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Physics/Instrumentation: Image Reconstruction & Data Simulation

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Evaluation of advanced SPECT reconstruction technologies

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Aim: Each of the three major manufacturers of SPECT systems offers as an advanced option iterative reconstruction incorporating the modeling of spatially variable resolution and of scatter. This work aims at assessing the performance of the new algorithms by measuring spatial resolution and noise using a realistic physical phantom and the manufacturer recommended reconstruction schemes in a clinical setting. Materials and methods: On three SPECT/CT systems, manufactured by General Electrics, Philips and Siemens, all of them installed recently a phantom was imaged using high resolution collimators and otherwise identical acquisition parameters. After the SPECT acquisition (360°, 6°/step, 40sec./frame) an additional CT scan was done and used for attenuation correction. The phantom consisted of the trunk of the IEC/NEMA body phantom into which line sources were inserted. The line sources were filled with 99m-Tc, and tomographic acquisitions were made alternatively in air, with the phantom filled with water and with a 99m-Tc solution producing a warm background. Reconstructions were carried out following the manufacturers' recommended protocols using the Evolution (E;GE), the Astonish (A;Philips) and the Flash3D (F;Siemens) software and attenuation correction, with and without filtering and scatter correction. As a reference the data were processed using standard iterative reconstruction algorithms (OSEM and MLEM). From a representative transaxial slice the FWHM (full width at half maximum) of the line sources and, for the slices with a warm background, the noise in a background region was calculated. Results: Spatial resolution decreased significantly with the new algorithms for all measurement conditions. Typically, FWHM with scatter was 7,9/11,6 (no filter/filter) mm for A, 7,6/11,8 mm for E and 8,4/11,0 mm for F. Corresponding reference values were higher by 40/20 % (A), 36/9 % (E) and 15/0 % (F). Depending on the reconstruction mode and parameters, the total number of counts in the slice varied by up to a factor of 4, indicating unequal scaling used by the different algorithms. Noise variance was inconsistent between different reconstruction modes, most likely due to the varying scaling and/or different reconstruction parameters. Conclusions: Spatial resolution improves by an average of 30 percent using the commercially available advanced reconstruction technology in a realistic clinical setting. Great care must be taken to avoid unnecessary filtering which may be included by default in some protocols. For all three software systems, preservation of counts is not maintained, so that quantitation of radioactivity needs careful calibration for each reconstruction protocol to be used.

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Development of optimized cone-beam brain SPECT

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Aims: (1) To maximize contrast-to-noise ratio (CNR) for brain SPECT imaging with optimized half-cone-beam collimators (HCBC) and optimized acquisition orbits and (2) to reduce truncation and sampling artifacts. Materials & methods: We studied a brain SPECT using dual-head gamma camera with two HCBCs or a HCBC combined with a fan-beam collimator (FBC). The HCBC was used to avoid collision with patient's shoulders. Two parameters were optimized: the acquisition orbit shape and the focal length of the HCBC. The constraint was a total acquisition time. The following orbits were considered: helical with two HCBCs, and one HCBC combined with one FBC in a single-circular-orbit. Tc-99m HMPAO brain SPECT scan was simulated by Monte Carlo package (SimSET) for the numerical Zubal brain phantom in a 128×128 matrix with HCBC focal lengths = 30, 20 and 15 cm, FBC focal length = 40 cm, and the radius of rotation = 32 cm. Analytical projection sets were created for a numerical mini-Defrise phantom with the same collimators. The detector response, scatter and Poisson noise were considered in Monte Carlo simulations, but not in analytical projections. All projections were reconstructed using ordered subsets expectation maximization with a volumetric system model and exact attenuation correction (OS = 5, up to 100 iterations). Results: Both qualitative and quantitative evaluations indicate that axial distortion artifacts are always present in the reconstructed images acquired in the single-circle-orbit using HCBC and FBC since it cannot satisfy the Tuy's sampling sufficiency condition. These artifacts could be suppressed by using helical orbits. The CNR is significantly enhanced within HCBC field of view, as compared to conventional two FBCs single-circle-orbit brain SPECT imaging. This enhancement is higher for the shorter focal length and decreases with increasing distance from the image volume center. Conclusions: The improved contrast-to-noise and artifacts-free reconstructed images are obtained in brain SPECT with helical orbit with two HCBCs at a cost of extended acquisition time and required modification of SPECT camera. Combined HCBC-FBC SPECT with a single-circle-orbit improves contrast-to-noise ratio but also create axial distortion artifacts. However, these artifacts might be made small enough by proper selection of HCBC parameters to be acceptable in clinical practice. Such solution might be preferable over helical HCBC SPECT because it could be readily implemented on the existing gamma cameras.

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3D Volume-of-Interest Quantitative Reconstruction from Phantom SPECT/CT Scans

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Aim: Our motivation is to improve the accuracy of reconstructed activity distribution for tumor SPECT scans. Conventional procedures reconstruct the activity distribution in the whole object, resulting in relatively poor accuracy/resolution for tumors and wasting resources trying to rebuild diagnostically useless background. In this study, we apply a "local" reconstruction concept to the volumes of interest (VOIs) surrounding tumors located in low background. **Materials and Methods:** Our experimental setup reproduced the clinical SPECT study with cylindrical 33ml vials (tumors) located inside 7000ml thorax phantom (Data Spectrum Corp.). In total, four experiments with Infinia-Hawkeye SPECT-CT camera (GE Healthcare) were performed. In each study, 3-5 vials (each containing 6-9MBq of Tc-99m activity) were placed in different locations inside the phantom. Modeling high-uptake tumors in low background, we scanned phantoms without (experiments 1 and 2) and with inactive (experiments 3 and 4) water. Following the Tc-99m-MDP protocol, camera made 90 stops (30 seconds each) over 360 degrees. We compared two reconstruction concepts. First, "global", method used ordered subsets expectation maximization (OSEM) algorithm (2-8 iterations) and recovered activity in the whole phantom volume. To increase the quantitative accuracy of reconstructions of activity distribution inside vials, we implemented corrections for resolution loss (RC), attenuation (AC) and scatter (SC). In the second approach, we surrounded each source by a cubic VOI (290ml each) and reconstructed activity only inside this volume. The VOI-based system matrices incorporated the same corrections (RC, AC, and SC) and were analytically calculated. While the matrix in the first approach is under-determined (although the majority of unknowns are not of interest), VOI-based matrices are over-determined. This "extra" information from the acquired data can be used to apply a finer grid inside VOIs (to increase resolution) or employ improved methods to solve systems of equations of relatively small size (to increase accuracy). We investigated the second opportunity and applied non-iterative Gaussian elimination method to find weighted penalized least squares (VOI-WPLS) solution. **Results:** The "local" VOI-based WPLS led to more accurate recovery of activity distribution inside VOIs than the conventional "global" OSEM algorithm. The errors of total activity of vials reconstructed by standard OSEM were 15-17% and by VOI-WPLS - 6-11%. In addition, the relative voxel-by-voxel deviation from the true activity distribution provided by OSEM was 27-32%, and by VOI-WPLS - 22-24%. **Conclusion:** VOI-based reconstruction of activity distribution may potentially provide improved quantitative accuracy for SPECT/CT imaging of low-background tumors.

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Respiratory motion in small animal PET using Monte Carlo simulations

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Aim: Respiratory motion is known to affect the quality of PET imaging, hindering the location, lesion detection and tracer quantification in oncology. The use of the dynamic respiratory feature available in the MOBY mouse phantom can allow obtaining insight on the impact of respiratory motion on the detection of lung tumors using FDG-PET. We used a Monte Carlo simulation system in order to produce realistic simulated mouse scans and evaluate the degradation on lesion detection for whole-body mouse PET imaging, due to normal breathing. Material & Methods: The Geant4 Application for Tomographic Emission (GATE) Monte Carlo platform was used for modeling the microPET® FOCUS 220 system and implementing the digital MOBY phantom. We have changed the 4D MOBY respiratory model to produce physiological "stress breathing" condition, in order to reproduce the respiratory mouse motion during a typical PET examination. A spherical lung lesion was implemented and its motion modeled as a function of the non normal tidal breathing condition. For that purpose, a set of static and dynamic (includes the mouse breathing motion and the tumor motion) FDG simulation scans were performed considering different lesion radius (0.375 mm, 0.5mm, 0.625 mm, 0.75 mm and 1.0 mm) and different activity uptakes. The whole-body activity distribution was set according to the activity distribution assigned to the different whole body structures, obtained from real FDG data. In all the performed simulations, physical effects and tissue attenuation were not considered in order to obtain a full correction of positron range and gamma accolinearity. Results: In the static images the lesion is clearly shown, keeping its spherical shape. For the dynamic images, the lesion appears blurred and elongated as a consequence of the breathing movement. However, lesions with a size less than 0.75 mm diameter and a contrast of 1.5:1 may remain undetected. Conclusion: The location and detection of lesions in thoracic and abdominal mouse imaging can be affected by the respiratory motion due the displacement of the organs during the normal breathing. This effect should be taken into account when searching lesions and quantifying tumor tracer uptake in highly deforming structures such as the lungs. The optimization of acquisition protocols, image correction procedures and reconstruction methods for the whole body mouse will therefore be done in the future.

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Monte Carlo Simulation of The GE LYSO-Based Discovery RX PET/CT Scanner Using GATE: a Validation Study

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The Geant4 Application for Tomographic Emission (GATE) is an open source Monte Carlo simulation platform developed for PET and SPECT studies and is suported by the OpenGATE collaboration. GATE provides the ability of modeling time-dependent phenomena, such as geometry element movements and source decay kinetics, allowing the simulation of time curves under realistic acquisition conditions. It also provides the ability to model and account for the effects of photon noncollinearity, off-axis detector penetration, detector size and response,

positron range, photon scatter, and patient motion on the resolution and quality of PET images. The purpose of this paper is to validate a GATE model for the simulation of the GE Discovery RX PET/CT Scanner to demonstrate the flexibility and accuracy of GATE besides showing the potential benefits of a validated PET scanner simulation in protocol optimization and in system design. The scanner possesses high NECR, low scatter fraction, and good spatial resolution characteristics. The three-dimensional GATE model consists of 4.2 x 6.3 x 30 mm3 LYSO crystals grouped in 9 x 6 blocks. There are 24 rings with 630 crystals per ring for a grand total of 15120 crystals. The ring diameter is 88.6 cm and the transaxial and axial fields of view are 70cm and 15.7cm, respectively. The validation is carried out against actual measurements performed in accordance with the National Electrical Manufactures Association (NEMA) NU 2-2001 protocols. Overall results for the sensitivity, scatter fraction and count rates performance show very good agreement between the simulated and the experimental data. The ratio of the sensitivities with sources radially offset 0 and 10cm from the scanner's main axis are agrees to within 1% of measurements. The simulated scatter fraction for the NEMA NU 2-2001 phantom also agrees to within less than 3.5% of measured values. The experimental peak true count rate of 453.6 kcps and the peak activity concentration of 30.8 kBq/cc were matched by the simulated results to within 0.5%. The simulated count rate curves also resulted in a peak NECR of 120.41 kcps at 22.5 kBq/cc compared to 117.7 kcps at 21.7 kBq/cc from experimental values. In summary, we have demonstrated the GATE Monte Carlo code is a useful tool for modeling of scanner geometry for the purpose of design optimization and performance prediction.The model in this study is being improved in order to explore what gains in PET performance could be achieved if the timing resolution was improved.

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Analytic and Monte Carlo Derived System Matrices for Small Animal PET Imaging

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Aim: System matrices required for iterative image reconstruction can be categorized by the quality of the resultant images and the computational speed necessary to produce a matrix. While system matrices derived by Monte Carlo simulations include the complete response of the scanner with the full description of the detector process, the simulations are very time consuming. Analytic models are faster, but, it is important to determine how accurate they describe the system matrix. The aim of this work is to evaluate the performance of two analytic models, one based on Siddon ray-tracing [1] and the other on modeling the detector response function (DRF) [2]. These models can be compared with Monte Carlo derived system matrices by reconstructing with an MLEM iterative algorithm and comparing the overall image quality. Methods: Three small animal PET scanner geometries are considered: a dual-layer crystal ring geometry, and two single-layer ring geometries with crystal lengths 10 and 14mm. For each geometry, system matrices are calculated using Monte Carlo simulations via the GATE code as well as two analytic models (i.e. Siddon and DRF). Reconstructions using an MLEM iterative reconstruction algorithm and Derenzo and capillary phantoms are used to obtain images for performance evaluation. The spatial resolution is compared for each geometry and system matrix model. Results: The results show that reconstruction using Monte Carlo derived system matrices gives the best overall qualitative images with the highest spatial resolution (FWHM ~1mm, half the crystal size). The analytic models are fast but rely on an accurate calculation of the geometric part of the system matrix. If the geometry is poorly described, then artifacts occur in the reconstructed images. This is predominantly seen in images reconstructed using the Siddon algorithm, where strong artifacts occur at the edges of the FOV. The DRF model offers improved images since it includes information concerning detector efficiency. In general, for all system matrices, the dual-layer ring geometry offers higher spatially resolved images than the single-layered ring geometries. Conclusions: Analytic models are faster than Monte Carlo simulations, but, the image quality is strongly affected by how well the scanner geometry and the detector efficiency are described in the system matrix. Future work will involve optimization of the DRF model to achieve a good compromise between image quality and computational time. References: [1] Siddon R.L., Med. Phys. 12 (1985) 252 [2] Strul D. et al., Phys. Med. Biol. 48 (2003) 97

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Multi-Camera Comparison of HMPAO SPECT Simulated Lesion Detectability Using a Subresolution Sandwich Phantom

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Aim Use of a normal database in quantitative analysis of brain single-photon emission computed tomography (SPECT) facilitates the detection of defects in individual or group studies by reducing observer subjectivity. The ability to simulate normal and abnormal images would allow various important areas in rCBF SPECT analysis in general and topics related to the use of normal databases in particular to be studied. These areas include the optimization of the detection of abnormal blood flow and the portability of normal databases between gamma camera systems. To investigate this further we have constructed a hardware phantom and scanned various combinations of radioactive brain patterns and simulated skull configurations on a number of different gamma cameras. Materials and Methods A subresolution sandwich phantom with a simulated skull was assembled using a high-resolution segmented MR scan printed with a 99mTcO4- mixture and scanned using four camera systems in three different centres. Previous work had established a printed phantom configuration (involving optimization of the printed GM:WM ratio and simulated skull) that was considered normal on SPM comparison with a database of normal subjects. Abnormal phantom configurations were then created by introducing hippocampal and precuneal lesions into the normal printout pattern. Both normal and abnormal printouts were scanned multiple times on the camera systems. Three of the systems were standard double-headed gamma cameras equipped with parallel hole collimators. The fourth system was a four-headed dedicated brain camera with parallel hole collimators. The abnormal images were compared to both the normal printout scans and various databases of control subjects using the standard data processing settings. Results Considerable variability was observed in the detectability of the simulated lesions on the four camera systems. In particular, the reconstruction method (FBP vs OSEM) and different filter choices strongly affected outcomes. Conclusion The ability to simulate realistic normal and abnormal HMPAO SPECT scans has been demonstrated using a subresolution phantom. This technique has proved to be useful in the optimization of lesion detectability.

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Cardiovascular: Heart Failure

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Gated blood pool SPECT automatic detection of LV regional wall motion abnormalities validated by quantitative cardiac magnetic resonance imaging

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Objective: To validate detection of left ventricular (LV) regional wall motion abnormalities by gated blood pool SPECT (GBPS) using cardiac magnetic resonance (CMR) as the reference standard, and to determine whether automated (A) or manual (M) GBPS calculations are as accurate as visual (V) detection of LV regional motion abnormalities. **Materials and Methods:** GBPS data were analyzed by "BP-SPECT" A algorithms for 35 patients with cardiac disease and compared to ECG-gated True-FISP cardiac magnetic resonance (CMR) evaluations. A algorithms isolated LV counts and formed 3rd order Fourier fits of time-activity curves to compute global LV ejection fraction (EF). M GBPS calculations, requiring identifying optimal vertical long axis and short axis tomographic sections and drawing LV outlines on these images, also were performed by an experienced observer without knowledge of A or CMR results. A and M regional EF calculations were performed by isolating volumetric counts into 17 conventional LV segments and performing 3rd order Fourier fits to each of the 17 separate curves. Regional CMR wall motion was performed by Medis "MASS" algorithms, measured by manual endocardial contours for 60°-samples of short axis cines over 11-13 tomographic slices, re-sampled into the conventional 17 segmental model. GBPS and CMR values were compared against previously determined normal limits to identify abnormally low GBPS regional EF and abnormally low CMR regional WM cases. An experienced cardiologist graded his visual (V) impression of regional wall motion abnormalities on a 5-point scale independently on two separate occasions (V1 and V2), without knowledge of quantitative GBPS or CMR results. Data were analyzed separately for left circumflex (LCX), left anterior descending (LAD) and right coronary artery (RCA) territories. **Results:** For all coronary territories, M and A GBPS agreed equally well with CMR in identifying wall motion abnormalities (84±2% versus 84±2%, p=0.83), and were superior to V1 (78±2%, p=0.005) and V2 (79±2%, p=0.02). M and A detection of wall motion abnormalities were significantly more accurate for LCX than LAD territories (p=0.02) but were similar for RCA territories (0.09) (see Table). M and A accuracy was similar to V1 and V2 for LAD territories, but significantly more accurate than V1 and V2 for LCX and RCA territories (see Table). **Conclusion:** Automatic GBPS computations accurately identified LV regional wall motion abnormalities, and were superior to visual analysis for this purpose, particularly for LCX and RCA territories.

Accuracy by coronary territory (*p<0.05 versus A)

	Automatic (A)	Manual (M)	Visual (V1,V2)
LAD	81±3%	83±3%	81±4%,79±4%
LCX	92±3%	89±3%	75±6%*,77±6%*
RCA	85±3%	84±3%	73±4%*,78±4%*

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SPECT Radionuclide Ventriculography in the Assessment of Advanced Heart Failure Patients: A Comparison of Planar Radionuclide Ventriculography, Transthoracic Echocardiography and Cardiac Magnetic Resonance Imaging

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Aim We assessed SPECT radionuclide ventriculography (SRNV) in severe left ventricular (LV) dysfunction patients undergoing cardiac resynchronisation therapy (CRT). SRNV was compared to planar radionuclide ventriculography (PRNV), transthoracic echocardiography (TTE) and cardiac magnetic resonance ventriculography (CMRV). **Materials and Methods** 40 patients (35 Men) including 16 in atrial fibrillation at baseline, median age 73 years (57 -77), with severe LV dysfunction with NHYA class III symptoms, prolonged QRS and on maximal therapy were studied prior to, after 6 and 12 months of CRT. All patients had same day imaging with TTE, PRNV, SRNV (latter both on ADAC Forte camera done in succession) and while CMR was possible within 2 weeks in 24/40 patients without devices. All investigators were blinded to results by the various techniques. Planar acquisition was performed with best septal separation view (32 frames, 20% window for R-R interval). SPECT was performed from RAO 45^0 to LPO 45^0 (16 frames, 20% window). The planar data was processed with Hermes (FUGA) and SPECT was processed with Cedars Sinai QBS software. TTE and CMR volumes were determined using previously validated techniques. **Results** In total, 84 planar RNV, 79 SPECT RNV, 65 Echo, 24 CMR studies were performed on 40 patients. In contrast to SRNV, PRNV acquisitions often needed more than 1 angle to achieve adequate septal separation. The mean (± standard deviation) LV ejection fraction (LVEF) were: PRNV 26.5 (±11.84), SRNV 29.13(±12.00), TTE 25.15(±9.34) and CMR 25.08(±9.03). There was highly significant correlation between the end-diastolic and end-systolic