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Simulation of PIXSCAN, a photon counting micro-CT for small animal imaging

F. Cassol Brunner, R. Khoury, D. Benoit, C. Meessen, A. Bonissent and C. Morel

Centre de Physique des Particules de Marseille (CPPM), CNRS-IN2P3 and Université de la Méditerranée Aix-Marseille II,
163 Avenue de Luminy, 13288 Marseille, France
E-mail: cassol@cppm.in2p3.fr

ABSTRACT: A main challenge in the development of new detectors is the achievement of a satisfactory comprehension of the instrument behaviour. We present the simulation work developed to understand and characterize an innovative micro-CT scanner. The PIXSCAN scanner is a photon counting device based on hybrid pixel detectors. Its working principle is expected to improve the contrast for soft tissues and to reduce both the scan duration and the dose absorbed by the animal. A prototype of the scanner, PIXSCAN-XPAD2, has been assembled and studied in order to achieve a proof of principle of the system. Simulations by analytical and Monte Carlo methods of the prototype and of the evaluation phantoms have been developed to ensure a satisfactory comprehension of the data. The Monte Carlo simulation was based on the GATE package. It included the complete simulation of photon propagation in matter, together with the modelling of the source spectrum, the scanner geometry and the sensor response. The analytical simulation is much more approximate, but its merit is the rapidity which permits fast preliminary results. Several figures of merit are studied and show good agreement with real data. Hence, the developed simulations can be used as a valid tool for the estimation of the ultimate PIXSCAN performances, in terms of spatial resolution, contrast measurement and dose reduction.

KEYWORDS: X-ray detectors; Models and simulations; Computerized Tomography (CT) and Computed Radiography (CR)

1Corresponding author.
1 Introduction

The design of particle physics experiments and their data analysis make largely use of simulation software. This permits in fact to optimize the construction of detectors by reproducing all particle interactions in the sensors, and consequently the expected output signal.

Moreover the correct simulation of a system allows the unfolding of the different components that act on the detector response, hence providing a complete understanding of the data. This paper describes the simulations of PIXSCAN-XPAD2 [1], a micro-CT scanner for small animals. The good agreement between data and simulation validates the use of these tools for the design and data analysis of the next version of the scanner, PIXSCAN-XPAD3 [2].

2 PIXSCAN-XPAD2 scanner

The PIXSCAN-XPAD2 is a cone beam micro-CT scanner demonstrator for small animals. The system consists of a rotating platform placed between an X-ray source\(^1\) and the photon detector. The mouse stands on the platform (fixed to a mouse holder), while the platform rotates 360°, step by step (typically, 1°/step). One X-ray cone beam projection of the object is acquired at each angle. The photon sensor is based on hybrid pixel detectors that were originally developed for high-energy physics experiments [3]. The sensitive surface is about 6.5 × 6.8 cm\(^2\) and includes 8 modules tiled as shown in figure 1, for a total of 36,800 pixels of 330 × 330 µm\(^2\). The whole set of projections

\(^1\)60 kV, 0.8 mA, 50 W, Mo target (Rontgentek, SEPH, France).
needs to be numerically processed before reconstruction. The pixel response must be normalized. After geometrical calibration of the detector [4], the cone beam projection is mapped to a plane geometry, as required by the image reconstruction algorithm. Defective pixels are masked, while a neighbouring pixel interpolation permits to fill the dead areas. Finally, a FDK-based reconstruction algorithm for cone beam tomography (supplied by CREATIS) is applied to reconstruct 3D images from the cone beam projections.

3 Scanner simulation

Two different simulation models were developed to reproduce the scanner data. A rather simple analytical model guarantees fast, but approximated results, whereas a Monte Carlo simulation, based on GATE [5], supplies a very accurate description of the system. Both simulations reproduce in detail the scanner geometry. Their output has a format that is identical to real data and follows the same numerical processing. Several evaluation phantoms of known geometry and material composition are simulated.

3.1 Analytical simulation

The model is based on the well known formula of propagation of photons in matter: \( I = I_o \times e^{-\mu d} \).

The intensity \( I \) of the beam measured by a pixel is defined by the initial beam intensity \( I_o \), the attenuation coefficient \( \mu \) of the material along the beam path, and the path length \( d \). \( e^{-\mu d} \) is determined by connecting the source to the center of each pixels and calculating the length of the ray in every phantom material. Statistical noise is added afterwards by introducing a Gaussian smearing to the pixel response, corresponding the typical scan statistics\(^3\) of 6000 photons/pixel.

3.2 Monte Carlo simulation

The simulation is developed in the framework of the GATE package. X-rays are generated by a 50 × 50 \( \mu m^2 \) square source, while reproducing the real source spectrum. All interaction processes

\(^2\)The prototype chip XPAD2 has about \( \sim \) 25\% of its pixels that are oscillating or non counting.

\(^3\)The scan statistics is defined by the counts per pixel in absence of objects between the source and the detector.
of photons and electrons in matter are modeled. As for real data, only photons that deposite more than 15 keV in the detector are counted. Due to the long simulation time, the statistics available for the Monte Carlo projections is limited to 3000 photons/pixel.

4 Data-simulation comparison

Several figures of merit are established to estimate the performance of PIXSCAN-XPAD2. This section presents the first results obtained from the scanner and their comparison with the simulation data.

4.1 Spatial resolution

The Modulation Transfer Function (MTF) and Line Spread Function (LSF) of the system are derived using the “edge method” procedure, as described in [6]. A half cylinder of PVC (12 mm radius) is used as phantom. The Full Width at Half Maximum (FWHM) of the LSF is assumed as index of the spatial resolution. A real data scan, in standard conditions, gives ∼ 500 µm. This value is well reproduced by both simulations, hence allowing to understand the resolution degradation factors. The simulation results show in fact that an ideal detector (not requiring raw data processing) guarantees a spatial resolution equal to the voxel size of the reconstructed image,\(^4\) i.e. ∼ 165 µm; the present raw data processing (as applied to XPAD2 before reconstruction) degrades the resolution by more than a factor 2 to ∼ 350 µm. Finally the introduction of defective pixels (equivalent to an increase of dead areas) permits to reproduce correctly the XPAD2 measurements, which achieved a spatial resolution of ∼ 500 µm. Figure 2 shows the evolution of the MTF for the above described situations, as reproduced by the Monte Carlo simulation.

4.2 Detector noise

The same phantom as in 4.1 is used to estimate the image \(\%\text{Noise} \)\

\[ \%\text{Noise} = \frac{\sigma_{\text{PVC}}}{CT_{\text{PVC}} - CT_{\text{air}}} \]

\(^4\)The image voxel size is half the detector pixel size due to the magnification fan beam effect of 2.
with $\sigma_{\text{PVC}}$ and $CT_{\text{PVC}}$, the mean and the standard deviation of the image CT values inside the PVC phantom, while $CT_{\text{air}}$ is the average CT value in air. Both the analytical and Monte Carlo simulations reproduce correctly the measured data. Figure 3 shows, for example, the evolution of the noise versus the number of projections measured during a complete rotation of the scanner, compared to the analytical simulation results.

### 4.3 CT linearity

The linearity of the scanner is estimated using a phantom (QRM-MicroCT-HA) of epoxy resin having cylindrical inserts at various densities of calcium hydroxyapatite. Figure 4 shows the match between data and Monte Carlo simulation. The linear fit represents the scanner calibration function. It permits to associate an attenuation coefficient value to each grey level of the reconstructed image.
4.4 Tomographic distortions

The back-projection FDK algorithm induces distortions in the image. They increase when moving away from the central plane perpendicular to the rotation axis and containing the source. A phantom after Defrise (QRM-MicroCT-MD) was imaged and simulated. Again, the simulations reproduce correctly the data, as shown in figure 5 in the case of the analytical model.

5 Prospects

The new version of the scanner, PIXSCAN-XPAD3, will be ready soon. This prototype has less than 1% defective pixels and the scanner aims at a spatial resolution of $\sim 70 \mu m$. The analytical and Monte Carlo simulations described in this paper will be used to optimize and assess the new system design. Moreover, the knowledge acquired on the XPAD2 data will help us in developing the new data processing, with the aim to limit as much as possible the degradation of the spatial resolution.

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