimum bed frame duration can be reduced from 20 to 10 s while maintaining the same DAR, compared to the DWB protocol currently in use. A considerable limitation of the implementation of this protocol is the unavailability of the MR system for MRI acquisitions during the DWB acquisition, which is caused by the bespoke utilities on which our experimental protocol was based upon. Finally, further considerations of permissible table speeds for patient safety and comfort need to be applied before using this protocol on human subjects.

Chapter 6

Dynamic Reconstruction Implementation and Application to a Patlak Simulation Study

As shown previously in multiple applications in the literature, dynamic reconstruction can improve activity and parametric image estimates by making use of dynamic models directly in the reconstruction process, enabling more accurate modelling of the noise in the raw PET data for the parametric estimation process [11].

In this chapter, we briefly describe the implementation of a dynamic reconstruction framework and dynamic reconstruction functionalities in CASToR. A fraction of this PhD project was focused on the development and validation of these functionalities, that were necessary to achieve the project aims. The developments were conducted in collaboration with other CASToR developers, mainly with Dr Thibaut Merlin, Dr Simon Stute and Dr Marina Filipović. In addition, dynamic functionalities were implemented within a generic framework that allows for future expansion and contributions by developers of CASToR, to include more dynamic models and enable more complex and higher dimensional modelling (eg. dynamic and respiratory "5D" modelling , etc.).

In the remaining of this chapter, we present work conducted with simulated and real data, on the use and respective benefits of various dynamic reconstruction strategies for DWB parametric imaging. This study was submitted to the journal of **Physics in Medicine & Biology** for review in May 2021.

6.1 Introduction

Positron Emission Tomography (PET) imaging is well known and established in clinical applications and pathways, with an important role towards the delivery of precision medicine [3]. The established clinical practices rely on static imaging after a certain uptake period and semi-quantitative measures, such as the standardised uptake value (SUV). But these measures are vulnerable to many unknown factors that can vary between PET examinations, such as body composition, retention clearance, inconsistencies in uptake time and imaging practices [106]. On the other hand dynamic PET imaging can be used to fully characterise underlying tracer kinetics and provide fully quantitative measures, that could overcome many limitations of current static imaging practices and enable use of PET for new applications in clinical practice [2, 19, 107]. Current clinical scanners are limited in coverage by their axial field of view (A-FOV), with values ranging from 15 to 26 cm [4]. This is sufficient for single organ dynamic studies but cannot directly provide synchronous whole-body coverage, which is essential for some clinical applications such as tumour staging in oncology. In practice for static imaging whole-body coverage is achieved using multiple bed positions at different axial locations to provide the desired axial coverage [5], or alternatively via continuous axial bed motion (CBM) during the acquisition [6]. Recently scanners with increased A-FOV have been developed [14, 15], even with nearly 2 meters long A-FOV which provides total-body coverage [16]. But these scanners are still not widely adopted in the clinic. Using similar methods as in static whole-body imaging, dynamic whole body (DWB) protocols have been developed using multiple bed positions and repeated whole-body passes [7–9]. These types of acquisition protocols have also been incorporated into clinical products [17], and it has been shown that their use in clinical practice is feasible [56, 57].

The immediate effect of transition from single bed dynamic studies to multi-bed dynamic studies is the introduction of temporal gaps in the acquired data of any given bed position. These are introduced at each bed position by the time spent on imaging other bed positions and by scanner system delays due to the time required to move the bed to the next position and prepare for the next acquisition. These gaps cause a significant reduction in the sensitivity of the acquisition, with fewer total counts collected for each axial location when compared to single bed dynamic acquisitions. Furthermore, estimation of fast temporal changes in tracer uptake are compromised as the early time points of the acquisition are not fully sampled for all beds. Finally the established clinical protocols that make use of image derived input function (IDIF) to ease integration in clinical practice further sacrifice imaging time in the study's early phase, which is spent in acquiring fast frames over a single bed location centred over the heart and the aorta [17].

The generation of parametric images from dynamic data requires fitting of the dynamic model of interest on time activity curves (TAC) for every voxel in the image. Due to the poor statistics and high noise associated with TAC measurements at the voxel level, in particular for DWB acquisitions, parametric image estimates

can be heavily corrupted by noise and potentially biased. The use of direct dynamic reconstruction has been proposed to improve on this task by making use of dynamic models directly in the reconstruction. These techniques allow for more accurate modelling of the noise from the raw PET data in the generation process of parametric images and can improve parametric image noise and reduce bias [11]. For DWB acquisitions specifically, it has been shown using simulated and real data that direct dynamic reconstruction provides reduced noise, bias and improved parametric image contrast when compared to post-reconstruction parametric imaging [55].

In this work, we evaluate the performance of dynamic reconstruction algorithms for DWB fluorodeoxyglucose ($[^{18}\text{F}]\text{FDG}$) PET imaging for various dynamic reconstruction methods and for different DWB acquisition protocols. The evaluation is based on simulations of single bed and multi-bed dynamic studies and results are illustrated in a real dynamic FDG PET study.

In detail we evaluate for WB Patlak K_i parametric imaging (1) the benefits of using direct Patlak dynamic reconstruction in DWB protocols against single bed dynamic protocols and indirect parametric imaging from regular 3D reconstruction, (2) the use of the Spectral analysis dynamic model [70] in dynamic reconstruction for indirect parametric imaging, (3) the use of two different optimization algorithms for dynamic reconstruction and finally (4) the impact of different DWB acquisition strategies.

6.2 Methods

6.2.1 Development of the dynamic reconstruction framework in CASToR

The framework for dynamic reconstruction was developed within the general CASToR framework and following its general principles, to allow for future expansions and in order to make our developments publicly available within the public release of CASToR. To handle the use of dynamic models in reconstruction a new component was implemented in the code (called Dynamic-Model-Manager) that interacts with the reconstruction process within the main CASToR iterative loop (steps *Estimate/Fit dynamic model* and *Estimate image from fitted dynamic model* of algorithm 1). The main tasks of the Dynamic-Model-Manager are to prepare dynamic models for use and to fit these models if needed, given an estimate of a time series of image data, and subsequently estimate the time series image data from the fitted dynamic model. As described in section 3.5, dynamic reconstruction for linear dynamic models can be made using a set of basis functions directly implemented within the system matrix [11, 93, 108]. But as this method results in algorithms with substantially slow overall convergence properties, the nested framework [97, 98] is preferred, which decouples the dynamic model fitting process over image space from the tomographic update process over the raw PET data. We have designed the Dynamic-Model-Manager in order to allow for both options

of dynamic reconstruction, which we will refer to as non-nested and nested dynamic reconstruction respectively. In the examples and evaluations in this project, we made exclusive use of the nested framework, for practical computational requirements, which is also the method that predominates in most applications of dynamic reconstruction. But the availability of the non-nested option can allow for comparisons between the two approaches as well as the use of dynamic reconstruction with optimisation methods that might not necessarily support extension to nested optimization.

A diagram of the implemented framework within the dynamic-model-manager is given in figure 6.1. A generic dynamic model (`vDynamicModel`) was designed as a virtual function, which implements the requirements for model fitting processes, as well as some common optimization algorithms (Least-Squares (LS) and Non-Negative Least-Squares (NNLS) optimization algorithms).

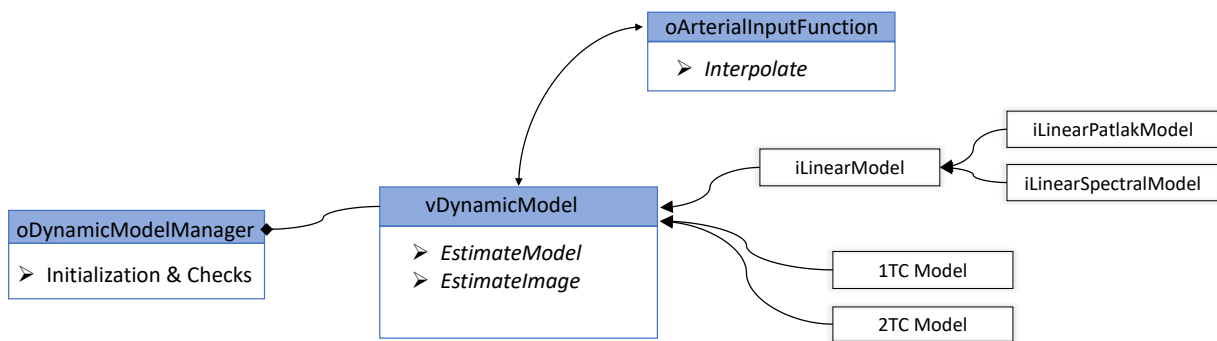


Figure 6.1: CASToR framework for dynamic reconstructions.

Specific dynamic models can be directly implemented by inheriting these functions from the `vDynamicModel` class, such as for example the implemented 1TC and 2TC models. These models are based on micro-parameters estimation of the respective compartmental models and make use of non-linear optimization or linearization techniques that are unique to these specific models. Beyond these specific models, many models used in practice for parametric imaging are linear models and share common optimization methods. For this reason, a generic Linear model (`iLinearModel`) was developed, with EM, LS and NNLS optimization algorithms included for model fitting over voxel TACs. This linear model can be used directly if basis functions are provided as input or alternatively other more specific linear models can inherit its functions and define their own temporal basis functions. In our implementation, we have implemented two specific linear models, the Patlak model [69] and the spectral analysis model [70]. Furthermore, as many dynamic models that relate to physiological kinetic parameters require a blood input function, a specific class was created (`oArterialInputFunction`). This class takes a provided input function and performs linear interpolation of the input data points, before its use by the dynamic model. Finally, an additional castor toolkit (`castor-imageDynamicTools`) was included in the public release to allow the use of the developed models for

post-reconstruction model fitting using the included image space optimization algorithms.

6.2.2 Development of analytical simulator for dynamic data

In a similar fashion to the design of the dynamic reconstruction framework, a dynamic modelling framework was implemented within an existing in-house developed analytical PET simulator [109]. Specifically the 1TC and 2TC models were implemented, using equation 2.7 and equation 2.11, while also accounting for blood fraction using equation 2.3. The simulator was used to validate the implemented dynamic reconstruction framework in CASToR and to conduct the simulations used in this study.

6.2.3 Simulated acquisition protocols

A single bed (SB) dynamic protocol (continuous in time with no temporal gaps) and three DWB acquisition protocols of five bed positions (with temporal gaps) were simulated for this study, using the geometry characteristics of the GE Signa PET/MR scanner [47]. With the provided 25 cm A-FOV per bed and a bed overlap of 3.34 cm, axial coverage of 110.3 cm can be achieved with five bed positions. The relatively small overlap (same as in the IsotoPK protocol and approximately half compared to routine clinical protocols) was selected to reduce the number of beds and subsequently the acquisition temporal gaps. A total study duration of 60 minutes was used in the design of all protocols, including an initial single bed dynamic phase of 3 minutes centred over the aorta to mimic requirements for IDIF estimation.

- The first DWB protocol (DWB-1) considers a step and shoot (S&S) acquisition using the timing characteristics of the Signa PET/MR, with a delay of 6 seconds between adjacent bed positions and 36 seconds between whole-body sweeps, resulting to 8 whole-body sweeps in the duration of the study. The timing characteristics of this protocol are similar to the ones considered in the design of the IsotoPK DWB protocol described in chapter 5.
- The second DWB protocol (DWB-2) differs from DWB-1 by use of system delays that mimic a continuous bed motion (CBM) acquisition of the same length, with no delays between adjacent bed positions and 12 seconds delay between whole-body sweeps to account for bed speed and acquisition overscan (used to obtain reasonable axial sensitivity at the edges of the acquisition [6]). This protocol results in 9 whole-body sweeps. The actual simulation for DWB-2 did not make use of continuous bed motion in the simulation process but made use of the accurate timings that reflect reduction of delays and framing achieved with CBM on the same system geometry. This is conceptually equivalent to CBM sinogram data (sometimes referred as "chunks" [110]) with uniform framing over the FOV instead of slice-dependent timings as in actual CBM sinograms.

- The third DWB protocol (DWB-3) replicates the timing properties of DWB-2 for CBM acquisition but utilises a bi-directional acquisition that reduces delays between sweeps to the time spent for the overscan. This acquisition motion provides more sweeps in the same study duration but results in non-uniform sampling. This protocol results in 10 whole-body sweeps.
- A fourth DWB protocol (DWB-4) was simulated, in addition to the above protocols, for evaluating parameters estimation that depends on early dynamic information. In particular, in this evaluation, we were interested in the estimation of K_1 parametric images. For this protocol, the timing of the DWB-1 protocol was considered, with the addition of an early dynamic single bed acquisition over the same bed location. The single bed acquisition was split into nine frames of 20 seconds each.

Unlike what will be presented in chapter 7 for multi-bed dynamic reconstruction, in this chapter and for this simulation study we consider the dynamic reconstruction of each bed position separately. The results of these reconstructions could still be used for WB parametric imaging, by post-reconstruction merging of each bed's parametric images [55]. This parametric merging approach was effectively used in chapter 8, due to limitations that will be discussed in that chapter by the use of the adaptive reconstruction algorithm.

Due to practical limitations and simulation time needs, the simulation study was focused on a single bed position from the assumed DWB protocols of five bed positions. The second bed position from the top was selected, to emphasise on sampling differences between uni-directional and bi-directional CBM motion. Furthermore, this option practically aided in the consideration for CBM timings in simulation as it avoids having to consider further complexity in CBM protocols (ex. overscan at edge position). This bed position is centred over the upper chest, as seen in figure 6.2. The PET data simulations were conducted solely for this bed position using the timing details of the protocols described above. The exact framing information are available in appendix B.

6.2.4 Digital phantom & analytical simulation

The Zubal brain phantom [13] was chosen for the simulations of PET [^{18}F]FDG data, even though its anatomy doesn't correspond to the anatomy that would be found in the axial location of the simulated bed position. The choice of the phantom was made to incorporate higher complexity structures than those offered from common lung/chest phantoms. Furthermore the use of the brain phantom, centred in the FOV, aided in avoiding analysis of areas falling in the overlapping regions, whose behaviour under DWB acquisition and reconstruction is yet another subject for investigation. The Zubal brain phantom was segmented into 19 unique regions and a non-reversible two tissue compartment model was assigned uniformly to each region to simulate realistic FDG kinetics, with K_1 , k_2 , k_3 and V_b values drawn from the literature and a real

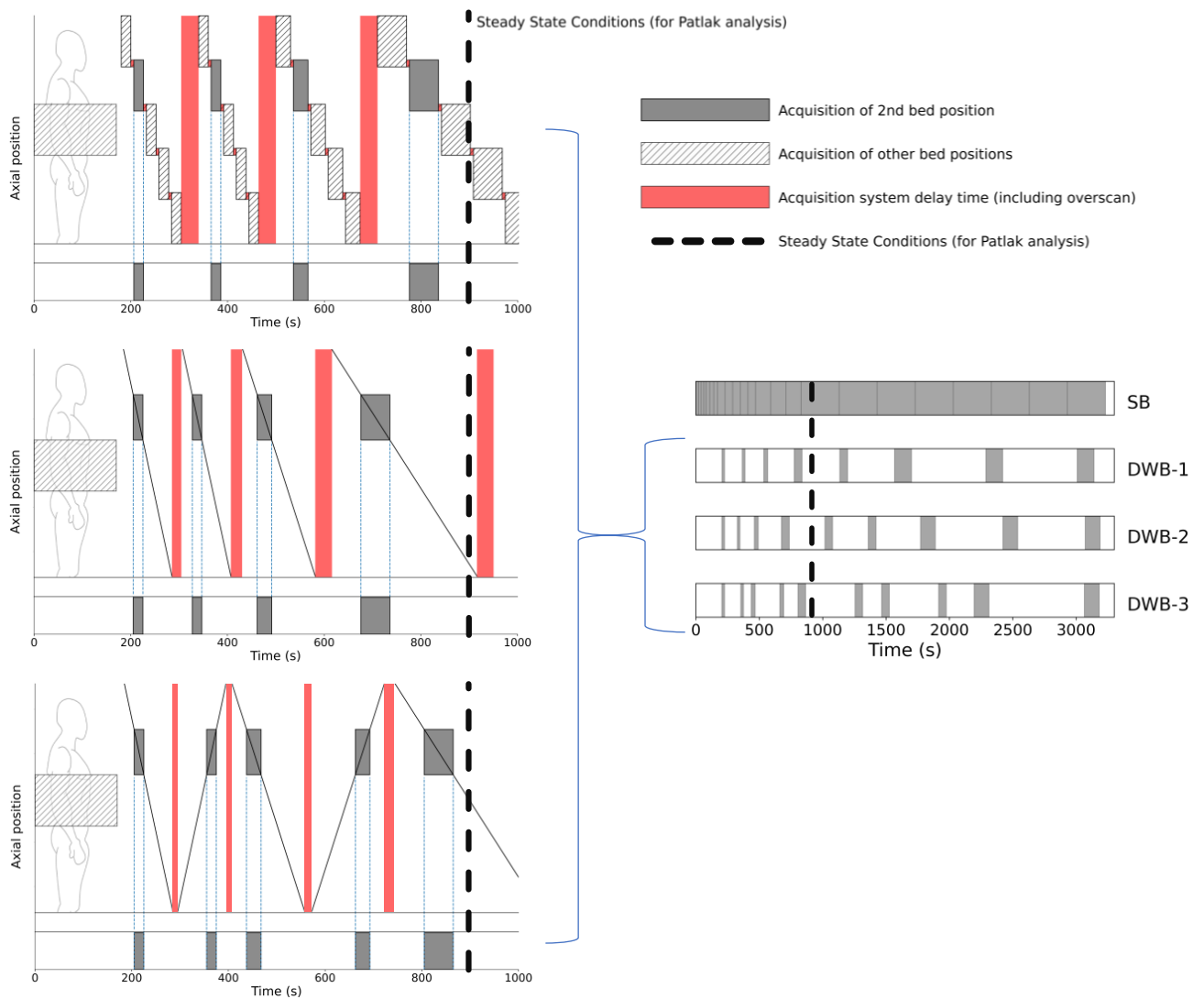


Figure 6.2: Dynamic whole-body acquisition protocols considered for simulation.

measured input function. A selection of the simulated kinetic parameters is provided in appendix B. The developed analytical simulator was used to generate raw PET sinogram data. The simulations included attenuation and detector resolution effects, scattered and random coincidences, while Poisson noise was added to the sinogram data. The simulation did not include time of flight (TOF) information in the data. Fifty different noise realisations were simulated for each DWB protocol. For the SB protocol the number of noise realisation was reduced to twenty as simulation and reconstruction times of the SB datasets were substantially higher.

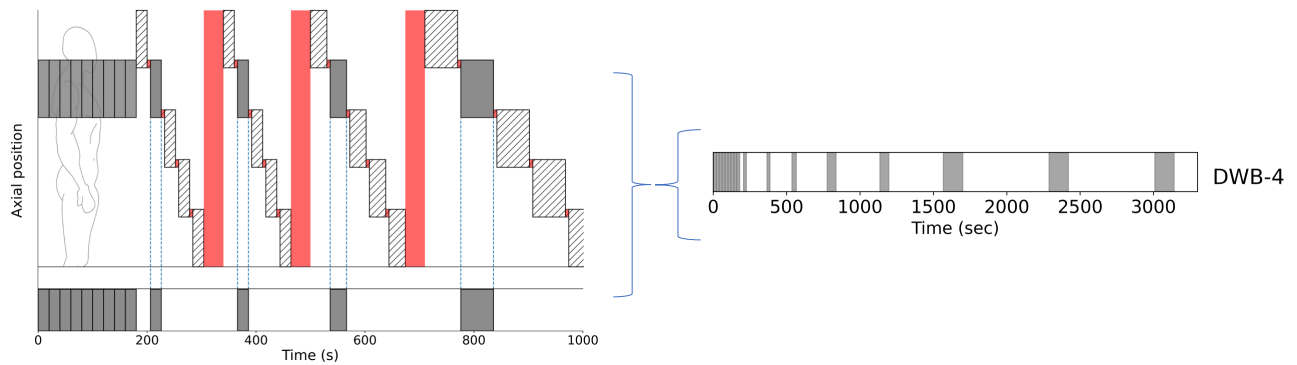


Figure 6.3: Fourth dynamic whole-body acquisition protocol considered for simulation, which includes an initial dynamic single bed phase centred over considered bed position.

6.2.5 Reconstruction and kinetic modelling

Both 3D and dynamic iterative reconstructions were used. All reconstructions were run within an OSEM framework, for 40 iterations and 28 subsets, using the developed dynamic reconstruction framework in CASToR [12]. All reconstructions were performed with a voxel size of $2.2 \text{ mm} \times 2.2 \text{ mm} \times 2.8 \text{ mm}$ and included resolution modelling as well as corrections for attenuation and for random and scattered coincidences (generated from the simulation). Dynamic reconstructions are made by combining dynamic models that describe the tracer kinetics with the tomographic reconstruction process. When the dynamic model of interest is used this technique results in direct reconstruction of parametric images of interest and allows for accurate modelling of the raw data noise in the estimation process [92, 93, 108, 111]. Use of generic dynamic models can also be made for dynamic reconstruction, where dynamic models impose temporal regularisation in the frame activity estimation process. Post-reconstruction (indirect) estimation of parametric images can then be made and indirectly benefit from the use of dynamic reconstruction [11, 112]. Linear dynamic models can be directly implemented within the system matrix [11, 93, 108] but result in algorithms with substantially slower overall convergence properties. Instead a nested optimization framework [97, 98] can be used, which decouples the dynamic model fitting process on image space data from the tomographic update process over the raw PET data. This allows for multiple nested sub-iterations of dynamic model fitting to be run within each tomographic iteration of the reconstruction process, resulting in convergence acceleration and reasonable computing time requirements. The separation of the two processes allows for various optimization algorithms to be implemented in the nested dynamic model fitting process [98]. One particular method of interest is the Non-Negative Least Squares (NNLS) algorithm [113], that enforces non-negativity and is commonly used in post-reconstruction kinetic modelling. The NNLS algorithm is self-terminating and for dynamic reconstruction it has been shown that a single execution of nested NNLS results in parametric images with similar Root Mean Square Error (RMSE) to that of 15 iterations of nested MLEM [98]. Therefore

use of nested NNLS optimization has the potential for reduced overall reconstruction times. In this work we made use of both nested MLEM and NNLS optimizations to compare their performance and reconstruction time requirements for their implementation within CASToR. The nested MLEM optimization was used with 20 sub-iterations of the dynamic model fitting process after each subset of the OSEM tomographic update process, which has been found to be the optimal number of sub-iterations in a previous similar study [55]. Hereafter we will refer to nested dynamic reconstruction simply as *4D reconstruction*.

In this work we evaluated two different linear dynamic models for 4D reconstructions, the Patlak model and the Spectral analysis model.

4D Patlak

The Patlak model describes the activity in tissue $C_T(t)$ as

$$C_T(t) = K_i \int_0^t C_P(\tau) d\tau + V_\alpha C_P(t), \quad t > t_{ss}, \quad (6.1)$$

where C_P is the activity concentration in arterial blood plasma at time point t , K_i is the steady state trapping rate and V_α the apparent volume of distribution. The Patlak model is valid once steady state conditions have been reached (denoted as t_{ss}). For a PET measurement the observed activity is

$$C_{PET}(t) = (1 - V_B)C_T(t) + V_B C_B(t), \quad (6.2)$$

where conventionally it is assumed that the blood fraction V_B is small (≤ 0.05) in most tissues. If we assume for FDG that the total blood activity concentration C_B is proportional to C_P with $C_B = rC_P$, define the Patlak slope $\theta_1 = (1 - V_B)K_i$ and the Patlak intercept $\theta_2 = V_\alpha + rV_B$, then the observed activity of acquisition frame f between time points t_{start} and t_{end} is modelled according to the Patlak model as

$$\int_{t_{start}}^{t_{end}} C_{PET}(\tau) d\tau = \theta_1 \int_{t_{start}}^{t_{end}} \int_0^\tau C_P(\tau_1) d\tau_1 d\tau + \theta_2 \int_{t_{start}}^{t_{end}} C_P(\tau) d\tau, \quad (6.3)$$

where $C_{PET}(t)$ is the observed activity map. Using this representation a linear model of two basis functions can be constructed, which when fitted to TAC data provides parametric images $\theta = [\theta_1, \theta_2]$. 4D dynamic reconstruction with the Patlak model directly results in parametric images of θ_1 and θ_2 . In our study 4D Patlak reconstruction was applied using frame data after the first 15 minutes, from where we assumed steady state conditions ($t_{ss} = 15$ min).

It is important to note that a limitation of the Patlak model is that the estimated K_i from the Patlak slope θ_1 is susceptible to systematic errors in its estimation and can deviate from the true underlying $K_i (= \frac{K_1 k_3}{k_2 + k_3})$.

In addition, V_B is not necessarily known a priori and Patlak analysis can not distinguish between K_i and $(1 - V_B)$. In this study we use the Patlak slope θ_1 as the K_i value of interest for parametric imaging, as well as the ground truth target, generated from Patlak fits on noiseless simulated TAC data.

4D Spectral

4D reconstruction using the spectral analysis model is inspired from the 1993 homonym method [70] that is used to describe the generic behaviour of any compartmental system as a sum of decaying exponential functions with decay rates β which describe the exchange between compartments, convolved with an input function [71]. For a measurement within an acquisition frame f between time points t_{start} and t_{end} , the observed PET activity can be described according to the Spectral analysis model with $M+1$ number of parameters ϕ as

$$\int_{t_{start}}^{t_{end}} C_{PET}(\tau) d\tau = \sum_{b=0}^{M-1} \phi_b \int_{t_{start}}^{t_{end}} e^{-\beta_b \tau} * C_P(\tau) d\tau + \phi_M \int_{t_{start}}^{t_{end}} C_P(\tau) d\tau. \quad (6.4)$$

Assuming C_B is proportional to C_P then the parametric map ϕ_M is proportional to the blood fraction V_B , while for irreversible kinetics the decay rate $\beta_0 \rightarrow 0$ and the parametric map ϕ_0 describes tracer trapping. Parametric maps $\phi_1 \dots \phi_{M-1}$ describe the exchange between compartments, with decay rates $\beta_1 \dots \beta_{M-1}$ chosen to be logarithmic spaced within a range of values that covers the expected underlying kinetics. In our tests we used 3 different sets of numbers of basis functions ($M+1=17, 9$ and 6), with $\beta_1 \dots \beta_{M-1}$ logarithmically spaced within the range of 3 to 0.001 min^{-1} .

Unlike the Patlak model, the spectral analysis model is valid from the start of the acquisition and by default was applied to all time frames. The parameters ϕ_b of the spectral model have physiological meaning and in combination can be used to derive macro-parameters maps such as K_1 and either K_i or V_D , depending on the irreversible or reversible kinetic behaviour [71]. However, this derivation is sensitive to the acquisition's early kinetics after the injection, which are not necessarily sampled for DWB protocols except for the bed position that matches the initial dynamic phase, commonly used for IDIF estimation. For this reason, the DWB-4 protocol was designed to evaluate the estimation of K_1 parametric images, for bed positions of DWB protocols that are covered by the single bed dynamic phase. Accurate K_1 estimation requires correction for the blood fraction ratio, as shown in equation 2.23. We intentionally ignored this term in the estimation of parametric images to avoid the introduction of noise by the voxel-to-voxel division with the blood fraction image. We will refer to this approximate value as K_1^* . In this project K_1^* parametric images were estimated

using

$$\mathbf{K}_1^* = \sum_{b=0}^{M-1} \phi_b. \quad (6.5)$$

The ability to derive and compare K_1 and K_i parametric images is clinically relevant, as it can reflect differences in the behaviour of early and late kinetics. For example, the use of images of this type for lung tumours has been shown to provide complementary information [18].

In the rest of the study, the main focus is parametric imaging of Patlak K_i , for which the spectral analysis model is used to enforce temporal regularisation without any strong assumptions on an underlying model [114]. The activity estimates of the 4D Spectral reconstruction are fitted post-reconstruction with the Patlak model to estimate the parametric images of Patlak K_i . In this sense the use of 4D Spectral reconstruction for parametric K_i imaging can be regarded as indirect dynamic reconstruction.

One could argue that since the parametric image ϕ_0 of the fitted spectral model describes tracer trapping, it could be used directly as an estimation of K_i . But it has been shown, in regular post-reconstruction spectral analysis, that separation of the irreversible trapping component between ϕ_0 and other spectral components is not complete due to noise and the correlation between the components. Empirical iterative filtering methods have been proposed to improve on such parameters estimations [115–117], but their use falls out of scope for utilisation of the spectral analysis model in 4D reconstruction. In 4D reconstruction, the spectral analysis model is used to enforce temporal regularisation without any strong assumptions on an underlying model. As such the number of spectral functions used is much smaller than the numbers suggested for spectral analysis, which makes the process of successful components separation even more unlikely.

Reconstructions details

As highlighted above the spectral analysis model makes use of all frame data, while the Patlak model uses data after t_{ss} . In order to make a closer comparison between the two models for 4D reconstruction, an additional comparison was made using only data after t_{ss} (reconstructions labelled with $t > t_{ss}$).

With the exception of 4D Patlak reconstructions that directly output parametric images of K_i , all other 4D and 3D reconstruction activity maps were fitted post-reconstruction with the Patlak model at the voxel level, using the Ordinary Least Squares (OLS) optimization algorithm, to generate parametric K_i images. For all 4D reconstructions and post-reconstruction fitting processes the true input function was used.

The reconstruction's namings and parameters are summarised in table 6.1 and table 6.2.

Table 6.1: Evaluated reconstruction parameters.

Name	Dynamic model	Nested Optimization	Algorithm
3D	none	n/a	OSEM(40it28s)
4D Patlak	Patlak	MLEM (20sub-it)	OSEM(40it28s)
4D Spectral(6bf)	Spectral	MLEM (20sub-it)	OSEM(40it28s)
4D Spectral(9bf)	Spectral	MLEM (20sub-it)	OSEM(40it28s)
4D Spectral(17bf)	Spectral	MLEM (20sub-it)	OSEM(40it28s)
4D Spectral(6bf)-NNLS	Spectral	NNLS	OSEM(40it28s)
4D Spectral(9bf)-NNLS	Spectral	NNLS	OSEM(40it28s)
4D Spectral(17bf)-NNLS	Spectral	NNLS	OSEM(40it28s)

Table 6.2: Additional reconstructions characteristics.

Additional Reconstructions	Characteristics
4D Spectral(6bf) $t > t_{ss}$	Provided only with data after t_{ss}
4D Spectral(9bf) $t > t_{ss}$	Provided only with data after t_{ss}

6.2.6 Evaluation metrics

The reconstructed and generated parametric K_i images were evaluated across noise realisations for voxel based and Volumes of Interest (VOI) based metrics. We define $\theta_{j,n}$ as the image K_i value for voxel j in noise realisation n , $\theta_{VOI,n}$ the VOI K_i mean value and θ_{VOI}^{GT} the ground truth value (as measured from Patlak analysis on the noiseless simulated TACs). The following voxel-based metrics were calculated, where (6.8) is the Root Mean Square (RMS) spatial average of (6.6) and (6.7) within a VOI.

$$Bias_j = \bar{\theta}_j - \theta_{VOI}^{GT} \quad , \text{ where } \bar{\theta}_j = \frac{1}{N_{noise}} \sum_{n=1}^{N_{noise}} \theta_{j,n} \quad (6.6)$$

$$CoV_j = \frac{1}{\theta_{VOI}^{GT}} \sqrt{\frac{1}{N_{noise}} \sum_{n=1}^{N_{noise}} (\theta_{j,n} - \bar{\theta}_j)^2} \quad (6.7)$$

$$\text{Metrics for } j \in VOI \left\{ \begin{array}{l} \%RMS \text{ Bias} : \frac{100}{\theta_{VOI}^{GT}} \sqrt{\frac{1}{N_{VOI}} \sum_{j \in VOI} Bias_j^2} \\ \%RMS \text{ CoV} : \sqrt{\frac{1}{N_{VOI}} \sum_{j \in VOI} CoV_j^2} \times 100 \end{array} \right. \quad (6.8)$$

The following metrics were used for VOI-based analysis, with the average VOI value being the parameter of interest (as opposed to the pixel value).

$$\text{Metrics for VOI} \begin{cases} \%Bias_{\theta_{VOI}} = \frac{100}{\theta_{VOI}^{GT} N_{noise}} \sum_{n=1}^{N_{noise}} (\theta_{VOI,n} - \theta_{VOI}^{GT}) \\ \%CoV_{\theta_{VOI}} = \frac{100}{\theta_{VOI}^{GT}} \sqrt{\frac{1}{N_{noise}} \sum_{n=1}^{N_{noise}} (\theta_{VOI,n} - \bar{\theta}_{VOI})^2} \end{cases} \quad (6.9)$$

Because Patlak analysis provides different fits on the simulated TACs depending on the DWB protocol framing, the θ_{VOI}^{GT} differ slightly per protocol. The ground truth values used in the evaluations are given in table 6.3. The cortex and an eroded thalamus VOI were evaluated in the analysis. The thalamus VOI was eroded by 2 voxels in order to be less susceptible to partial volume effects. By contrast the cortex VOI is subject to partial volume effects. The same metrics were applied to the parametric K_1^* images, for which θ_j represents the parametric image K_1^* value for voxel j and θ_{VOI}^{GT} the ground truth K_1 values.

Table 6.3: θ_{VOI}^{GT} and true K_i values for the simulated acquisition protocols (min^{-1}).

VOI Name	SB	DWB-1	DWB-2	DWB-3	K_i
Thalamus	0.0305	0.0309	0.0311	0.0303	0.0307
Cortex	0.0390	0.0391	0.0392	0.0388	0.0410

6.2.7 Real Data

A single-bed dynamic examination centred over the lungs region was used to test performance of the evaluated algorithms and to compare results against the simulation findings. Approval for the retrospective use of the real patient data was obtained for this study. The data had been collected with approval from a local ethics committee. The original dataset was acquired on a Signa PET/MR, starting at the injection of 177 MBq of FDG tracer to the patient, for a duration of 1 hour. The imaged patient had been diagnosed with a non small cell lung cancer (NSCLC) at the left lung. The raw list-mode dataset was retrospectively reprocessed (replayed) to create two new datasets. One dataset using the framing of the simulated single bed (SB) study and one dataset using the framing of the simulated DWB-1 study (DWB) including temporal gaps. Both datasets included TOF information provided by the Signa PET-MR. The datasets were reconstructed with and without the use of TOF information in reconstruction. An IDIF from the ascending aorta was measured on activity image data from 3D reconstruction and used for 4D reconstruction and post-reconstruction analysis. The two datasets were reconstructed using the same 3D and 4D dynamic reconstruction algorithms that were used in the simulation study using identical parameters. No respiratory motion correction or gating was applied on the data. Similar to the simulation study, post reconstruction Patlak analysis at the voxel

level was performed with OLS to generate parametric images of K_i . VOIs were drawn over the tumour, the tumour's background (left lung) and the liver, as shown in figure 6.4, to compare between reconstructions and against the findings of the simulation study. Using these the contrast to noise ratio (CNR) was estimated according to

$$CNR = \frac{\theta_{tumour} - \theta_{bkg}}{\theta_{bkg} SD_{liver}}, \quad (6.10)$$

where SD_{VOI} is the spatial standard deviation of a VOI.

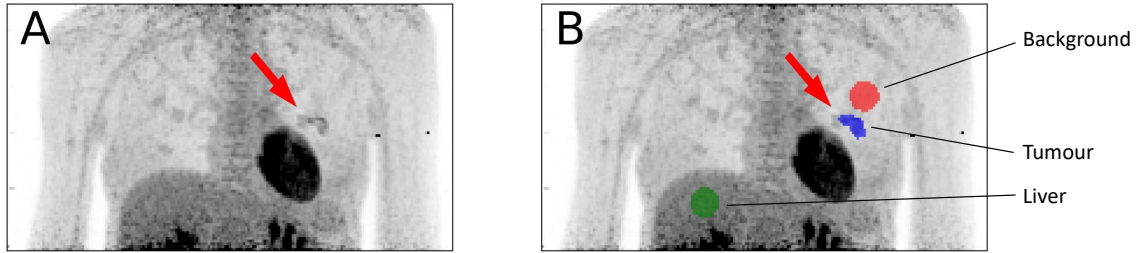


Figure 6.4: Real data MIP SUV image (A) and the drawn VOI (B).

Similarly, CNR was calculated in a single noise realisation of the simulation study to enable direct comparison with the real data. In this case the eroded thalamus VOI was used as the target region and the white matter as the background for both contrast and noise estimation.

6.3 Results

6.3.1 Comparison between SB and DWB protocol data

The VOI and voxel based metrics comparing 3D and 4D Patlak reconstructions for the SB and DWB-1 protocols are shown in figure 6.5. For both metrics and VOIs the 3D reconstruction followed by post-reconstruction Patlak fitting using DWB data resulted in higher CoV values, compared to 3D reconstruction of SB data at matched bias. For the first few iterations the 3D reconstructions of both datasets resulted to similar bias values, while further iterations resulted to a wider range of bias values for the DWB data compared to SB data within 40 iterations.

The use of 4D Patlak reconstruction on DWB data produced results with lower CoV on both evaluated metrics and VOIs, compared to the 3D reconstruction of the same data at matched bias, and a shorter range of bias values within 40 iterations. For the VOI metrics, CoV values of the 4D Patlak reconstruction on both evaluated regions approach those of 3D reconstruction of SB data. Furthermore, the 4D Patlak reconstruction of DWB data resulted in eroded thalamus bias values that evolved towards a steady value of positive

bias, at approximately iteration 12, after which further iterations resulted in small step changes towards lower bias. For the voxel metrics, similar behaviour is seen on early iterations of 4D Patlak reconstruction on DWB data for the CoV, with values approaching those of 3D reconstruction of SB data. But at further iterations the CoV for the 4D Patlak reconstruction in both VOIs surpasses values from 3D reconstruction on DWB data. On the eroded thalamus this was the case beyond iteration 24, while for the cortex from iteration 22 and beyond. These results show that there is a risk of increasing parametric image noise, greater than that of 3D reconstructions, when the 4D reconstruction is run at high iterations to achieve more favourable and stable mean VOI behaviour.

The use of 4D Patlak reconstruction with SB data showed similar effects on behaviour for CoV and bias on both metrics, compared to 3D reconstruction of SB data, and resulted in the lowest CoV values for these comparisons.

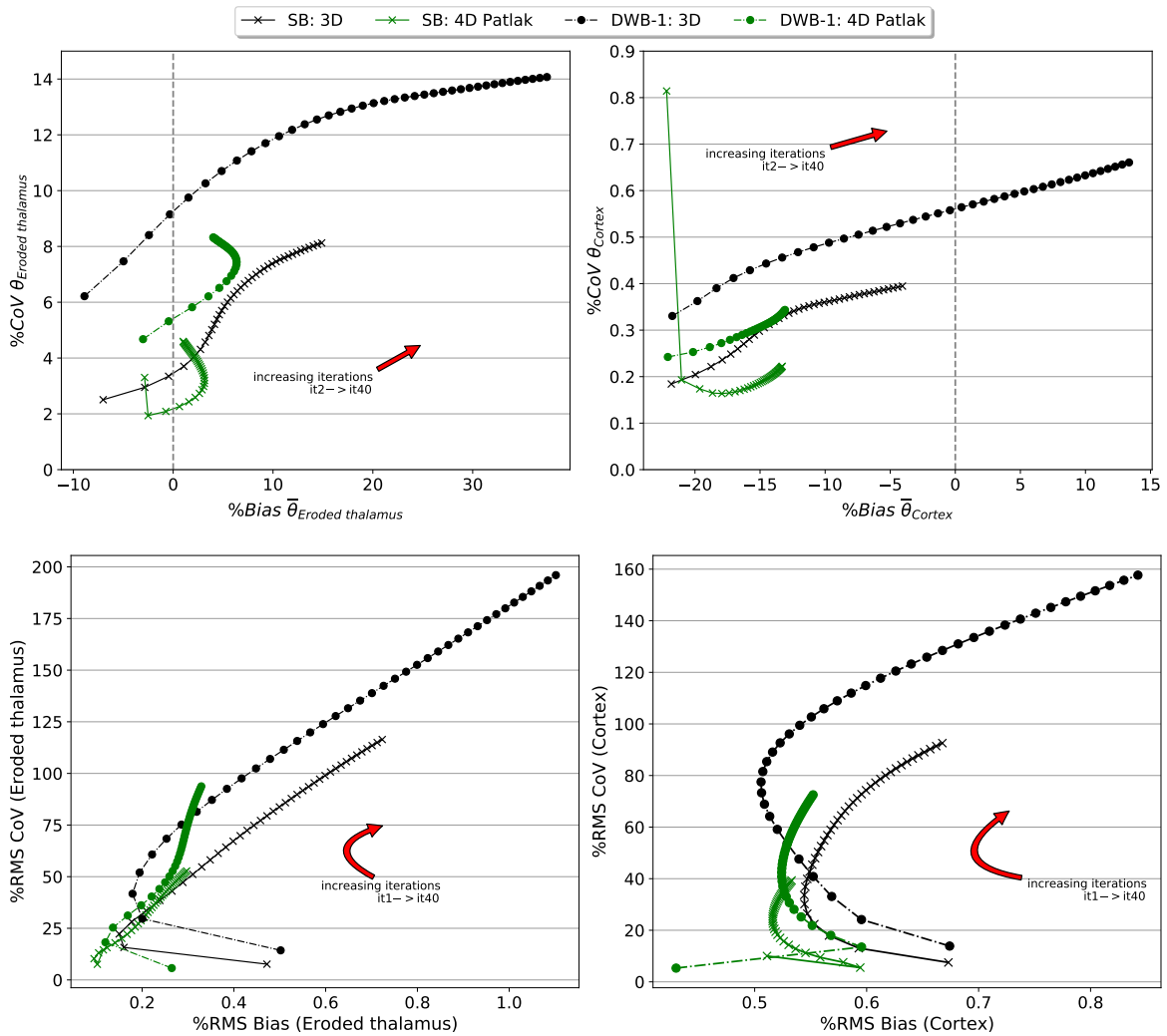


Figure 6.5: Simulation: Eroded thalamus (left) and Cortex (right) noise versus bias trade-off curves for 3D and 4D Patlak reconstructions. VOI based metrics (top row) and voxel-based metrics (bottom row).

6.3.2 Comparison between 4D Dynamic Reconstructions on DWB protocol data

The VOI and voxel based metrics are shown in figure 6.6 for comparison of 4D Patlak and 4D Spectral reconstructions of DWB data. On both metrics and for both regions the use of Spectral reconstruction with 6 basis functions provided the lowest CoV values at matched bias compared to other 4D reconstructions of DWB data and 3D reconstruction of SB data. However 4D Spectral reconstruction with 6 basis also provided the highest bias values in the eroded thalamus. On the cortex the difference on bias metrics was relatively small between all 4D reconstructions.

The 4D Spectral reconstruction with 9 and 17 basis functions resulted to similar bias and CoV values at both regions. Their use resulted in lower CoV compared to 4D Patlak reconstruction and 3D reconstruction of SB data, but higher compared to 4D Spectral using 6 basis. Nonetheless, at the eroded thalamus use of 9 and 17 basis provided improved bias values at matched CoV when compared to the use of 6 basis, closer to bias values from 4D Patlak reconstruction.

When the 4D Spectral reconstructions were provided with the same data as the 4D Patlak reconstructions (4 frames with $t > t_{ss}$) instead of all data (8 frames for DWB-1), it resulted in a noticeable increase of the CoV values, with very close noise versus bias trade-offs between 6 and 9 basis. Their trade-off curves got closer to the one of the 4D Patlak reconstruction, with lower bias values on both metrics but higher RMS CoV compared to the 4D Patlak reconstruction.

6.3.3 Comparing between nested optimizations in 4D reconstruction

Results of 4D Spectral and 4D Patlak reconstructions using MLEM and NNLS nested optimization are shown in figure 6.7. A clear difference in behaviour is seen going from MLEM to NNLS from early iterations, with 4D reconstructions using nested NNLS optimization resulting in higher CoV values at matched bias compared to the respective 4D reconstruction using nested MLEM (with 20 nested sub-iterations). At the same time, NNLS nested optimization often resulted to a slight reduction in bias at matched CoV values. No difference was seen in convergence properties such as convergence speed between the two nested optimization options. Nevertheless the use of a single run of NNLS optimization in each nested loop, instead of 20 nested MLEM iterations, resulted in notable reduction of overall reconstruction times. The average reconstruction times using the two methods on a computer using a 16-core 2.20GHz processor and 96GB of RAM memory are shown in table 6.4.

6.3.4 Comparison between DWB protocols

Comparison of 4D Patlak and 4D Spectral reconstructions between the three simulated DWB protocols is made in figure 6.8. For both VOI regions and 4D reconstructions, data from all three DWB protocols resulted

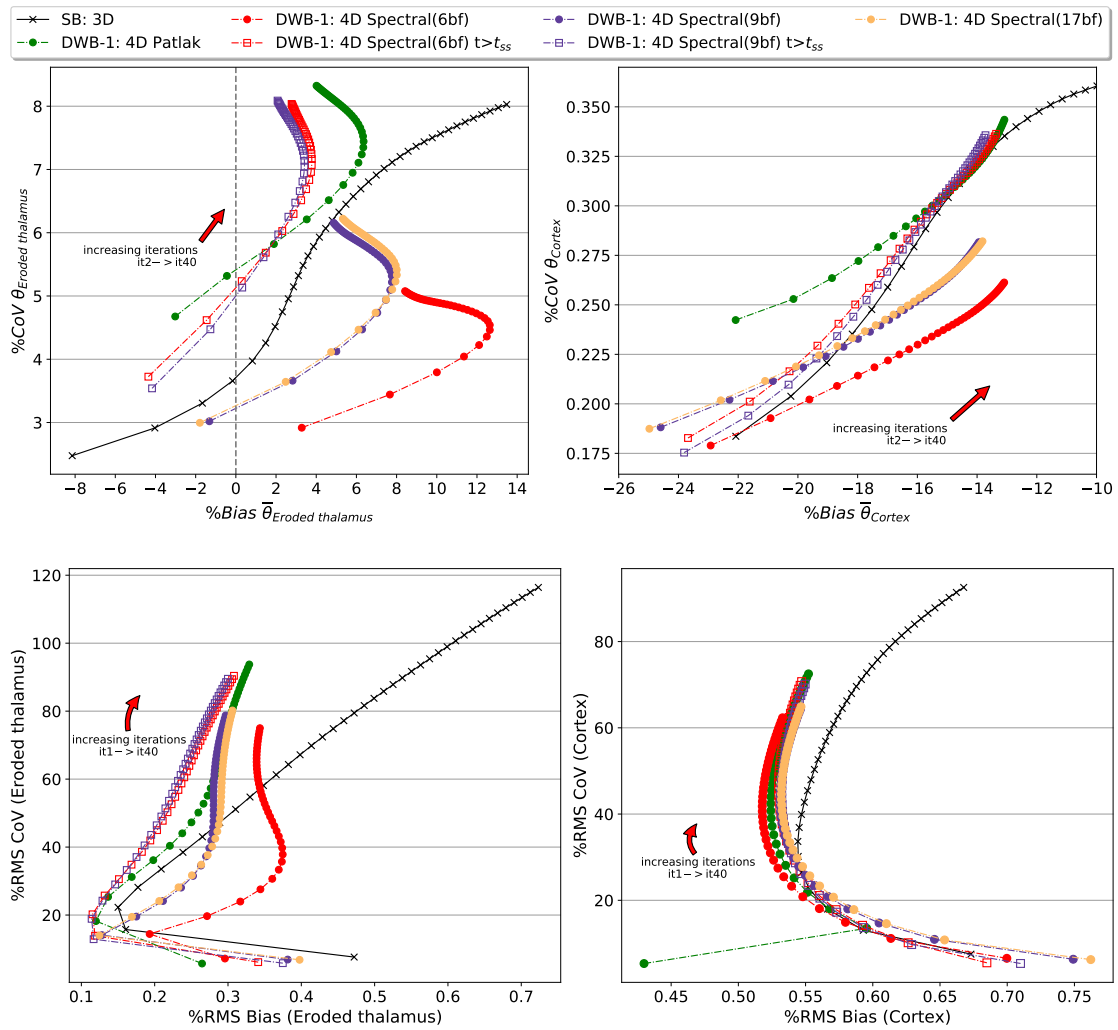


Figure 6.6: Simulation: Eroded thalamus (left) and Cortex (right) noise versus bias trade-off curves for 4D reconstructions of DWB-1 protocol data. VOI based metrics (top row) and voxel-based metrics (bottom row).

Table 6.4: Average reconstruction times for 1 full iteration (28 subsets) over DWB-1 data using CASToR.

Reconstruction	nested MLEM (min)	nested NNLS (min)
4D Patlak	9.6	6.7
4D Spectral(6bf)	14.0	8.2
4D Spectral(9bf)	15.8	8.3
4D Spectral(17bf)	26.6	11.2

in close bias values at matched iteration number, with a slight deviation in RMS bias towards late iterations. Differences in CoV at matched bias values are more profound in VOI metrics of the cortex region, where data from protocol DWB-2 resulted in the lowest CoV values and DWB-1 and DWB-3 data resulted to closer CoV values. This level of reduction in CoV was not seen on the eroded thalamus, neither on VOI or voxel based metrics. In the eroded thalamus the differences of DWB protocols on CoV at matched bias were smaller and their ordering was mixed between the two 4D reconstructions.

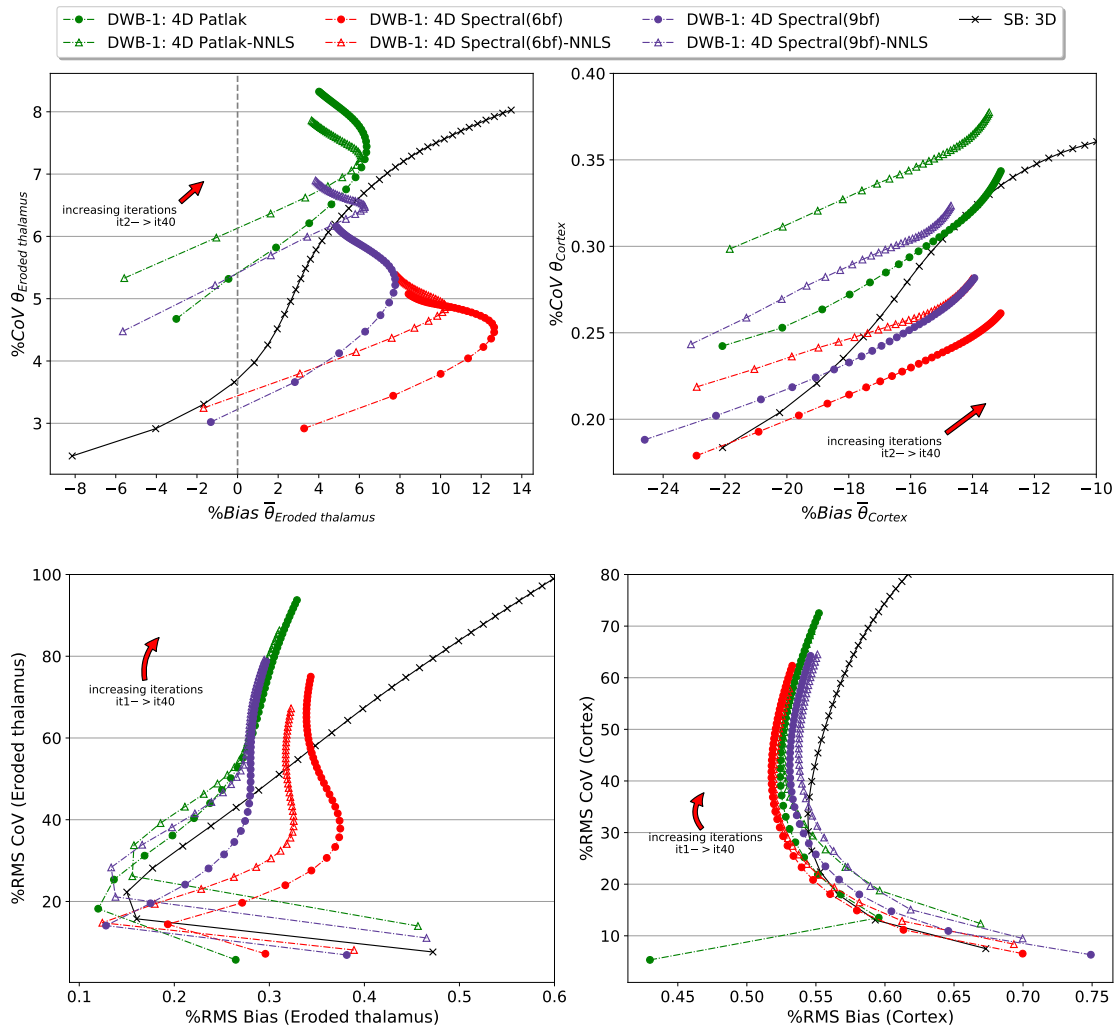


Figure 6.7: Simulation: Eroded thalamus (left) and Cortex (right) noise versus bias trade-off curves for 4D reconstructions, with MLEM and NNLS nested optimization. VOI based metrics (top row) and voxel-based metrics (bottom row).

6.3.5 Comparison with real data

The comparison of reconstructions using a real FDG dataset, reprocessed and reconstructed with the SB and DWB-1 protocol framings, is made in figure 6.9 for non-TOF reconstructions and in figure 6.10 for reconstructions using TOF.

A clear difference in convergence behaviour can be seen by comparing the evolution of CNR curves between the real data non-TOF and TOF reconstructions. For non-TOF reconstructions, a maximum CNR is attained after two to three full iterations, while for TOF reconstructions maximum CNR is seen from the very first iteration (indicating that maximum is attained within the first 28 subsets of the OSEM algorithm). Results in both cases showed similar evolution of CNR with increasing iterations for 4D and 3D reconstructions, in non-TOF and TOF reconstructions respectively. The 4D Spectral reconstruction using 6 basis functions

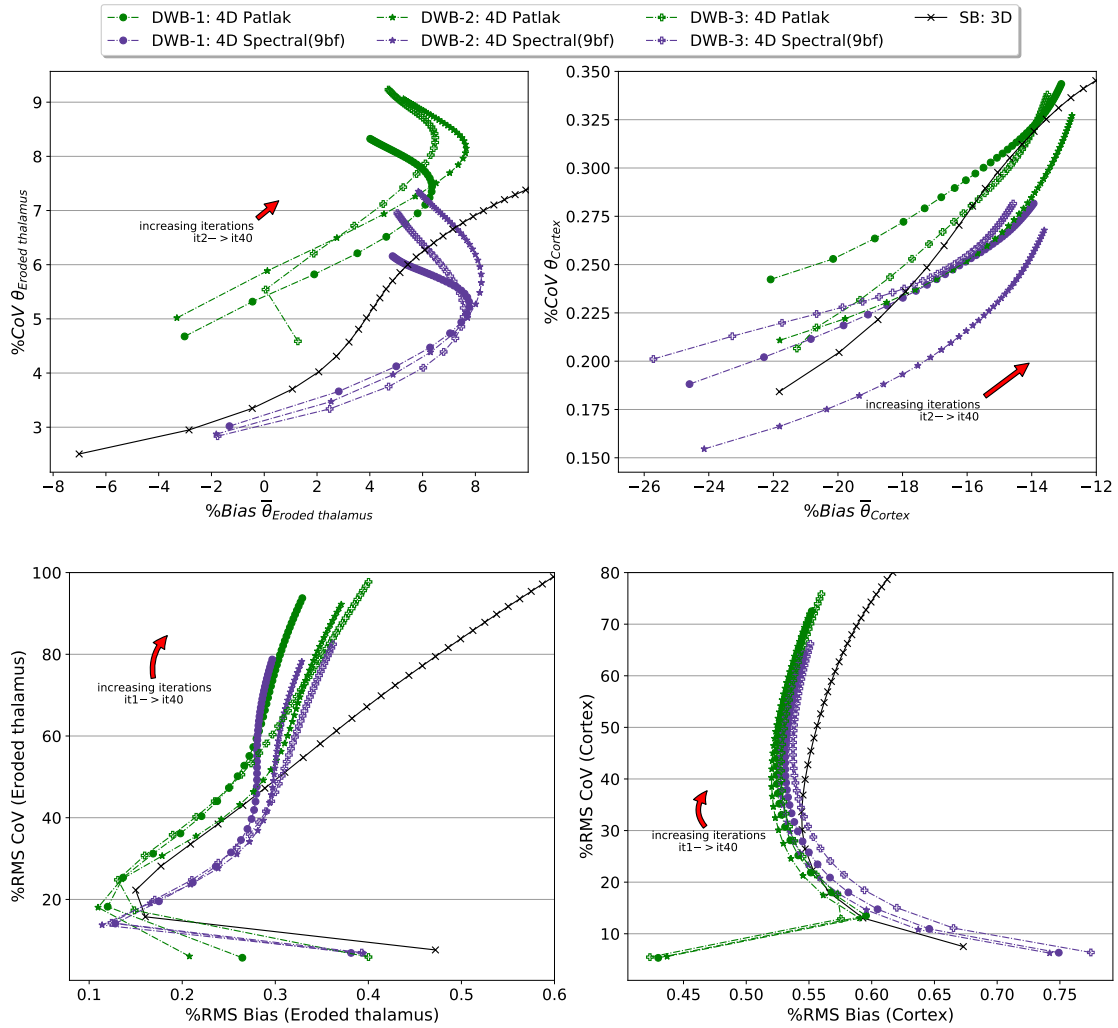


Figure 6.8: Simulation: Eroded thalamus (left) and Cortex (right) noise versus bias trade-off curves for 4D reconstructions of the simulated DWB protocol data. VOI based metrics (top row) and voxel-based metrics (bottom row).

provided the highest CNR values throughout all iterations, followed by the 4D Spectral reconstruction using 9 basis functions and 4D Patlak. Overall, CNR of all 4D reconstructions of DWB data was higher than that of 3D reconstruction of SB data and 3D reconstruction of DWB data.

The liver SD vs tumour mean trade-off curves showed close behaviour between 4D reconstructions using TOF, resulting to SD values in the first 15 to 17 iterations of 4D reconstructions which were lower compared to 3D reconstruction of DWB data at matched tumour mean values. Compared to 3D reconstruction of SB data, all 4D reconstructions of DWB data resulted in higher SD values (for matched tumour mean values where comparison is possible). For 4D reconstructions of DWB data without TOF information, SD values were lower to 3D reconstruction of DWB data for the first 16 to 25 iterations, while higher than 3D reconstructions of SB data at matched mean tumour values. Furthermore, the liver SD vs tumour mean trade-off curves of

4D reconstructions using TOF information showed very small differences in their evolution with increasing iterations. By contrast, the non-TOF 4D reconstructions showed a degree of separation of the 4D Patlak reconstruction from Spectral reconstructions.

Mean tumour K_i values were lower in reconstructions without TOF compared to all reconstructions using TOF at respective 3D and 4D reconstructions. The difference was also seen in VOI TAC measurements of the tumour between non-TOF and TOF 3D reconstructions and could potentially be attributed to differences in contrast recovery within the reconstruction by use of TOF information and its effects in reduction of motion induced blurring.

Parametric K_i images from 3D and 4D reconstructions with TOF at iterations with matched liver SD values of approximately $4 \cdot 10^{-3} \text{ min}^{-1}$ are shown in figure 6.11.

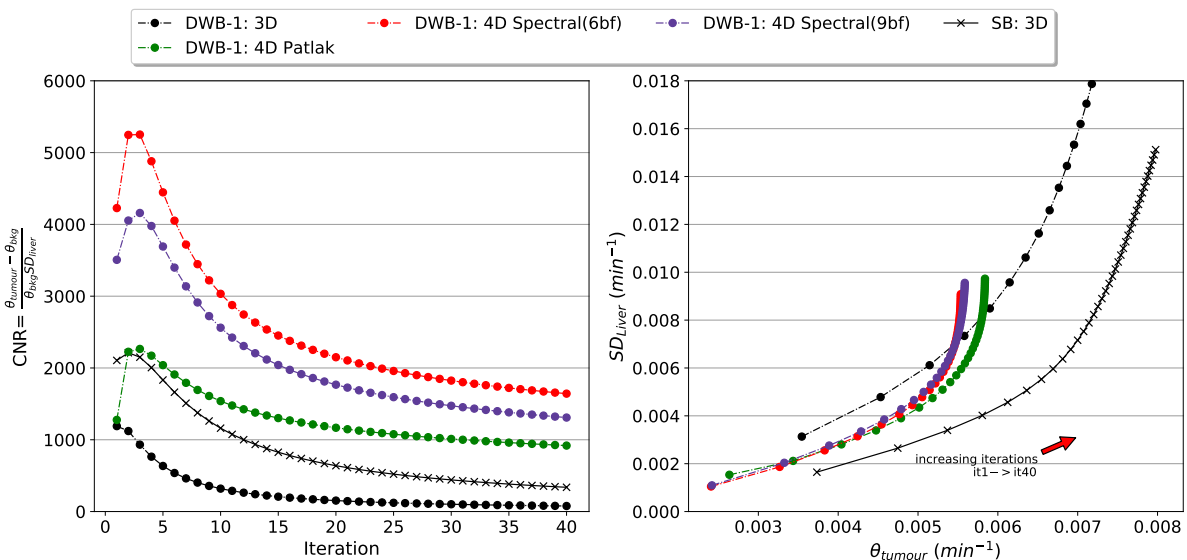


Figure 6.9: Real Data: Contrast to Noise ratio (left) and liver SD vs. VOI mean of the tumour (right) for 3D and 4D reconstructions without TOF information.

For comparison against the simulation study, metrics of CNR and SD vs VOI average trade-off curves from a randomly chosen noise replicate of simulation DWB-1 are shown in figure 6.12. Similarly to the real data, with or without TOF information, values of CNR are highest for 4D Spectral reconstruction using 6 basis functions followed by 4D Spectral reconstruction using 9 basis functions. For the simulation data and real data without TOF, 4D Patlak reconstruction provided lower CNR values compared to 4D Spectral reconstruction using 9 basis functions and closer to the values of 3D reconstruction from SB data at initial iterations. By contrast, real data using TOF resulted in similar CNR values between all 4D reconstructions. The evolution of CNR with increasing iterations was similar between non-TOF real data and simulated data. Finally, the simulation data SD vs VOI average trade-off curves of the eroded thalamus showed greater separation of 4D reconstructions, with 4D Spectral reconstructions providing lower SD values compared to

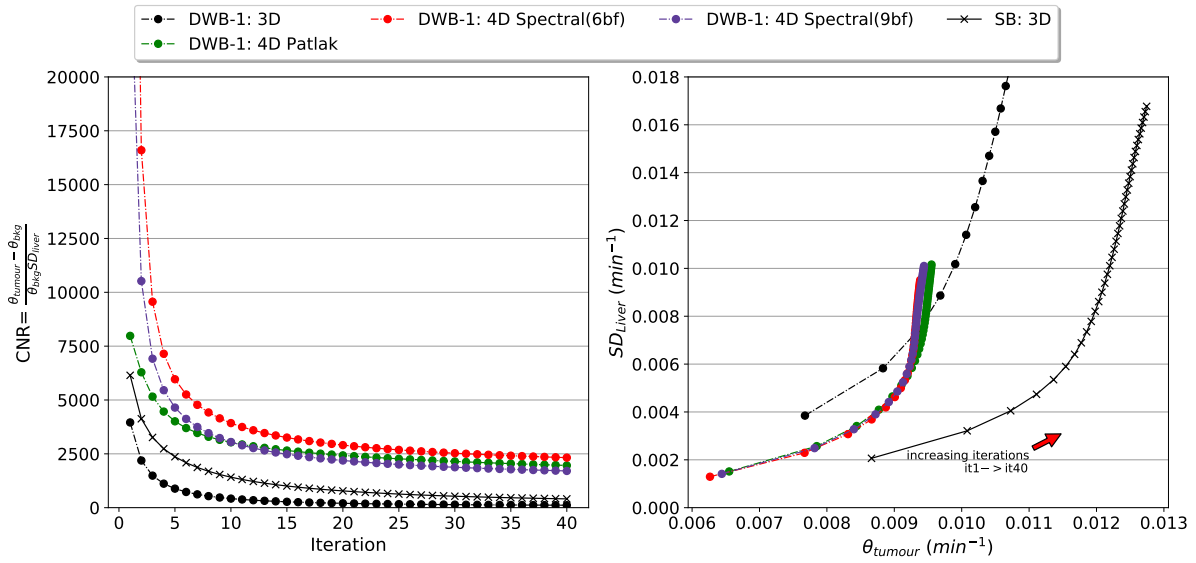


Figure 6.10: Real Data: Contrast to Noise ratio (left) and liver SD vs. VOI mean of the tumour (right) for 3D and 4D reconstructions using TOF information.

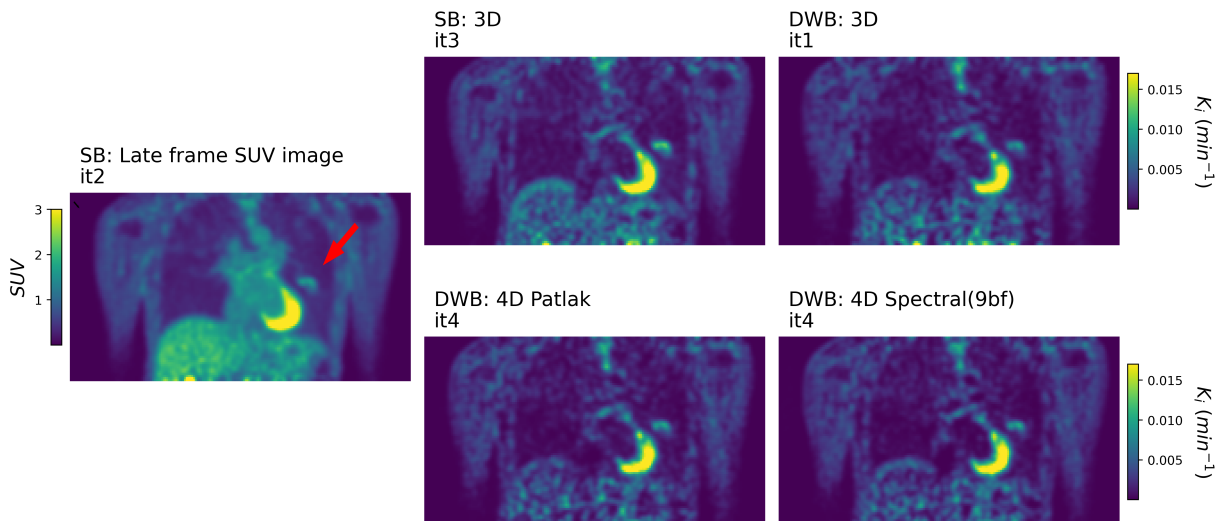


Figure 6.11: Real Data: Parametric K_i images (with 5mm Gaussian Filtering) from SB and DWB replay datasets from 3D and 4D reconstructions, using TOF information, at matched SD values over the liver.

3D and 4D Patlak reconstruction of DWB data, but at higher bias values as shown previously in the analysis of simulation results. Parametric K_i images of 3D and 4D reconstructions at matched RMS CoV values, of approximately 32% as measured at the eroded thalamus VOI, are shown in figure 6.13 for a single noise replicate along with images of mean bias over noise replicates. The single replicate images show that structures of the thalamus seen in 3D reconstruction of SB data are better resolved in DWB when using the 4D Spectral reconstruction. The images of bias show similar behaviour in the thalamus over reconstructions and illustrate the partial volume effects at the cortex region.

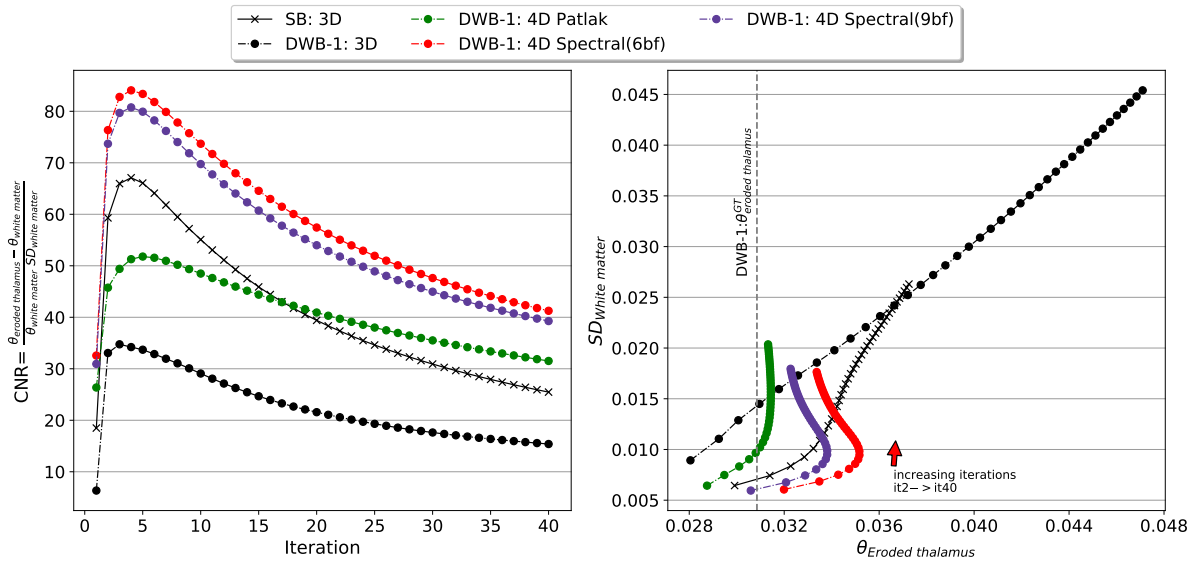


Figure 6.12: Simulation single noise realisation of DWB-1 data: Contrast to Noise ratio (left) and white matter SD vs. eroded thalamus K_i mean for 3D and 4D reconstructions.

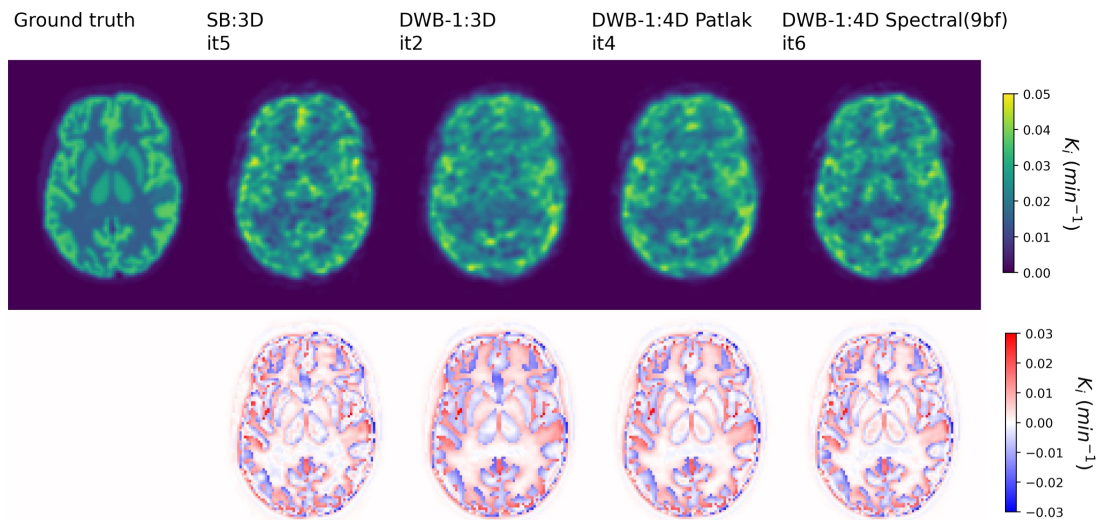


Figure 6.13: Single slice through parametric K_i images of one noise replicate (with 3mm Gaussian Filtering) (top) and their corresponding Bias images (over noise replicates) (bottom) from SB and DWB data 3D and 4D reconstructions at matched RMS CoV in the eroded thalamus.

6.3.6 Parametric K_1^* imaging from 4D Spectral reconstruction

The VOI and voxel based metrics for parametric K_1^* images from the SB, DWB-1 and DWB-4 protocols are shown in figure 6.14 and figure 6.15. For the results from DWB-1 the missing fast dynamic data in the early minutes of the acquisition results in extremely higher bias and noise than the other protocols, on both VOI and voxel based metrics. By contrast, the results from the DWB-4 protocol, which makes use of the early dynamic single bed acquisition along with the DWB acquisition, resulted in VOI and RMS mean similar to that of the SB protocol. For both protocols, results show overestimation of mean VOI measurements

in the eroded thalamus VOI and underestimation in the cortex VOI. It is important to note here that the ignored blood fraction correction in parametric K_1^* images contributes towards an approximate 3% negative bias in quantification if we consider the simulated blood fraction of 0.03 in the thalamus and cortex regions. Measurements of RMS CoV show that data from the DWB-4 protocol result in higher noise compared to SB protocol. Parametric K_1^* images of the evaluated acquisition protocols at matched RMS CoV values, of approximately 40% as measured at the eroded thalamus VOI, are shown in figure 6.16 for a single noise replicate along with images of mean bias over noise replicates. The images from the single replicates of SB and DWB-4 protocol data show similar structures and contrast of these structures, in comparison to the contrast of the ground truth values. The DWB-1 data show the erroneous overestimation of the values and loss of contrast between structures. This is also seen in the bias images for the DWB-1 data, while the bias structures in DWB-4 and SB data are very similar and closer to zero bias. The images of bias illustrate the effect of partial volume effects, similar to the effects shown for K_i imaging.

6.4 Discussion

Our simulation study shows that the dynamic reconstruction of DWB FDG data resulted in substantial reduction of Patlak K_i image noise and more favourable convergence behaviour, compared to 3D reconstruction based parametric imaging. These results, limited to a single level of noise, are in agreement with the findings of Karakatsanis *et al.* [55]. Moreover, we directly compared against a SB dynamic protocol, processed with 3D reconstruction, and showed that comparable values of parametric image noise and bias can be achieved with DWB protocols by the use of a dynamic reconstruction. The choice of the iteration number to terminate a 4D reconstruction algorithm is not evident. For a VOI-based analysis, the convergence of the mean K_i value in the cortex or in the eroded thalamus was not seen in the range of the 40 evaluated OSEM iterations, in particular for a 3D reconstruction. This behaviour was also observed for a 4D reconstruction algorithm, but to a lesser extent. A high number of iterations of 4D reconstruction algorithms provided more stable VOI mean values, but at risk of resulting to higher parametric image noise than that of a 3D reconstructions on the same DWB data. The results obtained with the real data-set showed similar behaviour with mean VOI values continuing to slightly increase even after 40 OSEM iterations and with 4D reconstruction parametric image noise surpassing that of 3D reconstruction at late iterations. This example illustrates that the relative aspects of 4D to 3D comparisons with simulated data for the tested DWB and SB protocols have the capacity to translate to studies with different levels of noise. Overall, the risks of excessive parametric image noise and under-converged K_i values will be lesser for 4D based reconstruction methods than for a 3D reconstruction, which demonstrated considerably more instability with increasing iterations. To ensure convergence of the K_i values while suppressing the increase of parametric image noise, further regularisa-

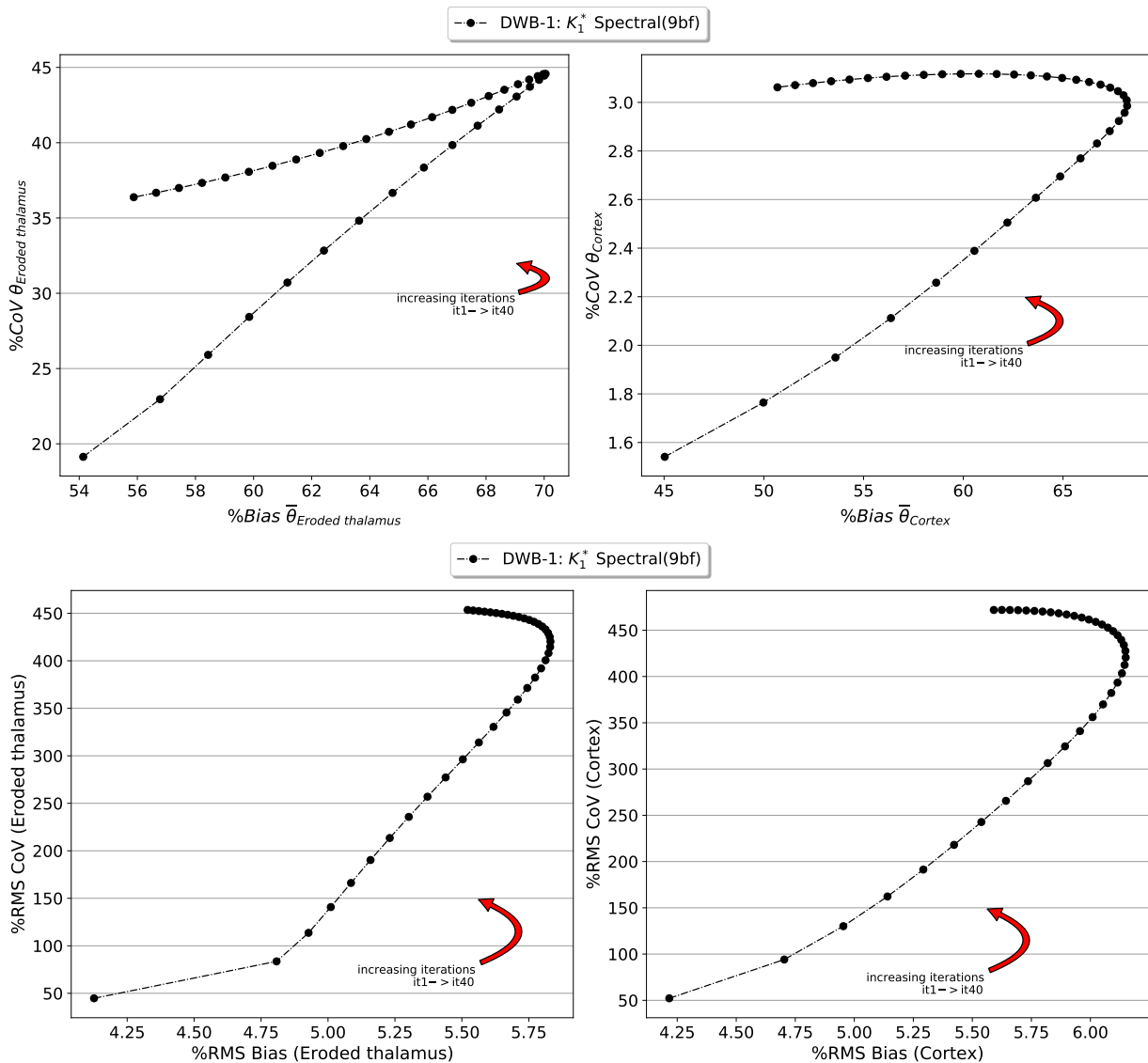


Figure 6.14: Simulation: Eroded thalamus (left) and Cortex (right) noise versus bias trade-off curves for K_1 parametric imaging from 4D spectral reconstructions of the simulated DWB-1 protocol data. VOI based metrics (top row) and voxel-based metrics (bottom row).

tion techniques can be used with methods such as 4D MAP reconstruction [11, 108] or kernel 4D dynamic reconstruction [112, 118].

Our nested optimization tests using NNLS instead of multiple MLEM sub-iterations did not provide any differences in the acceleration of the convergence and showed comparable behaviour to a previous study on the use of NNLS with the spectral model [98]. NNLS did provide computing acceleration by a factor of around two for our data sets, but resulted in an increase of the parametric image noise compared to MLEM sub-iterations for similar bias characteristics. Equivalent or higher acceleration could be potentially achieved if the nested MLEM optimization was conducted in graphical processing units (GPU) instead of the CPUs.

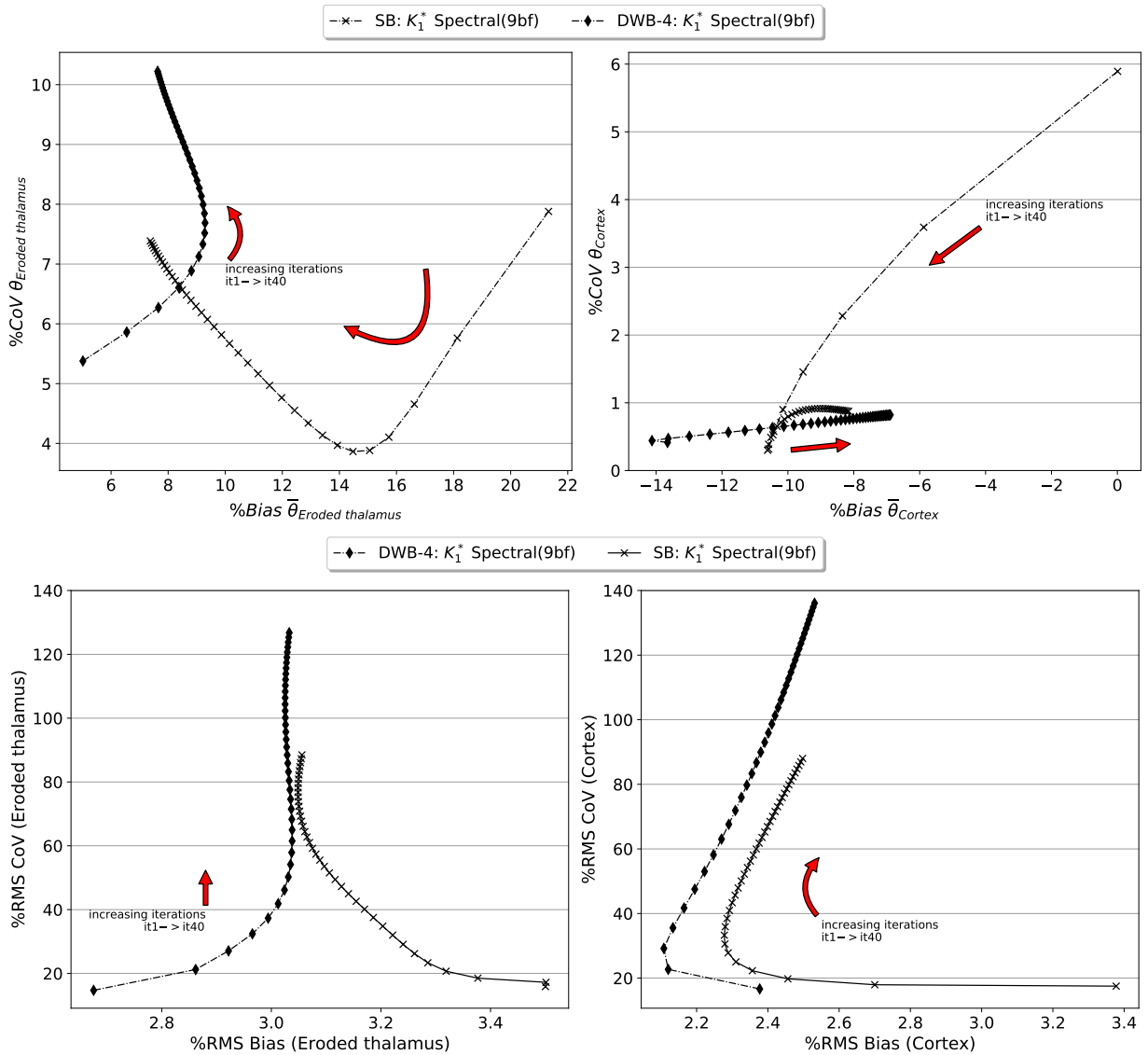


Figure 6.15: Simulation: Eroded thalamus (left) and Cortex (right) noise versus bias trade-off curves for K_1 parametric imaging from 4D spectral reconstructions of the simulated SB and DWB-4 protocol data. VOI based metrics (top row) and voxel-based metrics (bottom row).

In this work, we evaluated the use of an indirect dynamic reconstruction method based on a generic 4D Spectral reconstruction algorithm followed by a post-reconstruction Patlak model fitting. The genericity of the spectral model allows for flexibility in modelling dynamic processes that do not necessarily fall under the idealised behaviour of the kinetic model of interest. In this simulation study, we were limited to irreversible FDG kinetics that can be sufficiently described by the Patlak model. In this case, 4D Spectral reconstruction making use of the full dynamic data outperformed the direct Patlak reconstruction in terms of parametric image noise, while maintaining similar bias behaviour. The benefit of the 4D spectral reconstruction was less obvious when fewer frames were used in reconstructions using $t > t_{ss}$, indicating that its favourable behaviour was mostly due to the use of more temporal frames than the Patlak reconstruction. In real FDG

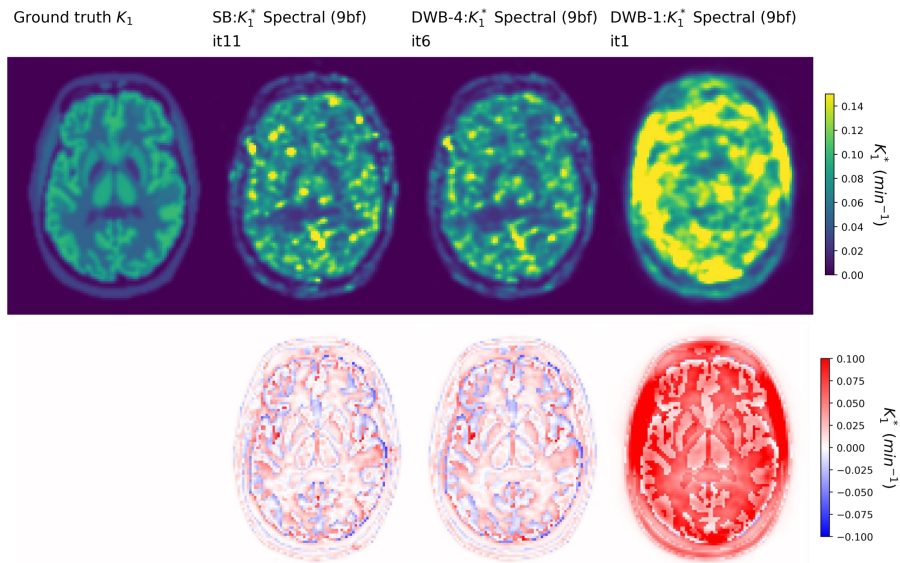


Figure 6.16: Single slice through parametric K_1^* images of one noise replicate (with 3mm Gaussian Filtering) (top) and their corresponding Bias images (over noise replicates) (bottom) from SB and DWB data, for 4D Spectral reconstructions at matched RMS CoV in the eroded thalamus.

studies, it can be desirable to account for reversible FDG kinetics and reduce the bias of the estimated macro-parameters arising from poorly modelled kinetics. The spectral model can allow for more complex compartmental modelling with no strong prior knowledge or enforcement of a specific model. As such it can account for more complex kinetic behaviours, including reversibility of tracer, in the reconstruction process and allow for post-reconstruction exploratory modelling to identify the best model to describe and present the data. Moreover for DWB studies where not all body regions and organs will necessarily be adequately described by a single dynamic model of interest, the proposed indirect method can allow for the assignment of different kinetic models in different regions of the body to ensure appropriate representation of the dynamic tracer behaviour. Depending on the availability of early frame data, the fitted spectral model can be used to directly estimate K_1 [98, 119], while post-reconstruction micro-parameter estimation could be performed for potential uses in clinical applications [112, 120] and indirectly take advantage of the 4D reconstruction temporal regularisation. An important parameter to configure for the spectral model is the number of basis function. Contrary to post-reconstruction spectral analysis where hundreds of basis functions are used to finely sample the space of kinetic exchange rates, a smaller number of basis is desirable in reconstruction to favour reduced image noise. In some cases of our findings the lowest number of basis functions used (6 basis) resulted in higher bias values which indicates less than adequate modelling of the underlying kinetics, compared to reconstructions with more basis functions and to 4D Patlak reconstruction. However this was not the case when fewer frames were used in reconstructions using $t > t_{ss}$ data. These findings indicate that the selection of number of basis functions is important not only for controlling the produced image noise

but also for controlling bias by adequately modelling the kinetics behaviour in reconstruction. For the higher numbers of basis functions, with 9 and 17, almost identical behaviour was seen on the DWB-1 dataset (of 8 frames). Overall on the choice of number of basis functions, results indicate a greater risk in image bias when using a too small number of basis functions, and a lesser risk in excessive image noise when using more basis functions than strictly needed to properly model the underlying kinetics. In any case the number of basis needs to be tuned for every DWB protocol, depending on the number of frames within the dataset and the range of underlying kinetics as well as the level of noise in the PET data.

In this study, the investigation between S&S and CBM DWB protocols was limited to aspects of sampling frequency and uniformity within the total examination time. Our results showed small differences in parametric image bias but noticeable reduction in parametric image noise when utilising CBM acquisition with uniform sampling. Overall differences were inline with previous findings of comparison S&S and CBM on a real data study using different metrics [121]. A limitation in our study is that we have considered a single axial location and hence we cannot generalise the results of the simulation study for the performance of the assumed DWB protocols over their effective FOV. Furthermore beyond the aspects of reduced acquisition delays and higher sampling frequency, CBM acquisition has other desirable properties for DWB acquisitions as outlined previously [121]. The most important aspect is the result uniform axial sensitivity profile at any choice of acquisition speed. That can be of importance in DWB parametric imaging where multiple regions of interest are expected in the effective FOV. In our study we have not considered this aspect for the CBM protocols and we did not examine regions in the overlap range of the S&S protocol. But the observed improvements related to reduced delays in acquisition coupled with uniformity of axial sensitivity favour the choice of CBM over S&S protocols. We investigated further potential reductions in system delays by allowing for non-uniform axial sampling using bi-directional CBM. In that case we did not see the same effects as in the transition from S&S to CBM. But our results on bi-directional CBM are limited to the specific framing of the evaluated protocol design which offered more total frames but resulted in less total counts compared to the other protocols. Additional tests are required on the exploitation of the flexibility offered by bi-directional CBM to assess other potential benefits against uni-directional CBM.

Finally an additional evaluation was made for parametric K_1 imaging, by use of the spectral model and the spectral coefficient images, to explore additional potential benefits from the use of 4D Spectral reconstruction in parametric imaging. The tests showed, as expected from previous single bed dynamic studies [119], that the first few minutes of the acquisition are crucial for the estimation of K_1 . Estimates of K_1 were extremely biased and noisy for estimates that did not made use of dynamic data from the first 3 minutes, as shown with K_1 imaging from DWB-1 protocol data. The DWB-4 protocol that made use of the first 3 minute acquisition provided results that were very similar to those of the single bed protocol data with no gaps. These results

are promising for the estimation of K_1 parametric images from DWB protocols that include an initial dynamic single bed phase. These estimations will be limited thought to the areas covered by this initial acquisition. A considerable limitation in our tests for K_1 parametric imaging using 4D Spectral reconstructions is that quantification accuracy was compromised by not considering the blood volume fraction in K_1^* estimation. Similarly to other works in the literature [66], this was done to avoid excessive parametric image noise by the division operation that is required by equation 2.23 to correct K_1^* for blood volume fraction. Alternatively to completely neglecting the blood volume fraction correction, a constant value could be assumed for certain regions of the image or smoothing and other denoising operations could be performed on the 4D spectral reconstruction estimated blood fraction image ϕ_M before being applied to the K_1^* image via division.

Finally, an open question remaining unanswered is whether a DWB protocol (limited by the scanner's hardware imposed acquisition delays) could be optimised in a way that it could provide sufficient dynamic information on early kinetics for the reliable estimation of K_1 maps over the whole-body. As already mentioned, K_1 information can be complementary to K_i and thus of interest to be estimated over the whole body. Furthermore, in pharmacological applications, such as the one presented in chapter 7, estimation of K_1 over the whole body could be of great interest.

6.5 Conclusion

Dynamic reconstruction capabilities were successfully developed and validated in CASToR, for multiple dynamic models and optimization algorithms. Along with dynamic developments for a PET analytical simulator, those tools have enabled an extensive evaluation of dynamic reconstruction methods for application in DWB imaging. The developed tools were used for the application of dynamic reconstruction on real data and were further evaluated and expanded for use with real DWB data, in the work that is described in the following chapter.

The study presented here focused on a single bed location, even though the simulation considered multi-bed acquisition protocols. In the following chapter, the use of the developed reconstructions will be extended to multi-bed dynamic reconstruction using a direct dynamic approach for all bed positions, which will be applied on real DWB data. The assumed approach in the study presented here was the reconstruction of each bed individually, which necessitate the DSB phase of the acquisition to be aligned with one of the bed locations of the DWB phase, in order to take advantage of the fast kinetic information within the dynamic reconstruction. As we will present in the following chapter, the developments on multi-bed dynamic reconstruction on CASToR lift this limitation.

In this study we have shown that 4D dynamic reconstruction is necessary in DWB parametric imaging to

achieve accurate and stable quantification. For FDG Patlak K_i parametric imaging we have shown results of direct Patlak dynamic reconstruction with noise and bias values that were comparable to 3D reconstruction based parametric imaging from single bed dynamic studies. In this work we proposed the use of an indirect method for DWB parametric imaging, based on the spectral analysis model. This more flexible approach allows for complex kinetic modelling to be used during reconstruction for temporal regularisation, with minimal assumptions on the underlying kinetics. In Patlak K_i parametric imaging this method outperformed the direct Patlak approach, by making use of all the acquired data for temporal regularisation from which post-reconstruction parametric imaging benefitted by further reduction of noise compared to the Patlak approach. Furthermore, the spectral model approach can be used for more complex post-reconstruction modelling, for example in parametric imaging of FDG micro-parameters. In our evaluation we showed that in addition to post-reconstruction fitting, dynamic reconstruction with the spectral model can be used for estimation of K_1 parametric images when early dynamic information are available.

Finally, we investigated the impact of various acquisition modes (for CBM and S&S) resulting in different temporal sampling of the data. Benefits of reduced delays and increased acquisition statistics were partially seen in reduced parametric image noise for the CBM protocol with uni-directional axial sampling. By contrast CBM using bi-directional motion resulted to parametric image noise levels that were similar to the S&S protocol. Further investigation is required to assess the potential benefits from bi-directional CBM against uni-directional CBM and effects of non-uniform sampling over the entire FOV of the DWB protocols.

Overall, use of 4D dynamic reconstruction for DWB parametric imaging offers desirable properties that enables the transition from single bed dynamic studies and common 3D reconstruction parametric imaging practices without loss of image quality and with additional benefits for accuracy of parametric images. Potential applications of DWB parametric imaging are expected to rely on quantification of images and so there should be no compromise between parametric image accuracy and image noise. Our results showed that 4D reconstruction need to be sufficiently iterated to ensure accurate quantification, with potential for improvement in maintaining low parametric image noise by use of additional regularisation methods.

Chapter 7

Extension of Dynamic Reconstruction to Multi-Bed Reconstruction and Applications in a Whole-Body Pharmacological Study

7.1 Introduction

Acquisition of DWB datasets in S&S mode with overlapping bed positions result in complex datasets of PET raw data, in relation to timing and positional information. Moreover, the addition of an initial DSB acquisition, conducted for IDIF derivation purposes or for the sampling of fast kinetics to allow for more complex kinetic modelling [120], increases the complexity of the PET raw dataset.

Suggested practices [8] and state of the art implementations [17] of DWB protocols regard the two datasets (DSB and DWB) as independent and suggest performing independent reconstructions on each dataset. Post-reconstruction kinetic model fitting is then used to combine the TAC information over both datasets. Furthermore, the DWB dataset contains locations at the overlapping bed regions which are sampled twice as much as central bed regions, as a result of the overlap sampling necessary to increase sensitivity at the bed position edges. The overlap timing information combines the timing of the adjacent bed positions. In post-reconstruction kinetic modelling, which is applied independently on each voxel TAC, suggested practices make use of modified timing information (average of two bed position timings) for voxels that fall at

overlapping regions [8] which result in a degree of degradation of the timing information. Another suggestion is to make use of independent dynamic reconstruction of each bed position from the DWB dataset, as it was conducted in the previous chapter, and apply post-reconstruction overlapping of parametric images [55]. In this case if the DSB data are to be included in the dynamic reconstruction, the placement of the DSB bed position needs to be identical to one of the bed positions of the multi-bed dynamic study.

It is important to note that DWB acquired in CBM mode, although free of the need of overlapping bed positions still require similar considerations to be taken into account for each axial location of the DWB acquisition [17, 121].

The flexibility offered by the CASToR reconstruction platform that allows for direct reconstruction of multi-bed data [50] can be expanded to direct multi-bed dynamic reconstruction of DWB data, using the exact timing information of the dataset and all bed positions within the same iterative loop. Furthermore, the offered flexibility can allow for the use of both DSB and DWB datasets within one unique reconstruction loop, with no constraints in the positioning of the DSB acquisition. In this chapter, we describe how this novel DWB protocol reconstruction concept was implemented in CASToR and present results from a dynamic reconstruction of real DWB data from the IsotoPK study, which were also presented in the EANM2020 conference [122].

7.2 Methods

7.2.1 Dynamic Whole Body Datasets

A diagram of axial position against time for an example three bed position DWB protocol is shown in figure 7.1, to demonstrate the differences in temporal sampling between central locations and locations at the bed overlapping regions. The bed locations in this example are identical to the setup used for the NHP study on the Signa PET/MR described in chapter 5. As it can be seen in the left diagram of figure 7.1 axial positions that fall outside of the overlap region result in framing that is equal to the framing of their respective bed positions. Positions over the overlap regions, seen at the right diagram of figure 7.1, result in framing equal to that of both adjacent bed positions, which gives twice the number of frames compared to locations outside the overlap. Locations at the overlap regions are not sampled continuously from both contributing bed positions due to the interruption by the movement of the bed and system delays. Finally, complexity is increased when the DSB data are included, as shown in figure 7.2, with that information contributing to different locations of the DWB acquisition that might fall in overlap regions or not depending on the protocol setup.

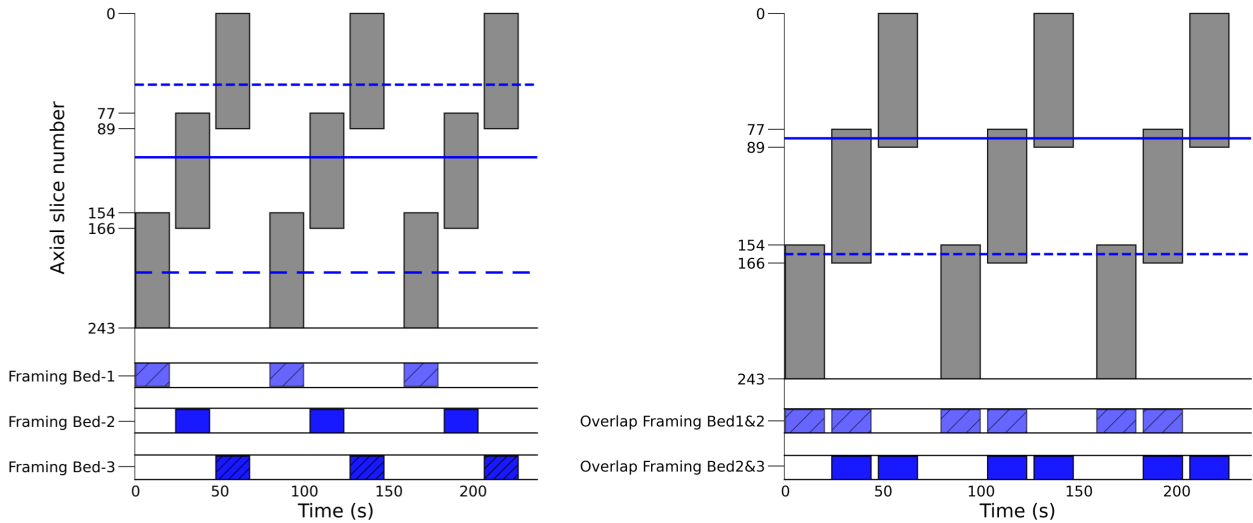


Figure 7.1: Axial slice number vs time for an example three bed positions DWB acquisition. Central axial slices (left) and slices at the overlapping regions (right) considered for the result framing.

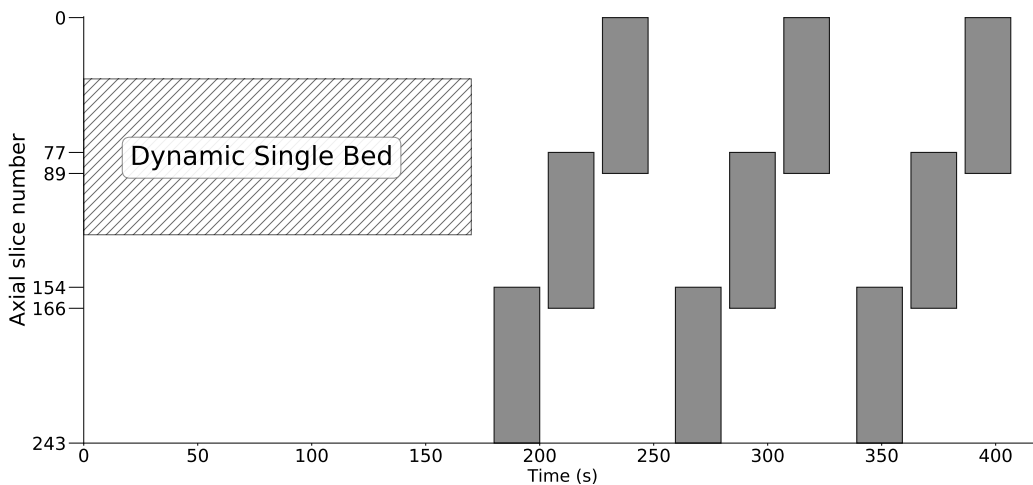


Figure 7.2: Axial slice number vs time for an example three bed positions DWB acquisition, including an initial DSB phase of 180 s.

If considering only the DWB dataset, and each individual S&S acquisition as an independent frame, the total number of frames in the DWB dataset will be defined by all the individual S&S steps. But not all frames need to be considered for all regions of the effective FOV. The choice of the appropriate framing for each location, whether within or outside the overlap, can be made using a mask image that indicates which locations are sampled on each frame. This type of mask could be used for example with post-reconstruction parametric imaging, applied at each voxel to mark which frames need to be considered.

With CASToR the use of multi-bed data can be made directly within a single iterative loop, using the methodology described in section 4.4. The same framework can be extended to direct multi-bed dynamic reconstruction of DWB datasets, using the same iterative loop. For linear dynamic models, dynamic reconstruction

(without the use of nested optimization) can be applied directly next to the system matrix, as shown in equation 3.30, within a single iterative loop over all dynamic data y_{ti} .

For DWB data, incorporation of the bed offset information in the projection operation can naturally lead to direct multi-bed dynamic reconstruction, where the selection of the sampled time points for the location of a voxel j is conducted by the projection operation. In this case, the projection operation and consequently the system matrix elements will depend on the frame index number t . This can also be expressed as an extension of the direct multi-bed reconstruction, described by equation 4.2, to dynamic reconstruction where the axial offset of each bed position is incorporated in the time-dependent information of the system matrix. This provides

$$\theta_{pj}^{(k+1)} = \frac{\theta_{pj}^{(k)}}{\sum_{t=1}^{n_t} B_{tp} \sum_{i=1}^{n_i} P_{tij}} \sum_{t=1}^{n_t} B_{tp} \sum_{i=1}^{n_i} P_{tij} \frac{y_{ti}}{\sum_{d=1}^{n_j} P_{tid} \sum_{q=1}^{n_p} B_{tq} \theta_{qd}^{(k)} + b_{ti}}, \quad (7.1)$$

where the set of basis functions B is precomputed for all time frames of the DWB acquisition, but is effectively applied in each voxel j for the time frames t that result to non-zero contribution by the back-projection operation ($\sum_{i=1}^{n_i} P_{tij} \neq 0$). It is important to note that with this unique iterative loop there is no need for additional considerations after reconstruction of the overlapping operation and regions. The result parametric images θ have dimensions of the effective FOV, having accounted for the overlap spatial sensitivity and timing information within the reconstruction.

Use of the same framework to perform individual frame reconstructions of DWB data is also possible, by setting the matrix B to be the identity matrix of size equal to the number of total frames. An example from the use of this framework for frame reconstructions is shown in figure 7.3 for a group of three consecutive frames from the NHP study of chapter 5. The sensitivity images for the same frames, as estimated by the back-projection operation $\sum_{i=1}^{n_i} P_{tij}$, are shown in figure 7.4. The sensitivity images clearly show the sampled locations per frame and the overlapping locations for adjacent frames. Individual frame reconstruction of DWB data results directly to images that account for the bed offset in image space, which can subsequently be directly used for post-reconstruction kinetic model fitting without the need for positional considerations. Additionally, for post-reconstruction kinetic model fitting, the result sensitivity frame images can be used as a mask for the application of the dynamic model on each frame and voxel combination.

In addition to DWB data alone, the described methodology for direct multi-bed dynamic reconstruction allows for any sequence of the acquired bed/frames to be used within the iterative reconstruction loop. Furthermore, the use of the DSB dataset can also be included in the iterative loop, regardless of its axial position, while also being sub-divided into multiple short frames.

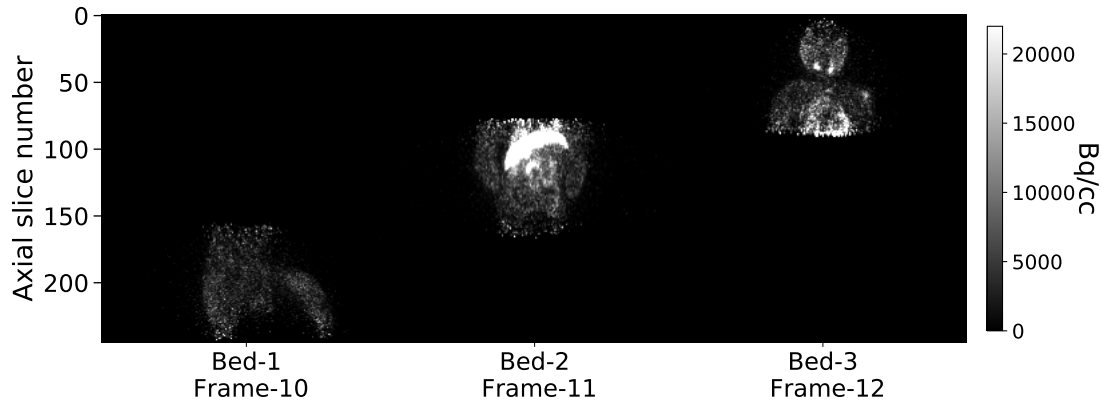


Figure 7.3: Example three frame images from a three bed DWB acquisition (NHP study of chapter 5)

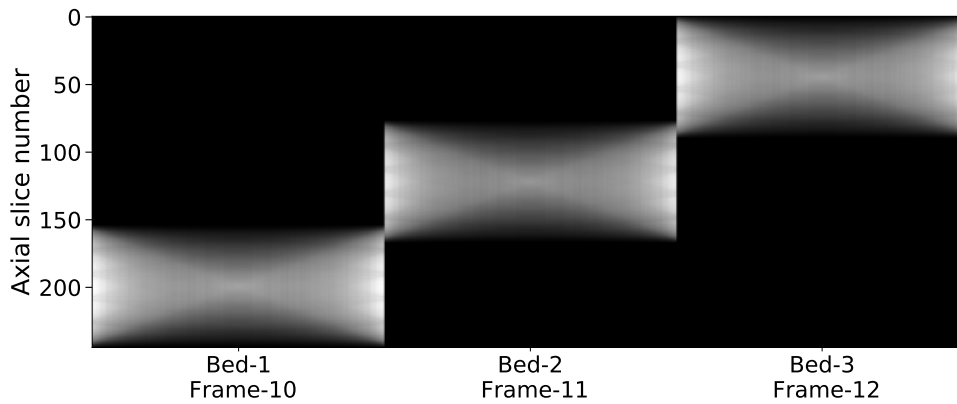


Figure 7.4: Example three frame sensitivity images from a three bed positions DWB acquisition.

7.2.2 Dynamic reconstruction: nested optimization for DWB datasets

As described previously, dynamic reconstruction is often performed using the nested optimization framework, to accelerate convergence [97, 98]. Some additional considerations need to be made before the use of this multi-bed dynamic reconstruction framework with nested optimization.

The nested optimization framework decouples the tomographic update process over the PET data from the dynamic model fitting process on image space. The two steps are conducted respectively with an MLEM update over the PET raw data using equation 3.27 to get an individual EM update image for each frame, followed by kinetic model fitting which optimises the likelihood function of equation 3.28.

For single bed dynamic data the sensitivity term of the likelihood function, $[\sum_{i=1}^{n_i} P_{ib}]$ of equation 3.28, can be ignored assuming that it is constant over time for each voxel b , and the likelihood function can be optimised using an image based EM update over image space with equation 3.33 [11, 97]. It is important to note that if dead-time corrections, necessary for accurate quantitative reconstruction, are included in the system matrix then the sensitivity term needs to be kept and accounted for in the nested optimisation.

But in most applications of nested optimisation on single-bed dynamic data in the literature this term is ignored.

In the case of DWB data and overlapping bed positions, the sensitivity term $[\sum_{i=1}^{n_i} P_{tij}]$ has to be maintained, as its value will change with different frames for voxels j in the overlapping regions. Thus the two step process, for direct multi-bed dynamic reconstruction with nested optimization, can be written as

$$\begin{cases} f_{tj}^{(EM)}(\boldsymbol{\theta}^{(k)}) = \frac{f_{tj}(\boldsymbol{\theta}^{(k)}) \sum_{i=1}^{n_i} P_{tij}}{\sum_{i=1}^{n_i} P_{tij} \sum_{d=1}^{n_j} P_{tid} f_{td}(\boldsymbol{\theta}^{(k)}) + b_{ti}} y_{ti} \\ \boldsymbol{\theta}^{(k+1)} = \arg \max_{\boldsymbol{\theta}} \sum_{t=1}^{n_t} \sum_{j=1}^{n_j} [\sum_{i=1}^{n_i} P_{tij}] \left[-f_{tj}(\boldsymbol{\theta}) + \ln(f_{tj}(\boldsymbol{\theta})) f_{tj}^{(EM)}(\boldsymbol{\theta}^{(k)}) \right]. \end{cases} \quad (7.2)$$

The tomographic update of this two-step optimization process is effectively an update over the DWB data for independent frame reconstruction, followed by an image space optimization process that now needs to consider the sensitivity $[\sum_{i=1}^{n_i} P_{tij}]$ of each time point t in the TAC of each voxel j . For linear models, where before an image based MLEM algorithm was used for this image space optimization process, a weighted MLEM update can be used with the sensitivity of each time point t as the weight. Alternatively, for linear and non-linear models, WLS based optimization algorithms can be used with the sensitivity value used as the weight. Both of these options were implemented in CASToR, with results shown in this chapter were produced by the use of the nested EM approach.

7.2.3 Real Data

Two DWB scans from the IsotoPK study were used for assessing the described direct multi-bed dynamic reconstruction method. Both scans were conducted on a single volunteer in a single day, without and with the use of the inhibitor (rifampicin) respectively. The two scans will be referred to as *CTRL* and *RIF* scans, standing for control and rifampicin. The two dynamic scans were conducted with the injection of 141.53 MBq and 90.77 MBq of ^{11}C Glyburide respectively. The first scan was conducted with 14 WB passes, with 9×20 , 5×30 s frames per bed position. The second scan included 15 WB passes, with 9×20 , 6×30 s frames per bed position. Both scans begin with a 180 s DSB acquisition centred over the liver, starting at the time of injection, before the DWB acquisition. By splitting the DSB into 18×10 s frames and considering each Step and Shoot acquisition as an individual frame, the two scans resulted in a total of 88 and 93 frames respectively. The planned bed positions are shown in figure 7.5 for the DSB and DWB phase of the *CTRL* scan.

The complete *CTRL* and *RIF* datasets, including the DSB and DWB data, were reconstructed within the

developed direct multi-bed dynamic reconstruction platform, using an OSEM algorithm with 28 subsets and EM nested optimization of 20 sub-iterations. Both datasets made use of TOF information within the reconstruction. As the IsotoPK study is an exploratory pharmacokinetic study, dynamic reconstructions were performed with the spectral model for temporal regularisation of frame activity estimates as well as for the direct estimation of K_1 parametric images, without imposing strong assumptions about the underlying kinetics. Additional dynamic reconstructions were performed for DWB data, without the use of the initial DSB data, to test extrapolation of the spectral model on early (non-sampled) frames. A total number of 17 spectral basis functions ($M = 16$) were used, with $\beta_1 \dots \beta_{M-1}$ logarithmically spaced within the range of 3 to 0.001 min^{-1} , while including β_0 and β_M to account for trapping and the blood fraction in the data. Similarly to the simulation study, the assumption of the total blood activity concentration C_B being proportional to the arterial blood plasma C_P was used in the estimation of the basis functions. Manual arterial blood samples were taken during both scans, to derive the input function and for blood analysis (to measure the metabolites fraction and for plasma binding of the tracer). The measured input functions were linearly interpolated and then used in the estimation of the spectral basis functions. Initial results on the study have shown very little metabolic activity of Glyburide, which did not require modelling, allowing for the assumption of constant ratio of arterial to total blood to be made.

Using the fitted spectral model, the approximate K_1^* parametric images were estimated similar to the methodology used in the simulation study of chapter 6. In addition to the dynamic reconstructions, individual frames (3D) reconstruction was performed using the same framework and OSEM algorithm with 28 subsets.

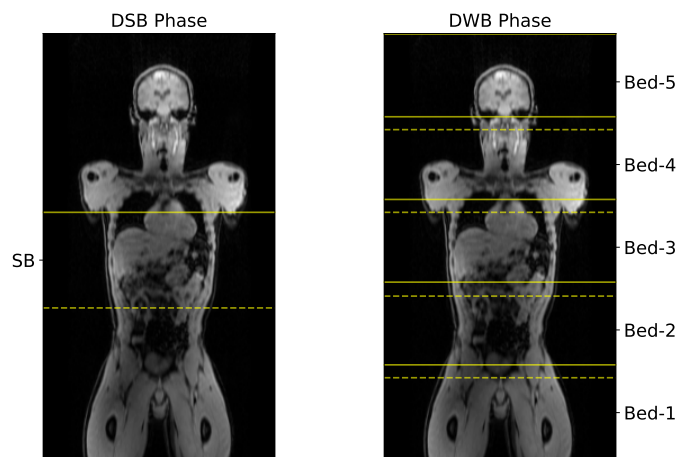


Figure 7.5: Planned DSB and DWB bed positions shown on coronal MRAC image, with bed start (——) and end (-----) positions.

The VOIs listed in table 7.1 were drawn manually and used to validate and compare the reconstruction methods.

Table 7.1: VOIs used for evaluation of DWB scans.

VOI Name	Availability in Data
Brain	DWB
Myocardium	DSB & DWB
Left Ventricle (LV)	DSB & DWB
Left Kidney (Kidney _L)	DSB & DWB
Right Kidney (Kidney _R)	DSB & DWB
Spleen	DSB & DWB
Liver	DSB & DWB
Aorta	DSB & DWB
Bladder	DWB
Leg Muscle	DWB

Liver dual-input function simulation

For the liver which is one of the main organs of interest in the IsotoPK study, as discussed in section 2.6.1, the dual input function model is necessary for accurate modelling of tracer behaviour. When this is not accounted for, parametric estimates derived from single input function models are expected to be biased. A toy simulation was conducted to study how quantification of K_1^* is affected by the use of the spectral model with a single input function and to study whether relative differences of true underlying K_1 , such as those expected from the comparison of the *CTRL* to the *RIF* scan, can still be accurately deduced using the spectral model's estimated K_1^* . This short simulation study is presented in appendix C.

7.3 Results

7.3.1 Comparison between 3D and 4D spectral reconstruction on DWB data

Coronal MIP images of 3D reconstructions from the *CTRL* scan are shown in figure 7.6 and figure 7.7, for a late frame of the DSB acquisition and early frames of the DWB acquisition respectively. Similarly, MIP images of 4D spectral reconstruction of the *CTRL* scan are shown in figure 7.8 and figure 7.9 for the same respective frames. As the spectral model is applied to the image space of the entire effective FOV, the 4D reconstruction results in frame images that are estimated from the fitted model on the entire FOV. As such, activity estimates of locations that are not sampled for a given frame within the DWB scan are interpolated from the frame data of the entire DWB scan. For the frames of the DSB scan, locations that are not sampled by the single bed acquisition have activity estimates that are extrapolated from the fitted spectral model of later frames.

Plots of mean VOI activity against iteration, for early and late frames over the liver and the leg muscle VOI were used to evaluate at which iteration the mean values begin to converge. These plots are shown in fig-

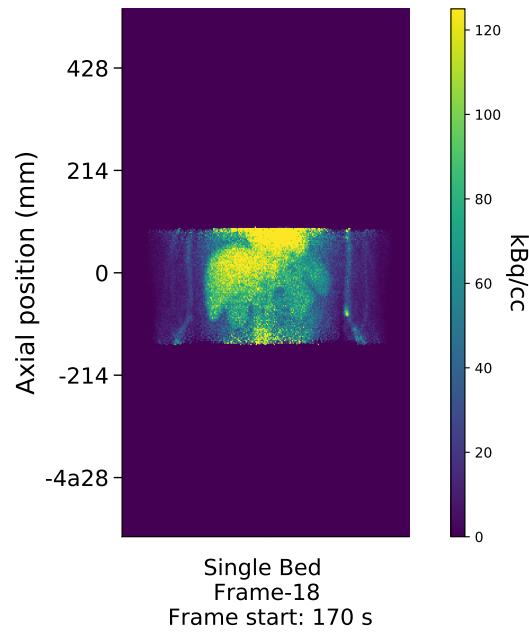


Figure 7.6: Coronal MIP image of 3D reconstruction (4it28sub) of a single frame from the DSB acquisition on the *CTRL* scan

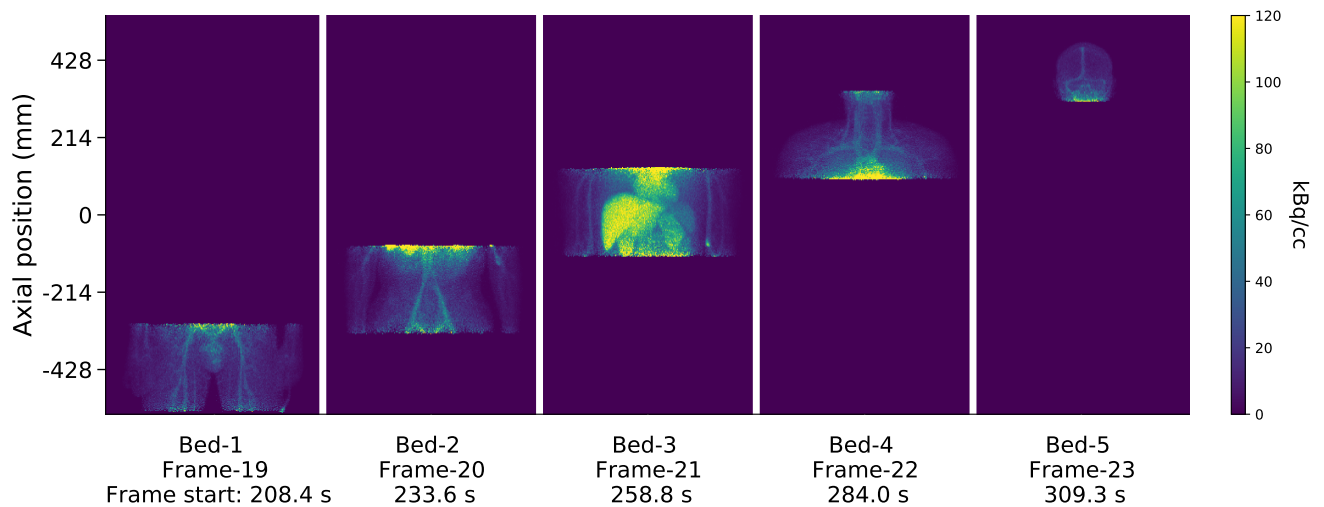


Figure 7.7: Coronal MIP images of 3D reconstructions (4it28sub) of a single frame per bed position from the first whole-body pass of the DWB acquisition on the *CTRL* scan.

ure C.1 and figure C.2 of the appendix C. For 4D spectral reconstruction, the evaluated mean values showed relatively stable behaviour from the 15th iteration onwards, which was chosen for subsequent comparisons of reconstructions. For 3D reconstruction mean values did not show stable behaviour in both regions within the first 8 iterations and the 4th iteration was chosen in subsequent comparisons as a compromise between the reliability of mean values convergence and image noise.

TACs of the evaluated VOIs are plotted in figure 7.10 and 7.11, for VOIs sampled in both DSB and DWB acquisitions and for VOIs sampled only during the DWB acquisition respectively. In figure 7.11 the time point

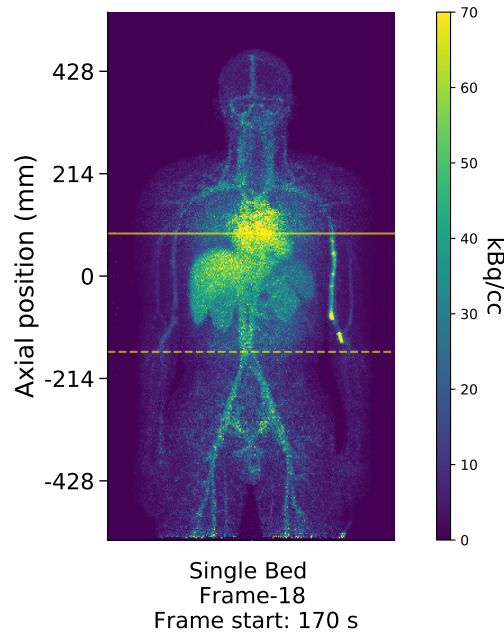


Figure 7.8: MIP image of a single frame from 4D reconstruction (15it28sub) of the CTRL scan

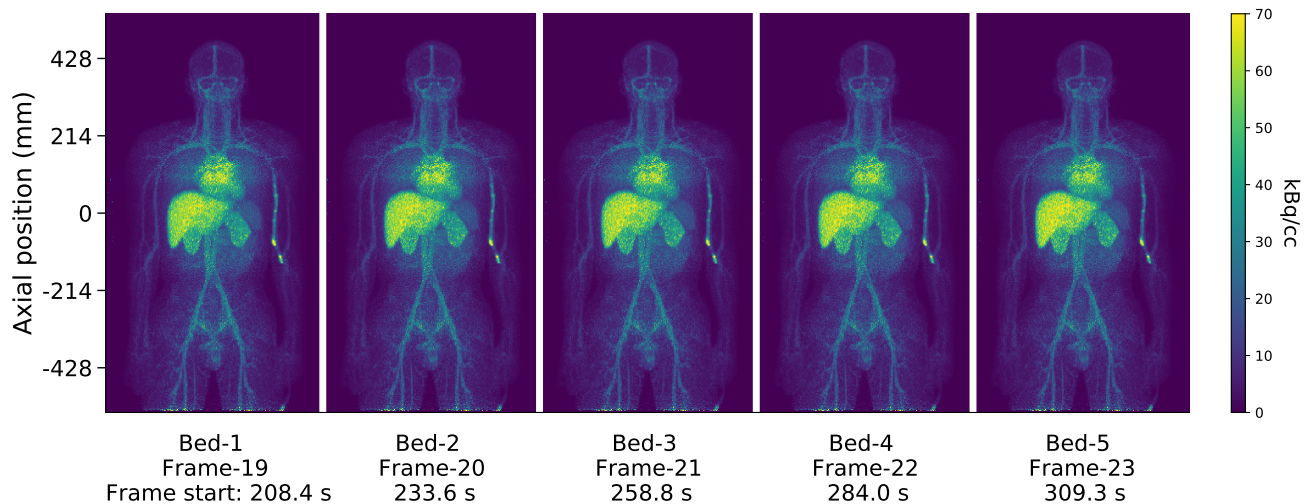


Figure 7.9: MIP image of the first whole-body pass frames from 4D reconstruction (15it28sub) of the CTRL scan.

of the start of the DWB acquisition is indicated by the red dotted line. As already mentioned, the 4D spectral reconstruction results in an activity estimate of every location of the image for every frame of the study, while 3D reconstruction results in activity estimates for the sampled frames only at each location. This is why the TACs from the 4D reconstruction of the *CTRL* data show a total of 88 frame points for all VOIs, while for 3D reconstruction a total of 32 frame points (18 from DSB plus 14 from DWB) is seen for regions included in the DSB acquisition and 14 frame points for regions seen solely by the DWB acquisition.

For the VOIs seen by both DSB and DWB acquisitions, the TACs between 3D and 4D spectral reconstruction

are in good agreement for all evaluated VOIs, as seen in 7.10. For the brain and muscle VOIs seen by the DWB acquisition alone, there is a relatively good agreement, with slight overestimation in early frames of the brain region and underestimation on later frames as seen in 7.11. By contrast, at the bladder VOI there is a strong mismatch of the 3D and 4D spectral reconstruction, with the 3D reconstruction showing clearly the bladder filling process and the 4D spectral reconstruction showing an increasing behaviour produced by the exponential functions. The VOI means of the spectral parametric images are given in the appendix material, where it is seen that the component of full trapping ϕ_0 is strongly used in the bladder region, in an attempt to fit the underlying process. But the use of the input function and the decaying exponentials is not enough to fit this process. Further considerations to this issue are addressed in the section 7.3.4.

7.3.2 Comparison of 4D Spectral reconstruction on DWB data, with and without the use of DSB data

A comparison between 4D spectral reconstructions, with and without the use of the initial DSB data, is made in figure 7.12, for VOIs covered by both DSB and DWB acquisitions. These show a good agreement of the two spectral reconstructions, with a consistent slight error in the early DWB frame estimations of the reconstruction without the use of DSB data. This error is relatively small compared to the mean activity of each VOI (maximum of 12.7% error seen in Spleen VOI). A very good agreement is seen on the liver between the two reconstructions.

The extrapolation of the fitted spectral model from DWB data alone can be made for the early non sampled frames. These show a sharp drop of the fitted TACs, indicating the inadequacy of the used data for extrapolation of the fast early frame behaviour and the cause for the systematic mismatch at early frames of the DWB acquisition. In particular, the extrapolated model is unable to reproduce the early peak, as seen clearly in the ventricle, the myocardium and the spleen, which indicates that separation between the exchange components and the blood fraction component of the spectral model is compromised when the early dynamic data are not available.

7.3.3 Direct WB parametric image estimation from 4D Spectral reconstructions

Using the set of equations 2.23 and specifically the equation for the derivation of K_1 , the parametric maps of K_1^* were produced by summation of basis $(\phi_0 - \phi_{M-1})$. Similar to the simulation study before, the blood fraction correction was neglected in favour of avoiding excessive noise propagation into voxel parameter estimates. The result parametric maps for both *CTRL* and *RIF* scans are shown in figure 7.13 and figure 7.14, as a MIP in the coronal plane and as a single coronal slice showing the liver, the kidneys and the spleen.

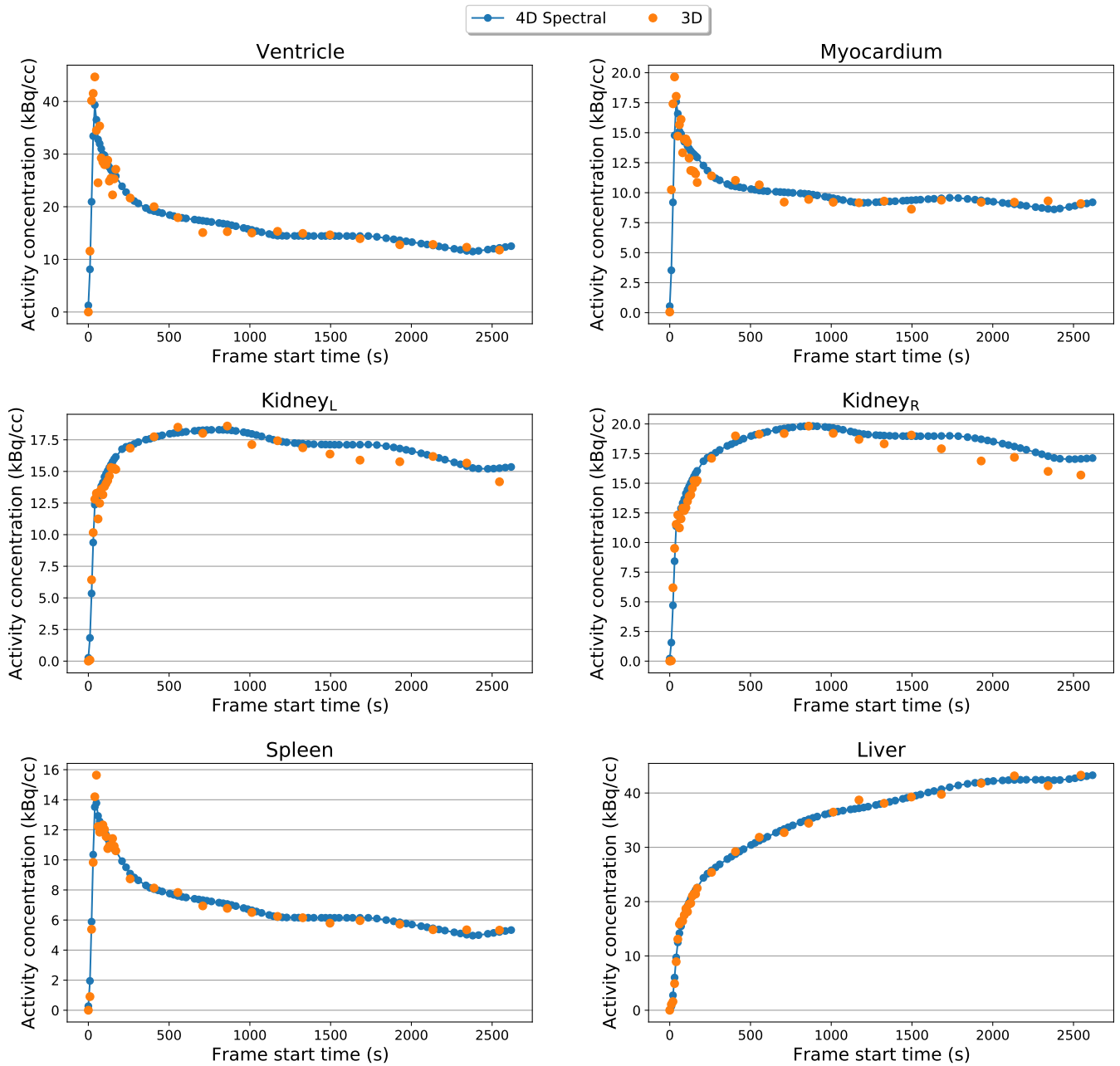


Figure 7.10: VOI mean time activity curves for 3D and 4D spectral reconstruction. VOI regions shown which are included in both DSB and DWB acquisition.

Mean VOI K_1^* values, shown in figure 7.15, show a considerable reduction from the *CTRL* to the *RIF* scan by the administration of the inhibitor. This drop reflects the difference between specific and non-specific uptake of the novel Glyburide tracer in the various imaged organs, with the strongest apparent difference seen in the liver.

The results of a short dual input simulation study, given in appendix C, indicate that accurate quantification of K_1 (or K_1^*) in the liver using only the arterial input function as an input is not achievable as expected. But the

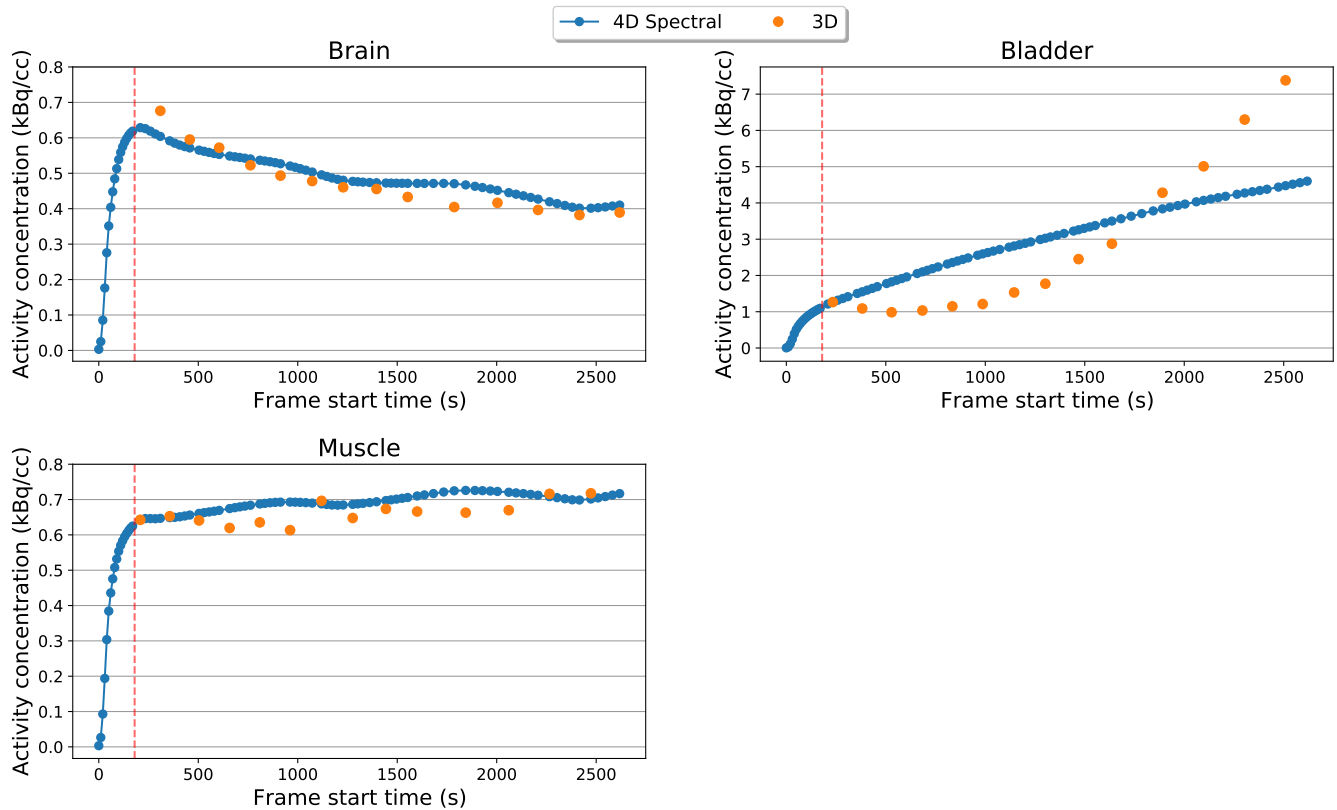


Figure 7.11: VOI mean time activity curves for 3D and 4D spectral reconstruction. VOI regions shown which are covered only by the DWB acquisition, whose start time is designated with a vertical dotted line.

simulation showed that a relative comparison of spectral model K_1^* estimates reflects approximately linearly the differences of the true underlying K_1 , without the explicit need for modelling the dual input function. These simulations are however based on a simple one parameter model for the portal vein, and do not include delay in the input functions (which can be expected, especially for the portal vein input function). Further investigations are needed in the use of the spectral model within the liver, starting from simple mathematical formulations of the problem before testing further using PET simulated data or the real data. In any case, knowledge or valid assumptions on the rate of dispersion and the ratio of portal to arterial blood in the liver can be advantageous as they would reduce the number of unknown parameters. Furthermore, joint estimation approaches in the estimation of parameters in the liver could be assessed for uses in WB dynamic studies.

7.3.4 Fit errors and error propagation

As seen in figure 7.11, the mismatch between the 3D and 4D spectral reconstructions at the bladder TAC is the strongest from all the evaluated VOIs. The source of this error is the inability of the spectral model to fit the bladder filling process, by any combination of the decaying exponentials convolved with the arterial input

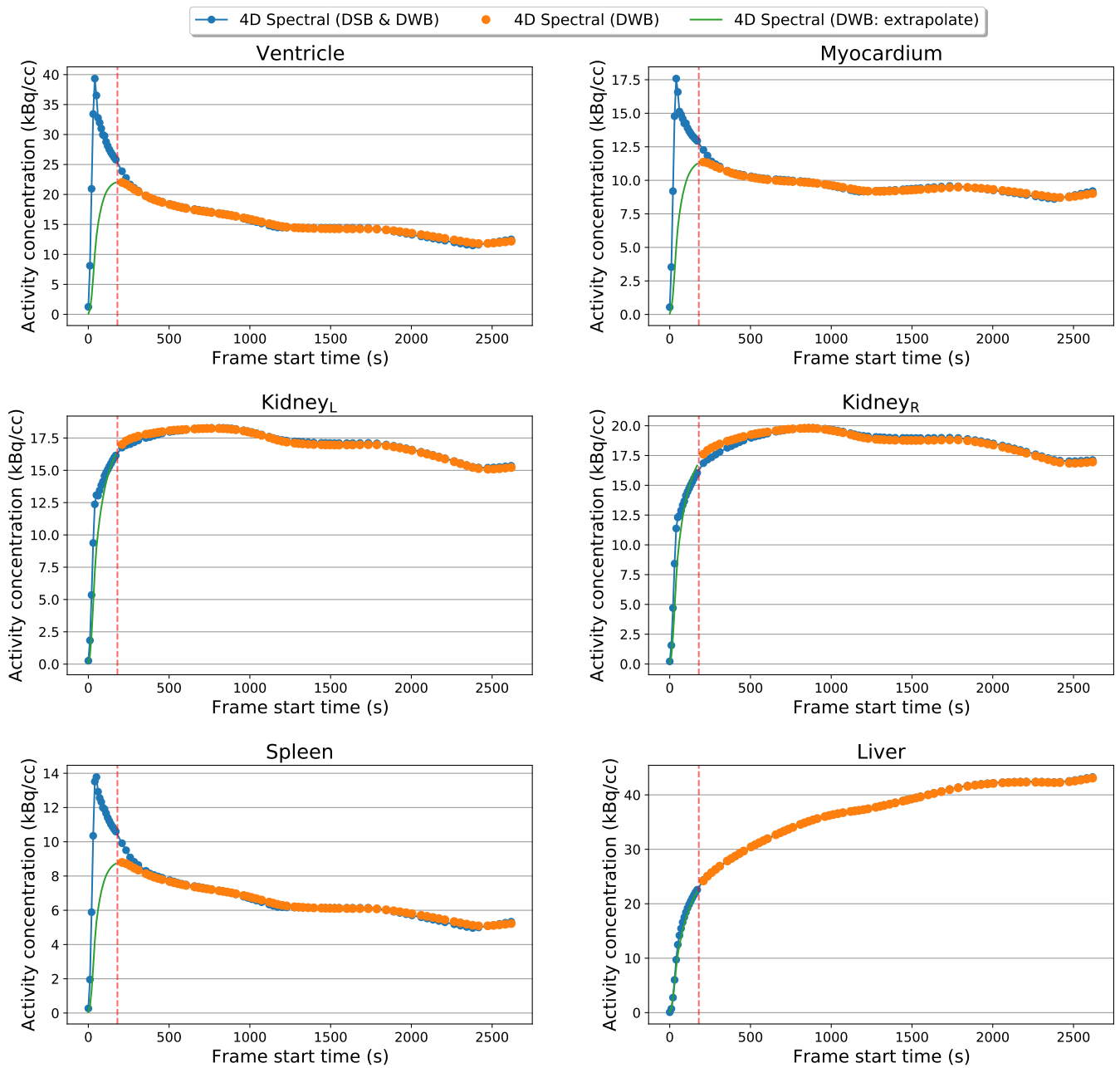


Figure 7.12: VOI mean time activity curves for 4D spectral reconstructions, with and without the use of DSB data. VOI regions shown are included in both DSB and DWB acquisitions.

function. This mismatch is of particular concern for dynamic reconstruction as it can be the source of errors that propagate spatially during the dynamic reconstruction process over the entire field of view [123, 124]. This issue is addressed further in the work presented in chapter 8 by use of adaptive residual modelling for dynamic reconstruction.

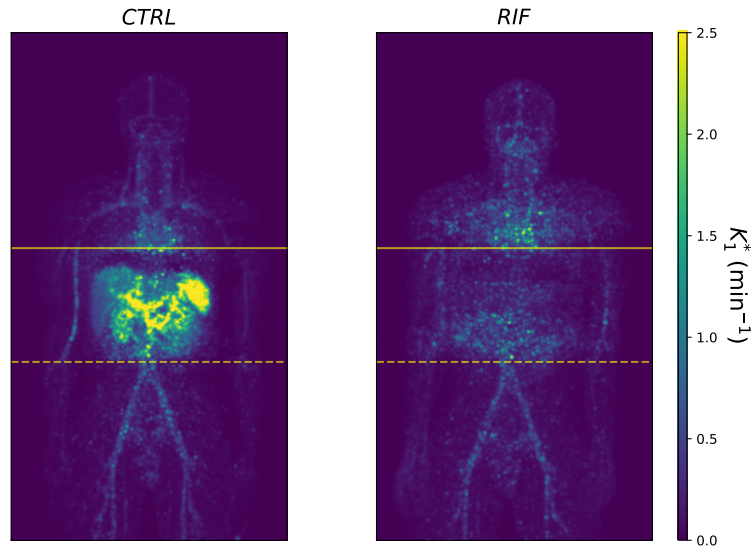


Figure 7.13: K_1 MIP images from the 4D spectral reconstruction using both DSB and DWB acquisitions, shown for the *CTRL* and *RIF* scan.

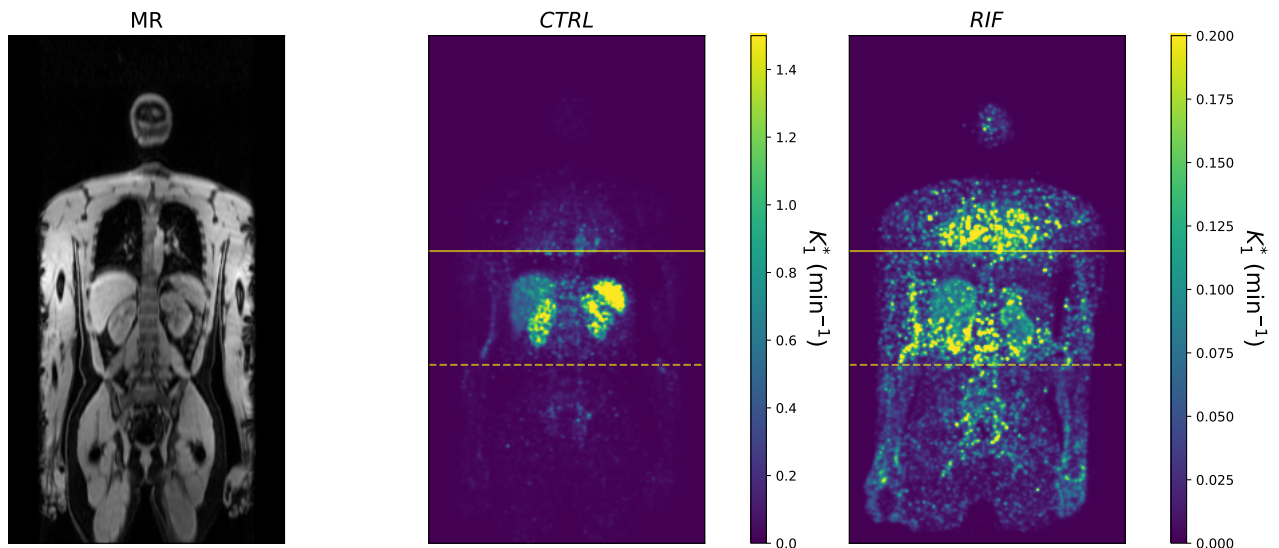


Figure 7.14: K_1^* values as estimated from the 4D spectral reconstruction for VOI regions included in both DSB and DWB acquisitions, shown for the *CTRL* and *RIF* scan

7.4 Discussion

We have developed and presented a framework for direct multi-bed dynamic reconstruction of DWB data, that allows for synchronous use of both DSB and DWB PET raw data, typically acquired in dynamic studies over the whole body [8]. This framework can be used for dynamic reconstruction by making use of the accurate positional and timing information of all the individual bed raw PET data within a single iterative loop, performed either directly within a single system matrix or using the nested optimization approach. In this study, we have tested this framework with real DWB data, from a first in man pharmacological study, where

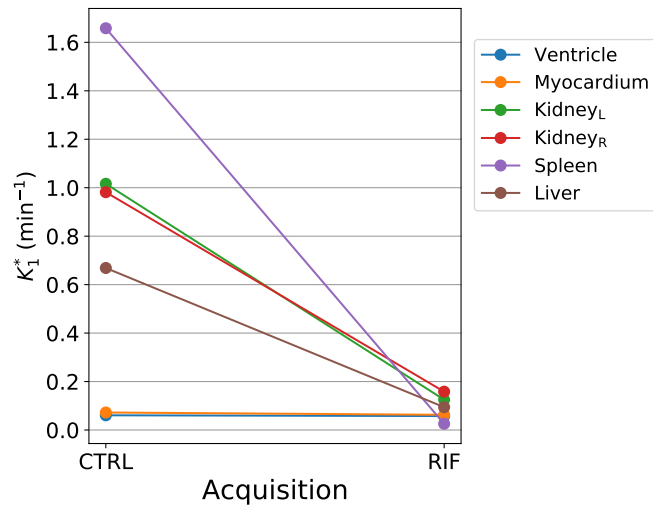


Figure 7.15: K_1^* values as estimated from the 4D spectral reconstruction for VOI regions included in both DSB and DWB acquisitions, shown for the *CTRL* and *RIF* scan

the spectral model was used within the reconstruction to avoid having to assume and enforce a specific compartmental model. The result (temporally regularised) activity images show estimates with a smooth transition in the axial direction across the effective FOV, in terms of image activity values and image noise. Although we hypothesised that use of the data within a single iterative loop results in improved estimates at the overlap region, compared to the state of the art methods that perform parametric image overlapping after reconstruction [17, 55], we do not directly compare with these methods. To address this comparison, we performed an evaluation study for these methods using the NHP dataset of chapter 5, but results were inconclusive and showed the need for a detailed simulation study to assess differences in terms of bias and noise properties of the overlapping regions against known ground truth simulated values.

The IsotoPK real DWB data used in this study included a 180 s DSB acquisition centred over the liver prior to the DWB acquisition. This has enabled the estimation of K_1^* parametric images over the region covered by both DSB and DWB acquisitions. As shown before in chapter 6, that initial information is crucial for the estimation of K_1 . Thus, although the use of the DSB initial phase allows for adequate sampling of fast kinetics and estimation of fast kinetics sensitive parameters in DWB studies, it still limits the estimation for parametric images to an axial coverage of a single bed position. All other regions outside this bed coverage were sampled with a 180 s delay, which as shown in chapter 6 produces erroneous estimates of K_1^* . In this study this relates to K_1^* estimates in regions outside the coverage of the DSB acquisition in figure 7.13 and figure 7.14. Further investigation in the setup of the acquisition protocol is required to quantify the minimum amount of fast kinetics sampling required for reliable deduction of parametric K_1 images and other parametric images sensitive to early fast kinetics. An analogous study conducted for the estimation of 2TC micro-parameters in FDG imaging resulted in evaluation of the sensitivity of micro-parameters against a

sampling of specific time points [125]. A similar study for the spectral model analysis method can evaluate the need of the DSB phase for estimation of K_1 and other parameters and if possible adapt the acquisition for reliable estimation of those parameters over the whole effective FOV. Another disadvantage of the need for a DSB acquisition is the uneven sampling over different locations of the effective FOV that results in different noise properties across the axial direction. Equal sampling of all regions is preferred to provide comparable noise properties in the axial direction of the FOV.

There are many challenges and limitations in dynamic reconstruction and parametric imaging, which are of particular concern for DWB imaging where the dynamic model is applied over the whole body [21]. Firstly, a single input function has been used for the estimation of the basis functions of the spectral model which is then applied over the entire effective FOV. The use of a single input function does not account for dispersion and delay effects that are varying for different locations in the body. As kinetic models and in particular the spectral model rely heavily on the input function, any errors or inaccuracies can lead to considerable estimation errors. Ideally, the delay and dispersion properties of the input function need to be estimated for each region, which would then be used for calculating a set of spatially variant spectral basis functions. Furthermore, the input function was derived from manual samples whose sampling frequency compromises the measurements of the peak of the input function. This information over the peak is of significant importance for the estimation of micro-parameters. Methods for joint-estimation of dispersion and delays or joint estimation of the input function itself within the reconstruction process have been previously proposed [11, 101], but so far have only been applied in DSB studies [11] and studies using total-body data [65] where sensitivity and sampling-frequency are much higher compared to multi-bed DWB imaging. Many considerations are needed to evaluate the translation of these methods in multi-bed DWB, where the poorer data statistics and sampling frequency might not allow for reliable estimation of all the involved parameters of these joint estimations. Image derived input functions can also be used as an alternative to manual samples, but they also suffer from limitations regarding sampling frequency over the input function peak and are normally measured from a few locations without accounting for delay or dispersion.

Moreover, regarding the application of the input function over the effective FOV, certain organs might not follow well the single input function models. In this study, a major organ of interest is the liver, which is supplied with blood via two different routes. We showed using a simple simulation that although the spectral model is able to fit the liver TAC relatively well, the result K_1^* parameters were strongly biased. Accurate quantification requires estimation of both input functions. Recently joint estimation approaches [78] and image derivation approaches [80] have been shown to produce good results in DSB studies. Their translation to DWB and generalisation for use with other tracers requires further research. Nevertheless, this example of the liver shows again that in the quantification of parameters there is a need for spatially variant modelling.

Still, the use of a generic model such as the spectral model has the ability to adequately fit the underlying tracer behaviour and provide temporally regularised activity estimates.

Another considerable limitation, that has not been addressed in this study, is subject voluntary and involuntary motion. Inevitably these types of motion will be present in dynamic studies, especially when imaging the whole body with DWB that involve frequent bed movements. In dynamic reconstruction these effects need to be accounted for within the reconstruction process, to avoid image artefacts and modelling errors. But when considering the whole-body, there are many types of complex motion taking place during the duration of a dynamic study. These include respiratory motion, cardiac motion, head movements, bowel motion and other internal organ movements, etc [21]. Estimation of all these types of motion is a complex task. Many data driven [126–128] and joint estimation approaches [129, 130] have been proposed for motion estimation and correction, but their use for complex elastic motion is still actively researched. Recently machine learning approaches have been proposed to improve on elastic motion estimation from low statistic gated images [131, 132]. For complex motion detection over the whole-body, the use of histo-images (COD images), which is constantly improving with TOF hardware advancements, is actively being researched for use in motion detection/estimation [133]. Nevertheless, the task of motion detection from dynamic PET data is more complex when considering a dynamically changing tracer distribution rather than a static tracer distribution, which is assumed in most approaches discussed above. Specifically for PET/MR imaging, the use of specialised MR sequences has been previously suggested and successfully used for complex elastic motion estimation [134, 135], but these motion detection MR sequences can be time consuming. In DWB imaging where delays between individual bed position acquisitions have a strong impact on the estimation of kinetic parameters, there can be a great impact on PET parametric image quality by the sacrifice of sampling frequency due to additional MR sequences on each bed position.

7.5 Conclusion

A direct multi-bed dynamic reconstruction method was presented and tested using real data from a DWB pharmacokinetic study. Evaluation tests for dynamic spectral reconstruction against regular frame by frame reconstruction of the data showed relatively good agreement of VOI TAC data in all regions except the bladder, where the filling process was badly modelled. Finally, there is a need for accurate motion estimation and correction within the dynamic reconstruction process that is imperative for artefact free and error free parametric image estimations over the whole body. Estimation of all types of complex motion over the whole body, using ideally data driven approaches, needs to be addressed further for DWB acquisitions.

Chapter 8

Dynamic Reconstruction Using the Spectral Model and Adaptive Residual Modelling

In this chapter, we discuss the complications arising from kinetic model fitting errors in dynamic reconstruction, for DWB imaging and WB parametric maps. We present our work towards the reduction of these errors using adaptive residual modelling for dynamic reconstruction, applied on the IsotoPK CTRL dataset presented in the previous chapter. The focus of this application was the model fitting mismatch over the bladder region and any potential propagating errors. To our knowledge, this is the first time a method of this type has been applied to real DWB data.

The results of this work were presented in the **IEEE/MIC** 2020 conference. This chapter is adapted from the conference record of this submission.

8.1 Introduction

Dynamic PET has been traditionally utilised in single organ studies, but recently there has been increased interest in dynamic whole body imaging, for research and for potential future clinical applications [9, 19, 56, 136]. Synchronous dynamic PET of the whole body requires scanner geometries that can encompass the entire length of the human body. Although systems capable of whole body axial coverage have been recently developed [59], their availability is not yet widespread. Current clinical scanners achieve whole body coverage using multiple axial bed positions or acquisition protocols with continuous axial bed motion. Based on these acquisition modes, dynamic whole body protocols have been developed that make use of repeated whole body passes [8]. Conventional analysis of dynamic data is performed with independent 3D reconstructions of frame data, followed by kinetic model fitting. Whole-body dynamic protocols make the task of reconstruction and subsequent kinetic modelling more challenging due to the introduction of large temporal gaps in the data which can lead to biased estimates and increased noise, especially for parametric maps. To improve image quality and account for the noise in the raw data, 4D reconstruction algorithms can be used to directly incorporate the dynamic model of interest in the reconstruction [11]. Depending on the choice of the dynamic model, these reconstructions can directly provide the parameters of interest or temporal regularisation on the reconstruction process of frame data. The spectral analysis model, inspired by the homonym method [70], fits on any underlying kinetic behaviour that can be described by compartmental modelling. When used in 4D reconstruction it provides temporal regularisation as well as direct estimation of some kinetic parameters. Use of this model has shown to reduce noise and bias of kinetic parameter estimates when applied on data from dynamic whole body protocols [137].

When considering the effective field of view of dynamic whole body studies, certain regions might not fulfil the generic assumptions of the spectral analysis model. For example processes such as delay of tracer delivery and non-arterial tracer delivery (ex. bladder filling). In 4D reconstruction, the tomographic update process is entangled with the dynamic model and errors from the temporal model fit have the potential to spatially propagate to other regions. Due to the fact that raw data from multi-bed dynamic whole body studies are acquired and reconstructed as separate beds, the potential for errors propagation is limited in the bed position where they originate from. It has also been shown that use of time of flight (TOF) information in the reconstruction aids in reducing spatial propagation of errors [124]. Nevertheless, model fit errors have the potential to propagate and when possible should be corrected or accounted for. For this reason, when 4D reconstruction is used and especially when applied on whole body datasets extra consideration has to be given on improving the model fit for all regions.

The application of an adaptive residual model as a second dynamic model has been previously suggested

for reducing model fit errors [138]. Its application in 4D reconstruction has been shown to reduce bias at the cost of increased noise for direct estimation of kinetic micro-parameters [123]. The objective of this work was to implement and evaluate adaptive residual modelling in 4D reconstruction, using real dynamic whole body PET data, with no prior knowledge of the underlying kinetics and the distribution of residuals. For this purpose, the spectral analysis model was used in conjunction with a residual model in 4D reconstruction to maintain genericity in the reconstruction with minimum assumptions on the underlying kinetics. The end objective was to assess if adaptive residual modelling can be permanently applied in 4D reconstruction, with no prior knowledge of kinetics and model fit errors, by relying on the selectivity of the algorithm for correction of underlying model fit errors, when and where those arise.

8.2 Methods

8.2.1 Data acquisition

Dynamic whole body (DWB) data using a novel ^{11}C -Glyburide tracer were acquired from a healthy volunteer on the GE Signa PET/MR, using a dedicated DWB protocol of 5 bed positions to provide sufficient coverage of the body. The data were acquired as part of the exploratory pharmacological study IsotoPK which is conducted in our centre for studying the distribution of OATP transporters in the body and their role in the delivery of drugs to tissues [10]. In this work a control scan was used (*CTRL* scan from chapter 7). In detail the dynamic acquisition consisted of a single bed acquisition centred over the liver, imaged for 3 minutes from tracer injection, followed by 14 whole body passes of 9x20s and 5x30s frames for each bed position. Arterial blood samples were collected manually during the whole study, to derive the input function.

8.2.2 Reconstruction

The spectral analysis model was used in all 4D reconstructions, using 6 spectral basis functions ($M = 5$) with $\beta_1 \dots \beta_{M-1}$ logarithmically spaced within the range of 3 to 0.001 min^{-1} , while including β_0 and β_M to account for trapping and the blood fraction in the data. The 4D reconstruction algorithm with adaptive residual modelling was developed using the spectral model as primary model and an adaptive secondary model, similar to the proposed method by Matthews et al. [138].

The steps of the adaptive residual modelling 4D reconstruction algorithm are:

1. Start with image estimate $\lambda_{tj}^{(k)}$, for voxel j and frame t at iteration k .
2. Perform tomographic update using MLEM to get the EM update images $f_{tj}^{(EM)}$.
3. Perform primary model fit using the NNLS algorithm on $f_{tj}^{(EM)}$ and estimate model parameters $\theta_j^{(k+1)}$.

4. Calculate residuals as $r_{tj} = f_{tj}^{(EM)} - f_{tj}^{(spectral)}(\theta_j^{(k+1)})$.
5. Perform PCA analysis on residuals to estimate a set of residual basis functions (RBF) which form the secondary (adaptive) model.
6. Estimate modelled residuals g_{tj} from the LS fit of the secondary model on the r_{tj} data.
7. Estimate optimal fraction K_j for residuals re-introduction, using generalised cross validation.
8. Add fraction of modelled residuals in image estimate $\lambda_{tj}^{(k+1)} = f_{tj}^{(spectral)}(\theta_j^{(k+1)}) + K_j g_{tj}$ and repeat from step 2,

where NNLS stands for Non-Negative Least Squares and $f_{tj}^{(spectral)}(\theta_j)$ is the spectral model which provides activity estimates for voxel j at frame t given model parameters θ_j .

In step (5) of our adaptive modelling implementation, the residual data were spatially smoothed with an isotropic Gaussian kernel of 32mm FWHM, to enhance the PCA analysis results. Smoothing of the residuals was not however applied in the fitting process of the secondary model in step (6). A fixed number of the most significant PCA components was used as basis functions of the adaptive residual model. The components were updated on each iteration of the 4D algorithm.

For the estimation of the optimal fraction K_j , the following equation from Matthews *et al.* [138] was used, which is derived from generalised cross-validation,

$$K_j = \frac{1 - \frac{r_{df}}{r_{RSS}}}{1 - r_{df}}, \quad (8.1)$$

where $r_{df} = \frac{n_s}{n_f - n_p}$, with n_p and n_s being the number of parameters of the primary and secondary model respectively, n_f the number of frames and r_{RSS} being the fraction of modelled to measured residuals sum of squares.

The dynamic data from each bed of the study were reconstructed as individual frames using 3D MLEM (150it), using 4D reconstruction (300it) and with the developed adaptive algorithm 4D-ResidMod (300it). No subsets were used for the reconstructions performed in this work. The adaptive reconstruction algorithm was evaluated using the 2 and 3 most significant PCA components as RBFs, referred to as 4D-ResidMod-2RBF and 4D-ResidMod-3RBF respectively. We also implemented a version of the adaptive algorithm with the addition of temporal Gaussian smoothing of 62s FWHM applied on the residual data used for PCA analysis in step (5) of the algorithm, referred as reconstruction 4D-ResidMod-3RBF-Tempfilt.

All reconstructions were performed with the open-source reconstruction platform CASToR [12], using resolution modelling and TOF information. Correction for motion has not been included in the reconstructions.

PCA analysis was performed using the Eigen library [139].

8.3 Results

As seen in Fig. 8.1 (top row) by the difference in activity estimates from 3D and 4D reconstruction in a late frame, the 4D algorithm with the spectral model alone resulted in lower activity estimates over the bladder region and higher activity estimates in some large blood vessels at the shoulders and pelvic regions. No noticeable differences were seen in other areas, apart from random variations in activity due to differences in noise levels of the compared reconstructions.

As expected, the filling process of the bladder seen in the bladder time activity curve from 3D reconstruction in Fig. 8.2 (bottom row) cannot be modelled by the spectral model because the filling process is not directly relatable to arterial tracer delivery at the local (voxel) level. Differences in some large blood vessels could potentially be attributed to delay of the input function, which is not accounted for in the spectral model where a single input function is assumed to apply for all regions.

Reconstruction of the data with adaptive residual modelling resulted in improved estimation of the bladder filling process, for both options of residual modelling using 2 and 3 residual basis, as it can be seen in the difference images of Fig. 8.1 (middle row) and the bladder TAC in Fig. 8.2. No improvements were seen for the differences at the blood vessels of the shoulders and pelvic regions.

At the liver, where most of the tracer uptake is concentrated, 4D and 3D reconstruction TACs show a subtle mismatch between 1100 and 1500 seconds (Fig. 8.2, top row). Analysis on the liver dome VOI (Fig. 8.3, top row) clearly shows this difference, which originates from underlying respiratory motion that has been captured in the PET dynamic data. 4D reconstruction alone was unable to model these fluctuations, as expected, but the adaptive algorithm using 3 residual basis has achieved to model for this behaviour as seen in Fig. 8.3. Since physiological kinetic processes, whether sufficiently modelled or not, are not expected to result in sudden changes of activity between adjacent frames, we implemented a version of the algorithm with temporal smoothing prior to PCA analysis to prevent from modelling changes due to fast processes such as respiratory motion. On this case this algorithm (4D-ResidMod-3RBF-Tempfilt) has managed to maintain the selective adaptive modelling behaviour over the bladder while avoiding fitting the motion related effects over the liver dome as seen in Fig. 8.3.

In all regions of the effective FOV the addition of adaptive modelling has resulted in the increase of image noise, compared to 4D reconstruction, with the higher number of residual basis resulting in higher noise. The introduction of temporal filtering in the adaptive model estimation process has aided in reducing the induction of noise for the majority of the evaluated regions in our study. A comparison of the effect on image

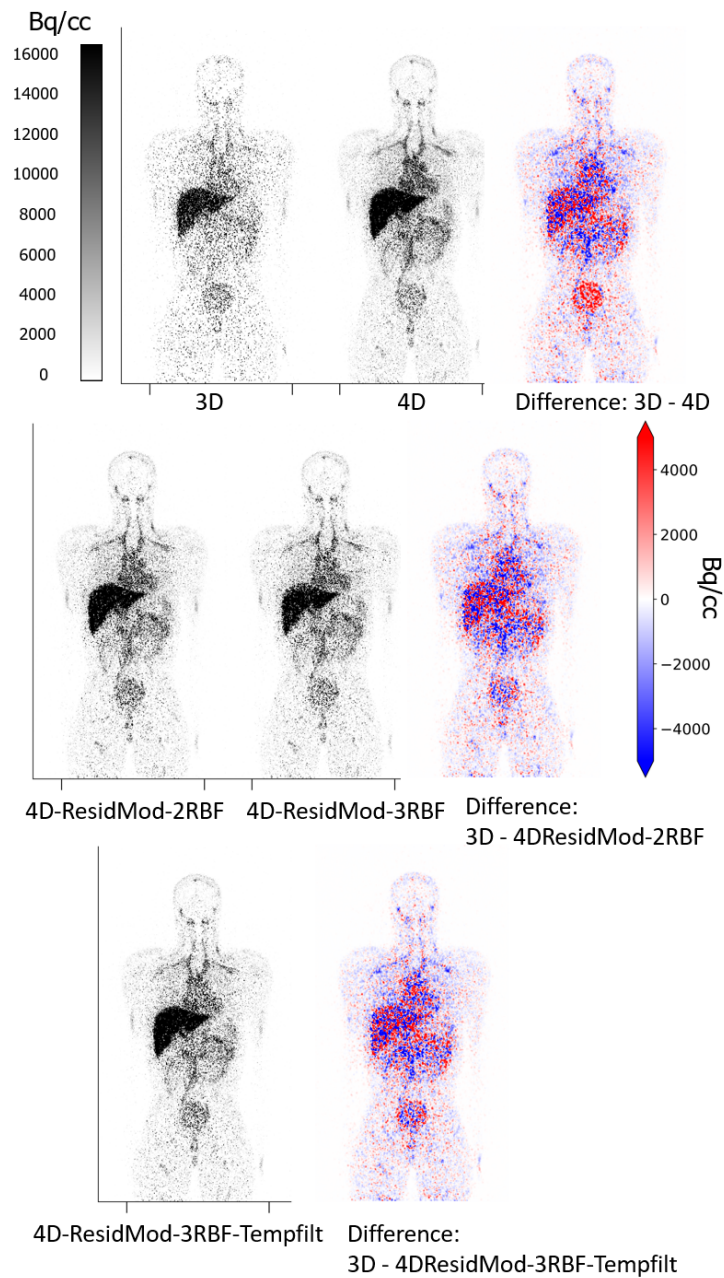


Figure 8.1: Coronal view of activity distribution from the evaluated reconstructions (frames of 41.2 to 44.1 minutes post injection). Difference images are also shown for selected cases against the 3D reconstruction.

noise across regions within this whole body study can be made by the VOIs standard deviation shown in Fig. 8.5 for all evaluated algorithms. An example map of the fraction K_j and the modelled residuals g_{jf} is given in Fig. 8.4. These maps demonstrate the desired selectivity of the algorithm, concentrated over the bladder in this case, but also the spill of noise from the residual space in these maps which is subsequently added in the reconstruction process.

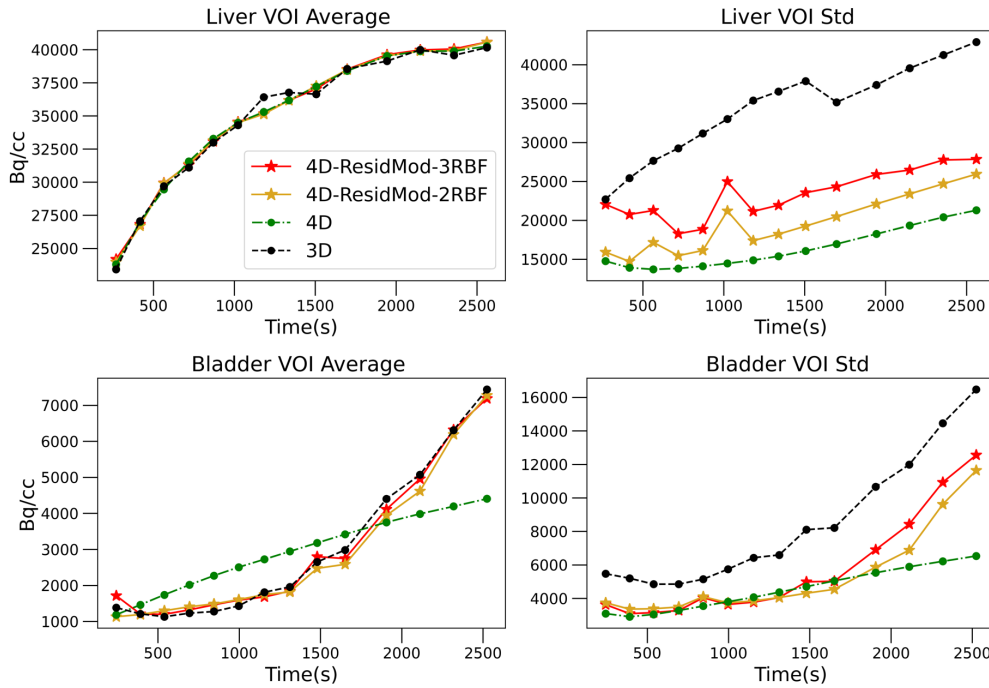


Figure 8.2: Average and standard deviation time curves of the liver and bladder VOIs, for the comparison of 3D to 4D reconstruction results as well as 4D reconstruction with residual modelling using different number of residual basis functions.

8.4 Discussion

In this work, we presented the application of a previously suggested method for adaptive residual modelling in dynamic reconstruction to reduce errors that arise from poorly modelled regions. General dynamic models, such as the spectral analysis model, can be useful in 4D reconstruction of DWB data using new tracers, as they do not impose strong assumptions about the underlying kinetics. But over the effective field of view of DWB imaging, certain regions and their physiological processes might not fulfil the general assumptions of the model. In these cases, the adaptive residual modelling strategy can be utilised to improve parameter estimates for these regions and help in minimising the risk of spatial propagation of errors to other well-modelled regions. In our application, 4D reconstruction with the spectral analysis model and adaptive residual modelling was applied on real DWB data from a first in man study of a new tracer. The algorithm identified and selectively corrected the image activity estimates over the poorly modelled bladder region, by modelling the residuals of that region. This resulted in a 4D reconstruction that did not suffer from the model fit errors over the bladder and potential errors propagated to other regions originating from the bladder region. But the use of the adaptive model as a secondary model increased the complexity of the modelling in the reconstruction process and resulted in an increase in image noise. The higher the number of residual basis functions used resulted in higher induction of image noise, as expected and inline with previous observations in a simulation study [123]. Overall, we saw that noise from the residual space propagates to

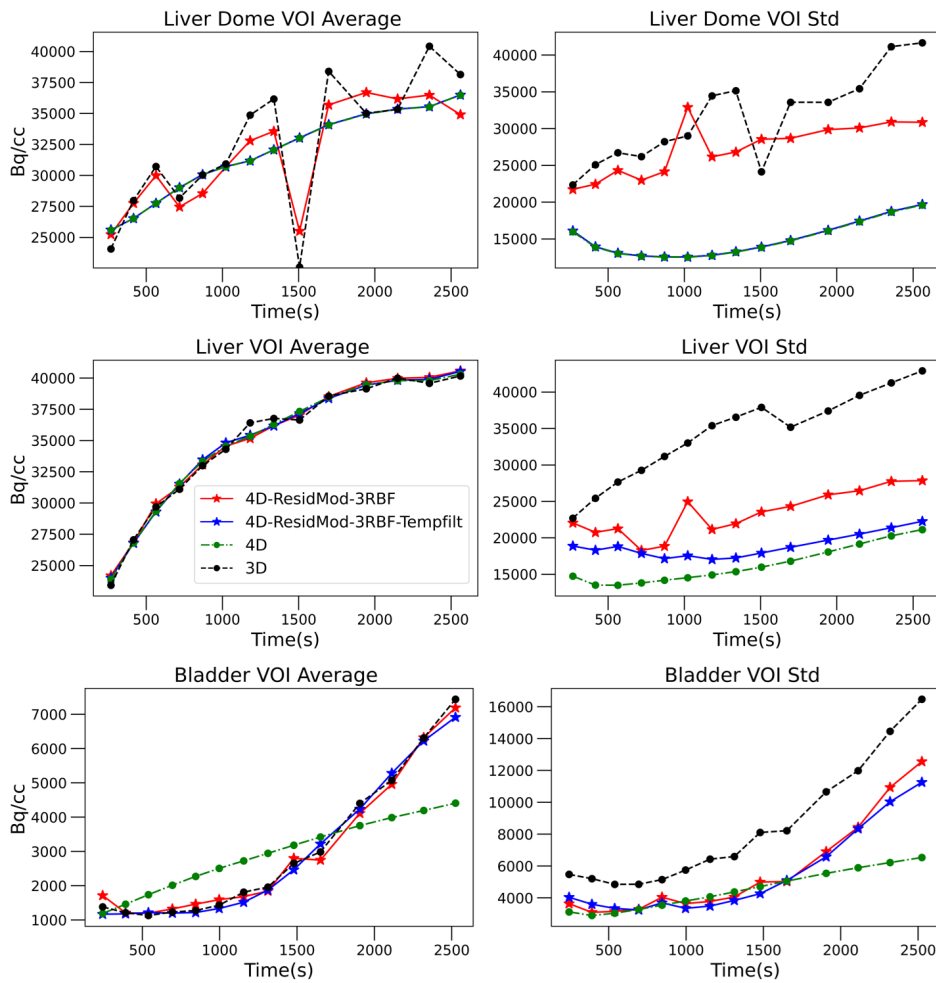


Figure 8.3: Average and standard deviation time curves of the dome of the liver the whole liver and bladder VOIs, for the comparison of 4D reconstruction with residual modelling with and without temporal filtering of residuals.

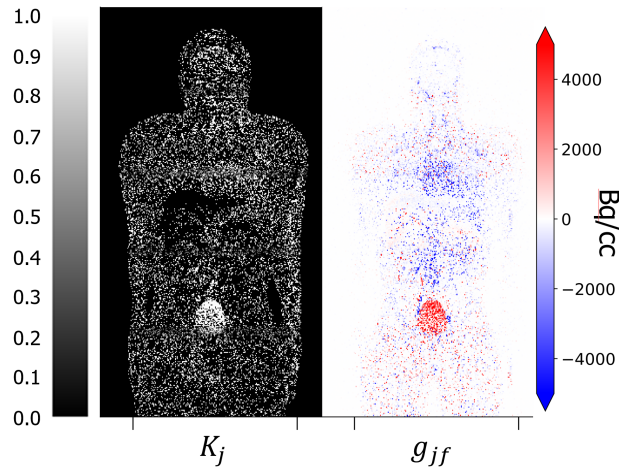


Figure 8.4: Fraction map of K_j and modelled residuals g_{jf} of the residual model 4D-ResidMod-3RBF-Tempfilt at iteration 75.

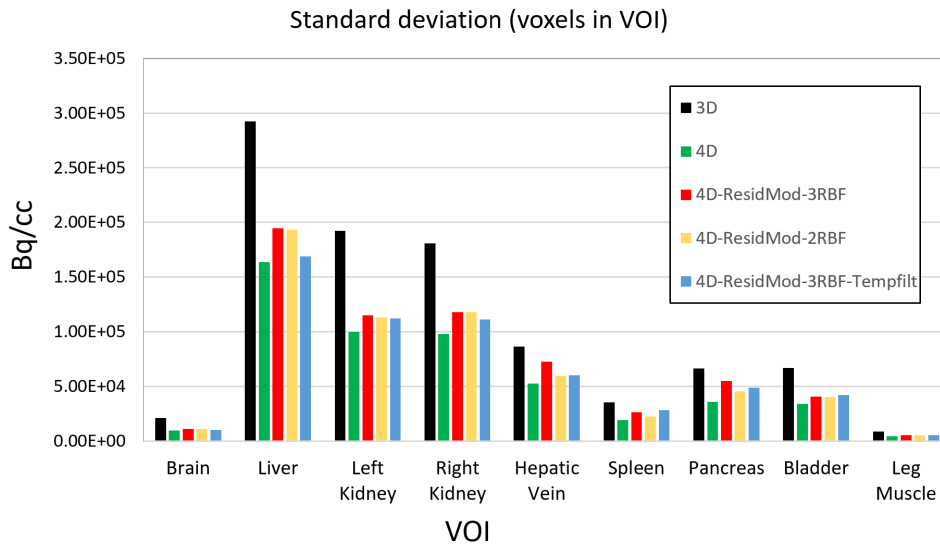


Figure 8.5: Standard deviation of VOIs for regions in the whole-body, for all evaluated reconstructions.

the modelled residuals and the optimum fraction values of the secondary model, as seen in Fig. 8.4, from where it is subsequently re-introduced in the reconstruction process.

Motion will unavoidably always be present in the raw data of dynamic studies. When it is not accounted for in the 4D reconstruction process it will give rise to model fit errors. In our evaluation we saw that the adaptive algorithm attempted to model residuals caused by respiratory motion, when the level of complexity of the secondary model permitted that, even though this was not the intended use for applying residual modelling. As any tracer's kinetic processes are expected to be slower than variations due to respiratory motion, pre-treatment of residuals with temporal filtering in the residual model estimation step aided in averting the adaptive model from fitting these motion induced differences. This temporal filtering approach did not compromise the methods ability to model kinetic processes. In addition, temporal filtering also aided in reducing the increase in noise from the use of the secondary model. But although spatial and temporal filtering in pre-treatment of residual data successfully avoided the fitting of motion induced residuals, these types of residuals should ideally not be considered as model errors since they involve TACs of multiple locations that are affected by motion. Motion correction can be easily integrated in the dynamic reconstruction with adaptive modelling, and should be performed when reliable motion estimations are available. Nevertheless, temporal filtering did reduce the induction of noise by the residual modelling process and thus can still be considered for general use even with motion corrected data.

A limitation in our approach is that we made use of full MLEM iterations (without the use of subsets) which resulted in slow convergence and necessitated to be run at high iterations. The implemented framework in CASToR could support the use of OSEM, with nested optimisation performed after each subset update,

followed by residual modelling in each subset. But initial tests had shown that the buildup of residuals on each sub-set update was not strong enough to be identified and re-introduced by the adaptive modelling approach, using the generalised cross validation derived optimum fraction. Further work is required in taking into account the differences in convergence and buildup of residuals by use of subsets in the optimum fraction K_j , without also resulting in excessive induction of noise from the residuals space.

Another limitation in adaptive modelling within multi-bed dynamic reconstruction is that each bed position is sampled at different time points. In our implementation PCA analysis was performed in a bed-by-bed basis, which enforced the use of individual bed dynamic reconstruction. Subsequently, for the application presented here, the reconstructed images of each bed were combined after reconstruction using weighted averaging. Further considerations are required for extracting residual information over different regions of the DWB scan, with attention to structures that fall in the overlap regions, to enable the use of this approach with direct multi-bed reconstruction. Segmentation approaches on residual space, previously proposed for residual modelling [140], could be employed for the extension of residual modelling in direct multi-bed dynamic reconstruction.

8.5 Conclusion

In this work we conclude that the use of the secondary adaptive model based on PCA analysis can be a practical solution to spectral analysis model fit errors, when added to a generic 4D reconstruction algorithm used with dynamic whole body data from new tracers. The combination of spatial and temporal filtering in the treatment of residual data prior to PCA analysis provided the optimal results in our tests, in terms of algorithm selectivity and levels of added noise. Further work is required to enable the use of data-driven adaptive modelling approaches for direct multi-bed dynamic reconstruction on the DWB setup.

Conclusions and prospects

The objective of this thesis was to explore and assess methods for improving whole-body parametric imaging, for clinical and research pharmacological applications, using multi-bed dynamic whole body PET/MRI data. As hybrid PET/MR scanners and the majority of other PET systems provide only a limited axial field-of-view (FOV), dynamic whole-body (DWB) protocols are used to extend the effective FOV over the required axial length. But these acquisitions come at the cost of limitations in acquisition counts and sampling frequency that degrade parametric image quality and accuracy. Several aspects were investigated, throughout the process of DWB data acquisition to data processing and reconstruction. We largely focused on the use of dynamic reconstruction algorithms for improving the use of the PET acquired data in the estimation of activity and parametric images.

Specifically, in this project we have

1. Developed an optimised protocol for S&S multi-bed DWB acquisitions on the Signa PET/MR.
2. Evaluated and compared advanced dynamic reconstruction algorithms for whole-body parametric imaging, with focus in oncological imaging.
3. Explored the use of a direct multi-bed dynamic reconstruction framework on a real WB pharmacological study.
4. Evaluated the use of adaptive residual modelling applied in DWB data and a generic dynamic reconstruction algorithm.

Firstly, we have worked closely with the manufacturer of the GE Signa PET/MR in methods for reducing the loss of counts and sampling frequency in DWB imaging by means of reducing delays in the acquisition process. This resulted in a custom fully-automated protocol that has shown to considerably reduce delays when applied on a real DWB study on a NHP subject. However, approval for use of this protocol with human studies requires a more thorough review of safety measures and closer collaboration with the manufacturer. Ideally, CBM acquisition techniques should also be considered for implementation as they can contribute

further towards improvements and flexibility in acquisition.

Secondly, we made use of dynamic reconstruction for DWB parametric imaging, with focus on oncology applications of dynamic FDG PET and Patlak parametric imaging, using simulated and real data. We proposed the use of an indirect method for DWB parametric imaging based on the spectral analysis model and dynamic reconstruction which allows for generic compartmental modelling to be used during reconstruction for temporal regularisation. While the Patlak model is limited to data after steady state conditions have been reached, this novel spectral reconstruction approach enables the use of all dynamic data in the reconstruction and offers greater modelling flexibility. Post-reconstruction Patlak parametric imaging using the regularised data of the spectral reconstruction outperformed direct Patlak dynamic reconstruction. But even this method did result in high parametric image noise when reconstruction was iterated sufficiently to ensure accurate quantification. Potentials for improvement should be examined further using additional regularisation methods to deliver acceptable parametric image noise for clinical applications and ensure accurate quantification. Finally, we have expanded our application of dynamic reconstruction to real data from an exploratory, first in man, WB pharmacological study. We extended the use of the dynamic reconstruction to direct multi-bed reconstruction, which enabled the use of the complete DWB dataset within a single iterative loop for dynamic reconstruction. This approach inherently handles the individual bed position data's sensitivity and timing information, notably for the bed overlapping positions where previously suggested practices made use of compromising solutions, while also allowing for the use of the DSB phase data independently of its axial position. In this type of applications, the use of spectral reconstruction is favoured as it does not impose strong assumptions on the unknown underlying kinetics. Preliminary results using VOI based analysis showed good agreement with results from 3D regular reconstruction. These applications also enabled the generation of surrogate parametric K_1 maps, for relative comparison between scans. Further comparisons with post-reconstruction parametric imaging need to be conducted to explore the reliability and additional benefits of this reconstruction approach towards accurate parametric imaging, but these were not conducted at this preliminary stage of the study.

In this application, we identified a limitation in the modelling process over the bladder, that had the potential to be the source of spatially propagating errors within the dynamic reconstruction process. To minimise this risk we have included an adaptive residual modelling approach within the reconstruction. This method identified and selectively corrected the model activity estimates over the poorly modelled bladder region, which provided a significant reduction of model fit errors at the cost of added noise over the entire FOV. Some optimisation advancements were made using pre-treatment of residual data, but further developments are needed for reducing the induction of noise by this approach.

A major limitation in the application of dynamic reconstruction on WB data is motion and motion induced

artefacts that affect image quality and quantification. In the setting of DWB imaging, complex motion exists in the PET data that ideally needs to be accounted for and corrected for within the reconstruction process. Many approaches for including motion correction in the reconstruction have been proposed and successfully used. But estimation of the underlying elastic motion vectors over time and over the WB is a challenging task. Moreover, the limited sampling of MR and PET in DWB acquisitions may reduce the sensitivity of many data-driven approaches for motion estimation. In our evaluations, using PET raw data and MR data from attenuation correction sequences, we were unable to use common motion estimation tools for the successful estimation of elastic motion vectors. Recently numerous Machine Learning (ML) applications for motion estimation and correction have been proposed in medical imaging. This increasing use of ML approaches for motion estimation could lead to further developments that could be useful in the DWB motion estimation problem.

During the course of this project, the introduction of the first Total-Body PET scanner in 2018 has ignited the research interest in DWB imaging. The considerable increase in sensitivity and sampling frequency by synchronous dynamic total-body scans resulted in research projects that span from clinical applications of parametric imaging to joint estimation of complex parameters over the whole-body. These also include innovative methods using the PET TOF information for motion detection and correction. But the availability of these systems is limited, due to the very high cost and no exclusive total-body clinical applications at this time.

More recently, extended FOV scanners became available by commercial providers with an axial FOV of approximately one meter. These offer considerably more coverage than current systems of 15-26 cm axial FOV. At this time there are two systems installed in clinics, with more underway. The greater availability of extended FOV (ex-FOV) systems will lead to more research projects of DWB imaging for clinical applications [20]. As in clinics the systems with limited FOV will still be used in the near future, there can be many opportunities for interesting comparison studies on WB parametric imaging to identify the limits of multi-bed DWB imaging with respect to synchronous DWB imaging by ex-FOV scanners. For example, it could be envisaged that for dynamic imaging of slow processes, such as in the case of Patlak FDG, the DWB protocols on regular scanners could provide sufficient parametric image quality for clinical applications and exclusive use of ex-FOV scanners is not necessary. On the other hand, for kinetics sensitive to early fast dynamics synchronous DWB imaging from ex-FOV scanners is expected to provide strong and clear benefits.

There is a considerable research focus on the subject, from whole-body modelling, whole-body corrections and reconstruction approaches, to ML applied in whole-body image analysis. The technological advancements are going to further fuel this growth of interest, but what is left to be seen is which applications of these techniques and technologies will be predominant in future clinical and pharmacokinetic applications.

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Appendices

Appendix A

Multi-bed Dynamic Whole Body PET: Data exportation and processing

Dynamic Whole Body Protocol implementation for IsotoPK study

The implementation of the DWB protocol used for human subjects of the IsotoPK study on the Signa PET/MR was made using a series of multiple static WB sweeps from a typical WB static protocol. Details of the WB passes are given in table A.1.

Export and offline reconstruction of IsotoPK DWB data

Reconstruction of DWB on the Signa PET-MR console is made with certain limitations and does not allow for full and accurate use of the acquired data, with the correct timing information per bed acquisition which is especially important in estimation of parametric maps.

To make better use of these datasets, an export and offline processing pipeline was developed as part of this PhD project. The pipeline is based on custom-made python scripts and matlab scripts, that integrate with the GE-PET toolbox. This is a toolbox provided by GE for certain offline reconstruction operations. In this pipeline the Toolbox is used for generation of image corrections. These include normalisation factors, attenuation factors from MRACs, random and scatter corrections as well as dead-time corrections.

Table A.1: Details of Whole Body Sweeps of IsotoPK DWB protocol.

Whole Body Sweep ID	PET Bed Frame Duration (s)	MRAC (Acquired or copied)
CE00 blanc	N/A	Yes
Liver	10x18	Yes
CE01	20	From CE00
CE02	20	From CE00
CE03	20	Yes
CE04	20	From CE03
CE05	20	Yes
CE06	20	From CE05
CE07	20	Yes
CE08	20	From CE07
CE09	20	Yes
CE10	30	Yes
CE11	30	From CE10
CE12	30	Yes
CE13	30	Yes
CE14	30	From CE13
CE15	30	Yes
CE16	30	Yes
CE17	30	From CE16
CE18	40	Yes
CE19	40	Yes

A.0.1 Export from Console

DWB studies are exported from the PET-MR console using a custom export tool provided by GE.

Those are then processed using the custom-made pipeline as follows:

- **Step1: Verify Injection Time**

Before organising the DWB data, it is important to verify the injection time point, to which all the DWB will be decay corrected to. In this pipeline we verify the injection time by inspecting the total prompt to time curve from the list-mode dataset of the single-bed dynamic phase, as shown in figure.

- **Step2: DWB data sorting**

The data are re-sorted to single directories per WB sweep, where each directory includes the list-mode data of sweep's five bed positions and their corresponding MRACs if acquired. Subsequently, for sweeps with no acquired MRAC, the MRACs of previous sweeps are copied in these directories. At this step all the timing information from the headers of the PET list and MRAC files are extracted and saved in a database.

- **Step3: GE-PET Toolbox processing**

The data in each sweep's directory are unlisted and reconstructed with the GE-PET Toolbox as individual static acquisitions. This process generates the required corrections for reconstruction. Similar

processing is applied for the single-bed dynamic phase, which is reconstructed by the toolbox as a dynamic study.

- **Step4: Conversion to CASToR datafiles**

The list-mode raw data and the generated corrections are used to make CASToR list-mode datafiles as well as normalization files for each bed position of the acquisition and for all dynamic frames of the single-bed dynamic phase. The time-tags of each list-mode file are modified accordingly, to the injection time point reference, using the database information build earlier.

Standard Operating Procedure: fully automated DWB protocol

A short SOP for the developed fully automated DWB protocol, that was tested on the NHP study, is given in the following steps:

1. Load "IsotoPK_Commander" python class and create new object on a terminal in the PET-MR console.
2. Perform scout of subject, plan the desired bed positions for PET acquisition and perform MRAC acquisition.
3. Capture the position of the planned PET bed positions.
4. Load the "Timing Table" with the frame duration per bed positions and sweep number.
5. If a dynamic phase is required, plan the acquisition and acquire an MRAC for this position.
6. Enable table emulation.
7. Initiate a one hour long PET acquisition and once acquisition is ongoing perform injection of the subject.
8. After adequate time has passed for the single-bed dynamic phase start the automated DWB procedure.
9. Once the acquisition has been completed, disable table emulation.

Table A.2: Example Timing Table, used as input for the fully automated DWB protocol.

Sweep	Durations(s)		
	Bed-1	Bed-2	Bed-3
1	10	10	10
2	10	10	10
3	10	10	10
4	20	20	20
5	20	20	20
6	20	20	20
7	20	20	20
8	20	20	20
9	30	30	30
10	30	30	30
11	30	30	30
12	30	30	30
13	30	30	30
14	45	45	45
15	45	45	45
...			

Appendix B

Simulation Study Supplementary material

The framing of the simulated PET protocols are given in table B.1. The TACs used in simulations were made using using equation B.1. A selection of the simulated kinetic parameters is given in table B.2 and the corresponding TACs are shown in figure B.1.

$$C_{PET}(t) = (1 - V_B) \left(\frac{K_1 k_2}{k_2 + k_3} e^{-(k_2 + k_3)t} + \frac{K_1 k_3}{k_2 + k_3} \right) C_P(t) + V_B C_P(t) \quad (\text{B.1})$$

Table B.1: Framing of simulated DWB protocols (sec). Frames used for Patlak analysis in bold.

Frame number	Single Bed		DWB-1		DWB-2		DWB-3		DWB-4	
	start	duration	start	duration	start	duration	start	duration	start	duration
1	0	20	206	20	205	20	205	20	0	20
2	20	20	366	20	327	20	355	20	20	20
3	40	20	536	30	461	30	437	30	40	20
4	60	20	776	60	676	60	662	30	60	20
5	80	30	1136	60	1018	60	805	60	80	20
6	110	30	1568	132	1360	60	1255	60	100	20
7	140	30	2288	132	1772	116	1465	60	120	20
8	170	60	3008	132	2422	116	1915	60	140	20
9	230	60			3072	116	2195	116	160	20
10	290	60					3065	116	206	20
11	350	60							366	20
12	410	60							536	30
13	470	120							776	60
14	590	120							1136	60
15	710	120							1568	132
16	830	300							2288	132
17	1130	300							3008	132
18	1430	300								
19	1730	300								
20	2030	300								
21	2330	300								
22	2630	300								
23	2930	300								
24	3230	300								

Table B.2: Parameters of simulated 2 tissue compartment models in the zupal brain phantom.

Region	$K_1(ml \cdot g^{-1} \cdot min^{-1})$	$k_2(min^{-1})$	$k_3(min^{-1})$	V_b	$K_i(min^{-1})$	Patlak slope(SB)
White	0.047	0.07	0.035	0.03	0.0157	0.0149
Cortex	0.102	0.073	0.049	0.03	0.0410	0.0390
Cerebellum	0.07	0.07	0.04	0.03	0.0255	0.0242
Putamen	0.081	0.052	0.032	0.03	0.0309	0.0302
Caudate	0.081	0.052	0.032	0.03	0.0309	0.0302
Thalamus	0.092	0.052	0.026	0.03	0.0307	0.0305
Muscle	0.05	0.163177	0.03	0.25	0.0078	0.0055

Table B.3: VOIs used for evaluation.

VOI Name	Number of voxels	Volume (cm^3)
Thalamus	915	12.40
Eroded thalamus	218	2.95
Cortex	46588	631.36

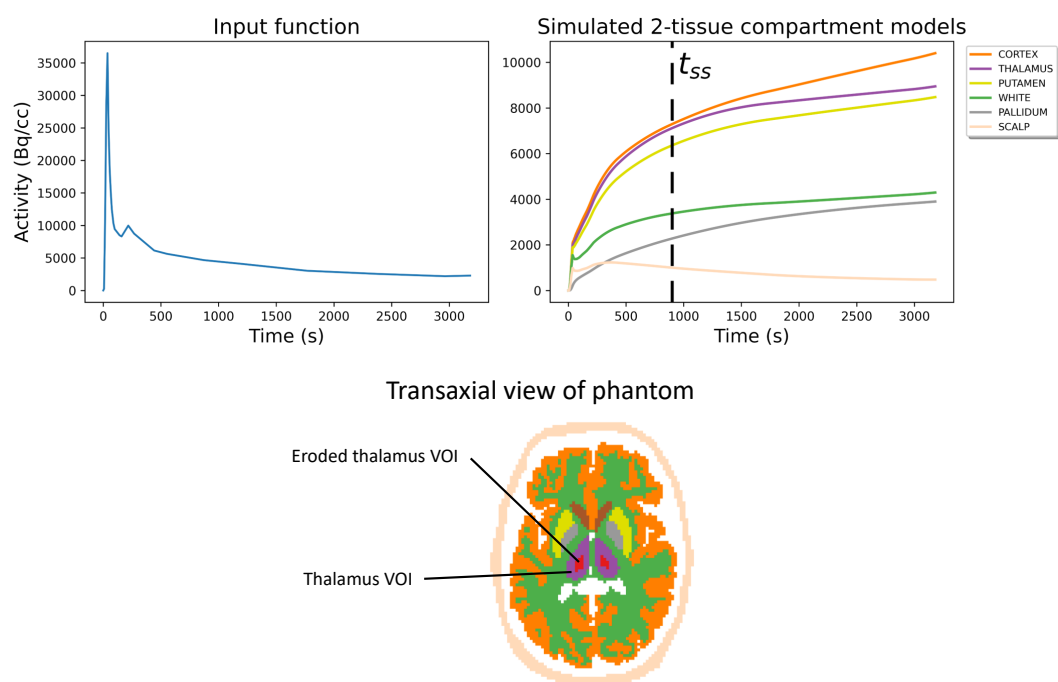


Figure B.1: Input function and selection of simulated 2-tissue compartment model TACs (top), and transaxial view of the segmented zupal phantom, with the addition of an eroded thalamus VOI (bottom). The same colours are used for the TACs and the VOIs.

Appendix C

Direct multi-bed dynamic reconstruction: Supplementary material

Supplementary graphs, used in the analysis of the evaluated IsotoPK studies of chapter 7, are provided here. Additionally, a brief simulation study for the behaviour of the spectral analysis model in the liver and the effects from the dual-input function is included.

Supplementary graphs

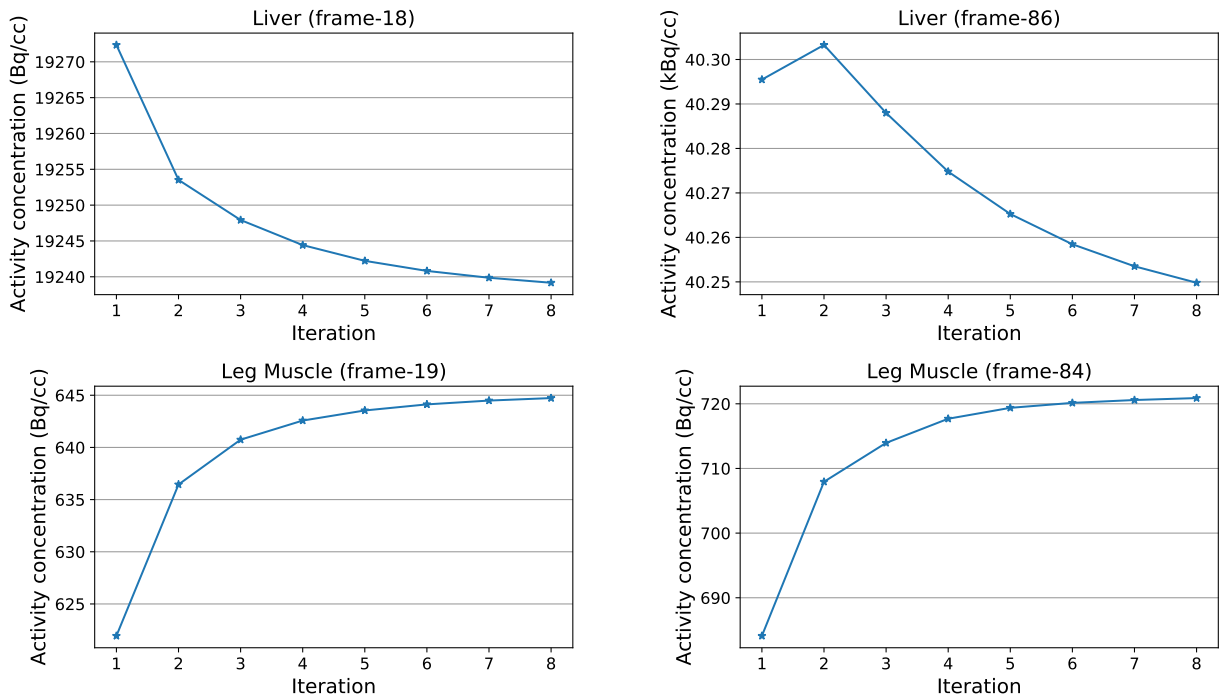


Figure C.1: Liver (top) and Muscle (bottom) VOI mean versus iteration curves for 3D reconstruction. Shown for early (left) and late (right) frames of the *CTRL* DWB acquisition including the DSB phase.

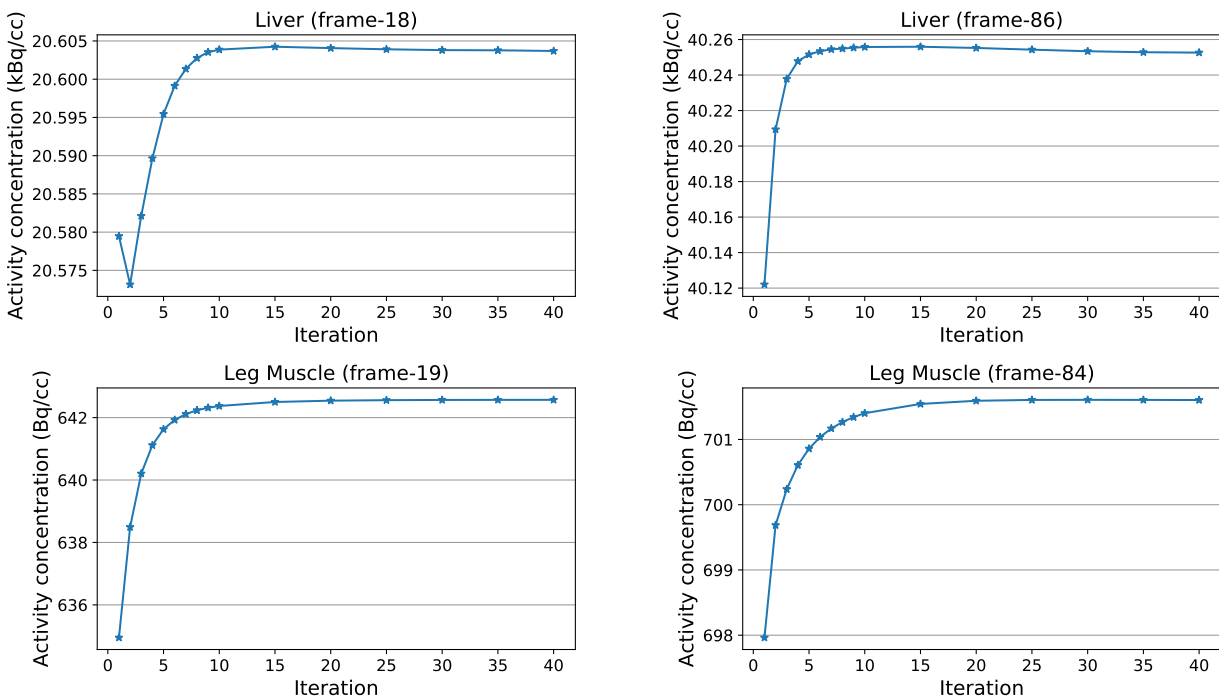


Figure C.2: Liver (top) and Muscle (bottom) VOI mean versus iteration curves for 4D spectral reconstruction. Shown for early (left) and late (right) frames of the *CTRL* DWB acquisition including the DSB phase.

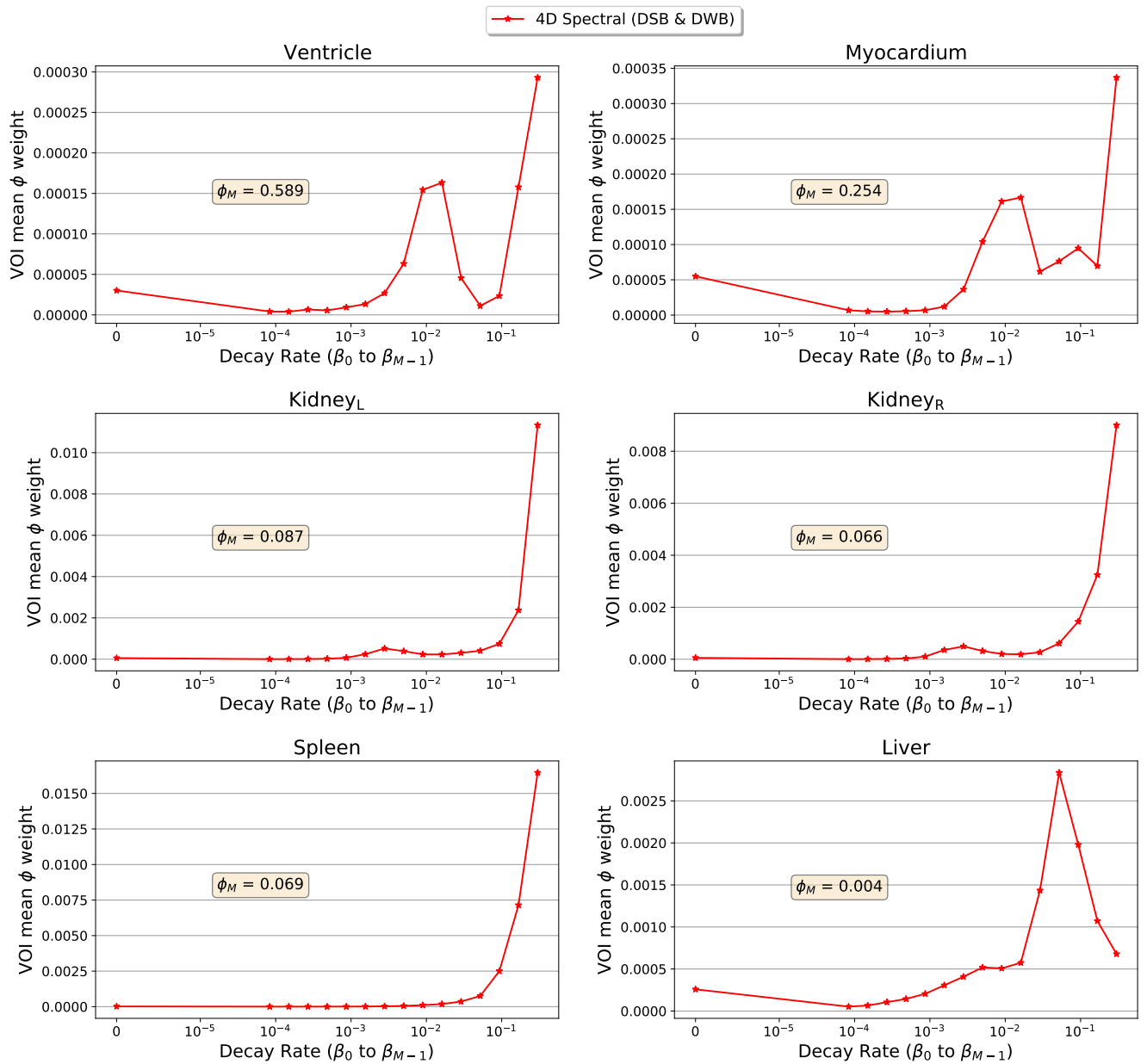


Figure C.3: Spectral model coefficients average in VOIs. VOI regions shown which are included in both DSB and DWB acquisition.

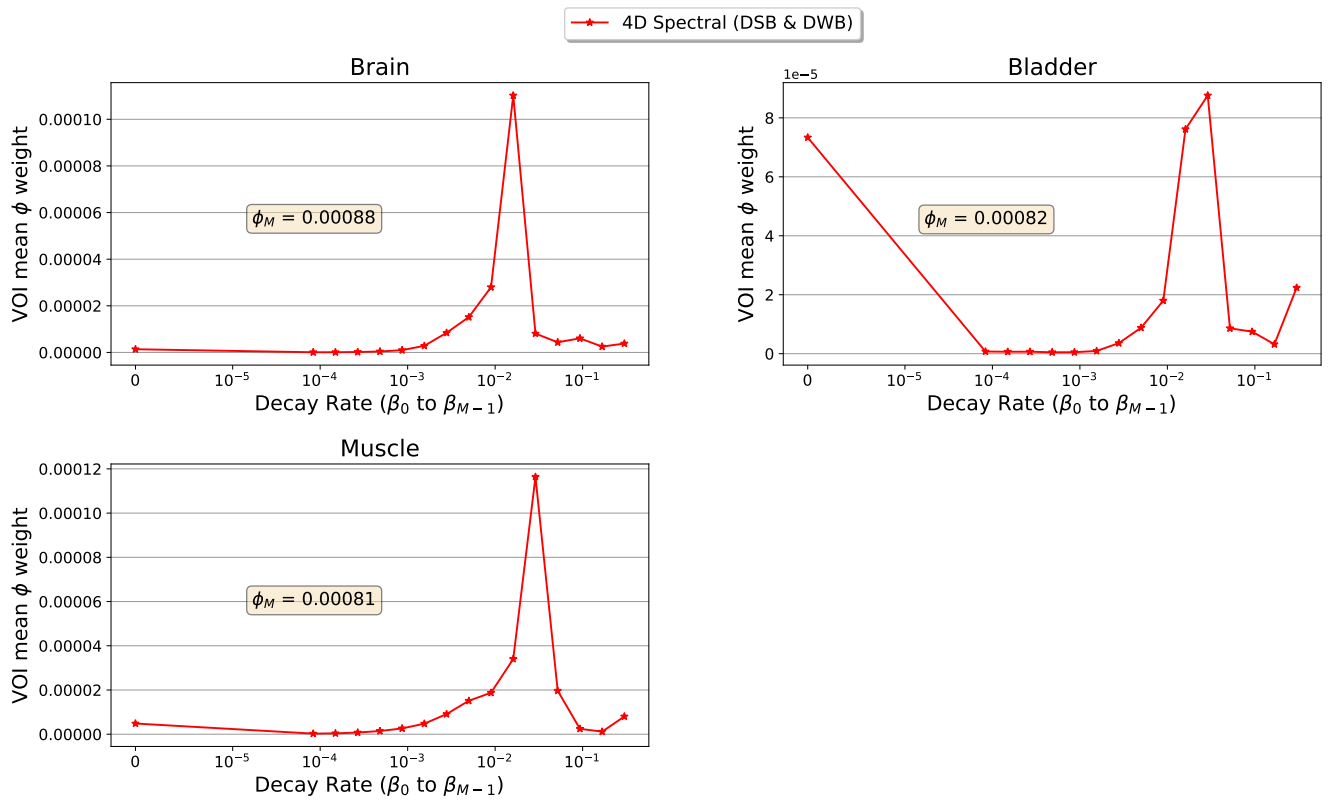


Figure C.4: Spectral model coefficients average in VOIs. VOI regions shown which are covered only by the DWB acquisition.

Liver dual-input function simulation study

This short simulation was conducted using noiseless TACs to test the effects of the use of a dual input function model against spectral analysis that only accounts for one single input function. The following equations were used for the simulation. The portal vein input function was simulated using equation C.1 and a dispersion value $k_g = 0.5 \text{ min}^{-1}$ from the literature [77]. The dual input function was then simulated with a 25/75 ratio using equation C.2 and provided to the equation C.3 of the 2TC model for simulating liver TACs. Finally the blood fraction was included using equation C.4. The simulated K_1 values varied between 0.3 and 2.4 min^{-1} . The simulated k_2 , k_3 and V_B values were 0.15 min^{-1} , 0.05 min^{-1} and 0.03 respectively. These values, using a $K_1 = 0.7 \text{ min}^{-1}$, approach the TAC of the IsotoPK CTRL scan from chapter 7. Spectral analysis was performed using the single input function of $C_P(t)$.

$$C_{PV}(t) = k_g e^{-k_g t} * C_P(t). \quad (\text{C.1})$$

$$C_H(t) = 0.75 \cdot C_{PV}(t) + 0.25 \cdot C_P(t). \quad (\text{C.2})$$

$$C_T(t) = K_1 \left(e^{-(k_2+k_3)t} + \frac{k_3}{k_2+k_3} (1 - e^{-(k_2+k_3)t}) \right) * C_H(t) \quad (\text{C.3})$$

$$C_{PET}(t) = (1 - V_B)C_T(t) + V_B C_H(t), \quad (\text{C.4})$$

The simulated TACs are shown in figure C.5, while the result K_1^* values of the spectral analysis against simulated K_1 values are shown in C.6. The results show an closely linear relationship between simulated K_1 and estimate K_1^* values, with a deviation from a slope of 1. A part of this deviation is attributed to not correcting the K_1^* values for blood fraction, but mostly it is due to unaccounted behaviour of the dual input function.

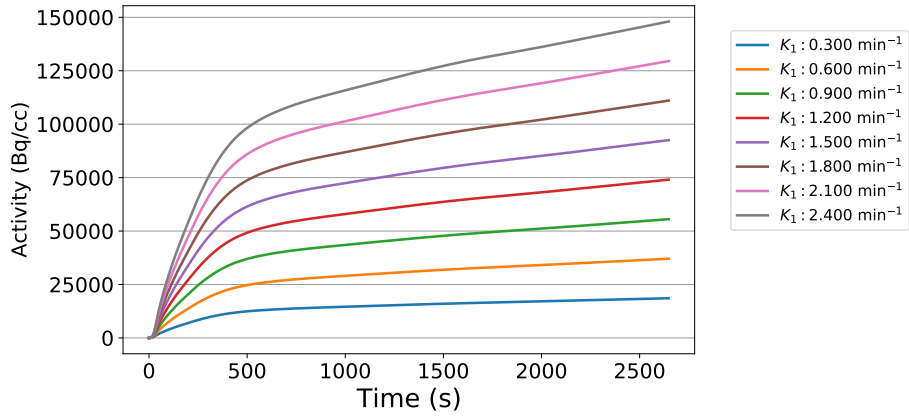


Figure C.5: Simulation of Liver TACs, using dual input function model and varying K_1 values.

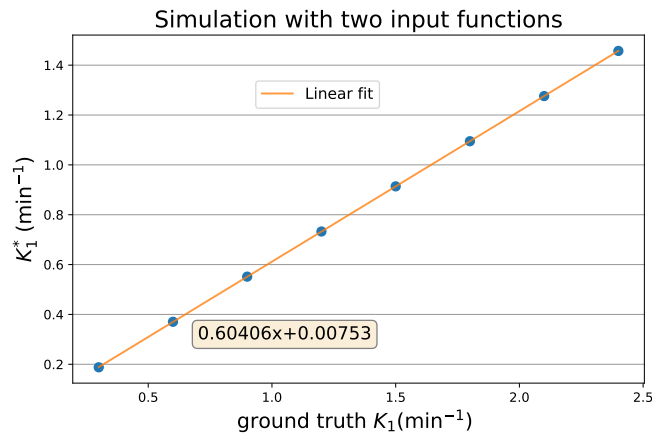


Figure C.6: Result estimates of K_1^* from spectral analysis on noiseless simulations of Liver TACs against ground truth simulated value.

Secondary Contributions

PET FDG Improved Tumour Definition using Deep Learning

Within the HYBRID secondments schedule, a 1-month secondment for Laura Dal Toso (LDT) from King's College London (KCL) was planned to take place at our lab. This secondment aimed in performing simulations for creation of large datasets that could be used for the training of Deep Learning (DL) methods.

For applications of PET imaging in oncology, quantification and shape of tumours are regularly used by medical professionals for the characterisation and classification of disease. For the case of NSCLC imaging, and not only limited to that, these image characteristics are often degraded by image noise and partial volume effects. In this work, a method for improving tumour shape definition and quantification was proposed, by use of Deep Learning (DL). As DL methods require a large number of training datasets, simulations were used to train the proposed DL method.

The aim was to ultimately use the DL method for real NSCLC image data from an mMR PET/MR scanner (installed at KCL). Thus the implementation of the mMR geometry in the PET analytical simulator was needed, which was performed by me (ZC) with guidance from Dr Simon Stute. After the successful integration of the geometry for simulations and validation of reconstructions using CASToR, a large dataset of ground truth tumours (placed within the XCAT phantom) was created by LDT and provided for PET simulation. A total of 2210 cases were simulated and reconstructed, using a custom made pipeline by ZC on two computer clusters of our lab. Details on the methodology used and results will soon be submitted for publication as a research paper.

Data Driven Motion Correction for Brain PET Dynamic Imaging

A 2-week secondment was planned for me at the MUW in Vienna, with the aim of making use of dynamic reconstruction techniques developed during this PhD project to a cohort of epilepsy dynamic PET data. But this secondment was performed mostly from distance due to the pandemic and the time was spent towards the implementation and evaluation of novel motion estimation method for dynamic PET brain studies.

Towards this goal, a method was developed using ultra-short frame reconstruction and a Cycle Generative Adversarial Network (cGAN). The cGAN was designed to improve image quality of the short frame reconstructions for better motion estimation. In the training of the cGAN, data from the cohort of epilepsy patients was used. The datasets had been acquired on an mMR PET/MR scanner.

During this project, a converter was adapted to support conversion of dynamic mMR PET data, including all corrections generated by the e7 tools, to the CASToR datafile format. Using the converted data, dynamic reconstructions were performed in CASToR using the involuntary motion correction option. These reconstructions were used to assess the effect of intra-frame motion correction in result activity and parametric images. The development work and application of the cGAN has resulted in the publication of Shiyam Sundar *et al.* [141]. The work performed using CASToR has not been included in this publication, but it is considered for use in a future project on the topic of motion correction.

Titre : Modélisation et reconstruction de cartes paramétriques corps-entier en imagerie pharmacologique TEP-IRM

Mots clés : Tomographie par émission de positrons (TEP), Imagerie par résonance magnétique (IRM), Imagerie dynamique, Reconstruction dynamique, TEP corps-entier dynamique, Imagerie paramétrique, Cartes pharmacocinétiques.

Résumé : La tomographie par émission de positons (TEP) est fréquemment utilisée pour des applications cliniques, avec une majorité des pratiques reposant sur des mesures qualitatives et semi-quantitatives. Mais l'imagerie TEP a la capacité de fournir des informations fonctionnelles entièrement quantitatives sur les processus sous-jacents explorés, grâce à l'imagerie dynamique et à la modélisation cinétique. Ces informations quantitatives peuvent être utilisées comme biomarqueurs pour des applications cliniques, en particulier pour la médecine de précision. Des protocoles avec des positions du lit multiples, dédiés à l'imagerie dynamique du corps entier (DWB), ont été développés afin d'étendre le champ de vue effectif, au prix de restrictions dans le nombre de détections et la fréquence d'échantillonnage. L'objectif de cette thèse est d'améliorer la qualité de l'imagerie paramétrique du corps entier pour les applications d'imagerie DWB sur un système hybride TEP-IRM.

Dans notre première contribution, nous avons présenté le développement d'un protocole entièrement automatisé pour l'imagerie DWB sur un système TEP-IRM clinique, qui a permis de réduire les délais d'acquisition, ce qui se traduit par une augmentation du nombre de détections et de la fréquence d'échantillonnage. Le recours à l'automatisation complète a permis d'optimiser la planification des positions des lits, en utilisant au mieux le champ de vue effectif.

Pour la deuxième contribution, nous avons développé des algorithmes de reconstruction dynamique dans un logiciel ouvert, et évalué les avantages offerts par l'utilisation de divers modèles cinétiques dans la reconstruction de données TEP dynamiques simulées et réelles. Ces évaluations étaient focalisées sur les reconstructions de lits individuels des protocoles DWB. Dans le cas particulier de l'imagerie DWB, la reconstruction dynamique a montré des propriétés favorables pour l'exactitude et la précision des images paramétriques du corps entier, tout en fournissant des images dont

le bruit est comparable à celui des protocoles dynamiques standards à position de lit unique, reconstruits avec des techniques ordinaires.

Dans notre troisième contribution, nous présentons une extension des fonctionnalités développées précédemment: la reconstruction dynamique simultanée de toutes les données multi-lits. Cette méthodologie permet l'utilisation synchrone de toutes les données d'acquisition DWB dans une seule boucle de reconstruction. La méthode a été appliquée à une étude pharmacocinétique DWB réalisée sur un système TEP-IRM. Une comparaison a été faite avec des reconstructions statiques standards suivies d'une modélisation cinétique post reconstruction. Les résultats obtenus avec les deux méthodes étaient en bon accord, sans introduction de biais sur les métriques évaluées. En outre, l'utilisation de la reconstruction dynamique a entraîné une réduction notable du bruit dans les images d'émission et paramétriques.

Dans notre quatrième contribution, une méthode de détection et de correction des erreurs de modélisation utilisant la modélisation résiduelle adaptative a été appliquée et évaluée. Elle a montré des résultats prometteurs pour la réduction des erreurs de modélisation et leur propagation, tout en permettant la généralité dans l'utilisation des algorithmes de reconstruction dynamique.

Nos résultats ont montré que la reconstruction dynamique est nécessaire en imagerie paramétrique corps-entier pour obtenir une quantification précise et stable. De nombreuses méthodes ont été proposées dans ce projet afin d'optimiser le processus de reconstruction TEP pour l'imagerie DWB, en utilisant au mieux les données dynamiques acquises sur plusieurs positions de lit. Pour généraliser son utilisation, certaines améliorations méthodologiques doivent encore être apportées pour garantir une imagerie paramétrique fiable et sans artefact, notamment en ce qui concerne les mouvements du patient.

Title : Modelling and Reconstruction of Whole-Body parametric maps in PET-MRI Pharmacological imaging

Keywords : Positron emission tomography (PET), Magnetic resonance imaging (MRI), Dynamic imaging, Dynamic reconstruction, Dynamic whole-body PET, Parametric imaging, Pharmacokinetic maps.

Abstract : Positron Emission Tomography (PET) is used extensively for clinical applications, with the majority of practices relying on qualitative and semi-quantitative measures. But PET imaging has the ability to deliver fully quantitative functional information of underlying imaged processes by use of dynamic imaging and kinetic modelling. That unique quantitative information can be utilised as biomarkers for clinical applications, especially in precision medicine. But clinical applications often require imaging over the whole body and the majority of clinical scanners provide a limited axial Field of View (FOV). Multiple bed position protocols for dynamic whole-body (DWB) imaging have been developed to extend the effective FOV, at the cost of considerable limitations in acquisition counts and sampling frequency. The objective of this thesis is to improve the quality of whole-body parametric imaging for DWB imaging applications on a hybrid PET/MR scanner.

In our first contribution we presented the development of a fully automated acquisition protocol for DWB imaging on a clinical PET/MR system, which resulted in reduced delays between whole body sweeps of the dynamic whole-body acquisition. These improvements can be used towards increasing acquisition counts and sampling frequency. Furthermore, the use of full automation enabled optimized planning of the individual bed positions for the best use of the effective FOV.

For the second contribution we developed dynamic reconstruction algorithms within an existing open source reconstruction software. We evaluated benefits offered by use of various dynamic models in reconstruction, using simulated and real dynamic PET data.

These evaluations were focused on reconstructions of individual beds from DWB acquisition protocols. Our results agreed with previous findings on the use of dynamic reconstruction. In the particular case of DWB imaging, dynamic reconstruction showed desirable properties for whole-body parametric image accuracy and precision, while providing

images of comparable image noise to regular single bed dynamic protocols processed with regular reconstruction techniques.

In our third contribution we present an extension of the developed functionalities on the reconstruction software for direct multi-bed dynamic reconstruction of DWB data. This methodology enables the synchronous use of all acquired DWB data within a single reconstruction loop. The method was applied on a DWB pharmacological study performed on a clinical PET/MR system and comparison was made with regular frame static reconstructions followed by post reconstruction parametric modelling. The results between the two methods were in good agreement, with no introduction of bias on the evaluated metrics. Furthermore, the use of dynamic reconstruction resulted in noticeable noise reduction in activity and parametric images.

In the fourth and final contribution, an adaptive residual modelling method was applied in reconstruction and evaluated on the DWB pharmacological study, to address modelling errors. This method showed promising results in reducing modelling errors and error propagation while also allowing for genericity in the use of dynamic reconstruction algorithms.

Overall, our findings showed that dynamic reconstruction is necessary in DWB parametric imaging to achieve accurate and stable quantification. Many methods have been proposed in this project that showed how reconstruction can be optimised for multi-bed DWB imaging, by making best use of all dynamic and bed PET raw data in the reconstruction process. But before widespread use of dynamic reconstruction, some methodological improvements need to be addressed further to guarantee artefact free and reliable parametric imaging. Most notably there is need for accurate estimation of underlying complex elastic motion in the dynamic datasets, followed by the correction of these motion types within the dynamic reconstruction process.