Low statistics positron activity reconstruction methods for proton therapy

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Abstract

Positron emission tomography (PET) is one of the most mature techniques for monitoring in ion beam therapy. PET allows to reconstruct the β^+ activity generated in the patient by the nuclear interaction of the ions. Taking advantage of the spatial correlation between positron emitters created along the ions path and the dose distribution, it is possible to perform a quality control of the treatment. Usually, to reconstruct the activity generated within the irradiated volume, standard 3D PET reconstruction techniques are implemented. In this work, we explore a new reconstruction method (Straight Forward Reconstruction) particularly useful for reconstructing activity distribution generated by mono-energetic pencil beams. The method is also able to correlate the spatial information with the annihilation time and was validated using the activity signals acquired with the DoPET system. Irradiations performed with mono-energetic pencil beams on phantoms mimicking human tissues were used for this study. Both reconstruction methods reach an accuracy in the reconstruction of the activity width of the order of 1.5 mm for $2 \cdot 10^8$ primaries.

Keywords: PET, positron, proton therapy

1. Introduction

Proton beam irradiations can deliver conformal dose distributions minimizing damage to healthy tissues thanks to their characteristic dose profiles. Nuclear interactions between the ions and the irradiated tissues generate β^+ emitters during the treatment delivery. The detection of the activity signal can be used to perform the treatment monitoring by means of dedicated PET prototypes. In this work, a novel algorithm, named Straight Forward Reconstruction (SFR), is proposed to reconstruct the activity width generated during the treatment. The SFR was compared with the standard Maximum Likelihood Expectation Maximization (MLEM) reconstruction algorithm using both experimental and simulation data. The data were acquired with the DoPET system at Trento Proton Therapy Centre, whereas the simulation was performed using the FLUKA Monte Carlo code [1]. The dependence of the activity width uncertainty vs the number of delivered protons was studied.

2. The DoPET system

DoPET is a dual-head planar PET system. Each head is composed of 9 detector modules consisting of a LYSO matrix of 23 $\times$ 23 pixels, coupled to a position sensitive photomultiplier tube model H8500 (Hamamatsu Photonics). The heads are stationary and placed in-beam at a distance of 48 cm. Acquisition is FPGA-based and works with a coincidence time window of about 3 ns. For more details see [2] .

3. Reconstruction methods

3.1. MLEM

Maximum Likelihood Estimation Maximization (MLEM) is one of the most popular algorithms used in iterative PET reconstruction [3]. More details on the implementation of the MLEM in the DoPET system can be found in in [4].

3.2. Straight Forward Reconstruction

A fast and direct event reconstruction of the activity distribution along the beam direction was developed in order to asses variation in activity range. The SFR reconstructs the annihilation position of each event by evaluating the intersection point between the Line Of Response (LOR) and the plane parallel to the detector faces and passing through the beam axis: this last information is provided by the delivery system. Each event maintains information, such as annihilation time after the β^+ emitters decay and is corrected to take into account for the detector acceptance. The annihilation time can be correlated with the emission position in the phantom, allowing future frequency study in selected regions.

4. Monte Carlo Simulations

The experimental set-up simulation is performed with the development version of the FLUKA code reproducing the conditions of irradiations performed at the Trento Proton Therapy Centre (IT). The β^+ activity and annihilation products in space and time are recorded. The detector geometry is implemented and the expected activity distribution is reconstructed with the same reconstruction process used for the experimental data [5].

5. Results

Two kinds of targets were used for this study: a uniform PMMA (Polymethylmethacrylate) phantom and a phantom composed of alternating brain equivalent tissue and PMMA slabs of 2 cm each (referred to as "ZEBRA"). A monoenergetic beam of 130 MeV was used for all the irradiations. Only data acquired for 120 s starting immediately after the end of the irradiation that lasted 8 s, were used for the analysis. To evaluate the reconstruction capabilities of the two methods, groups of 10 samples of different statistics were created, stating from an acquisition of 10^{10} primary protons and reducing, time by time, the used statistics. The activity width was evaluated. The errors of the activity width reconstruction was computed as the standard deviation over the 10 samples. The comparison of the reconstructed longitudinal profile (beam axis) is presented in Figure 1. Data are reconstructed with MLEM and SFR methods. The MC FLUKA prediction is reconstructed with SFR method. We characterize the activity range with the distance of the half maximum of the rising edge to the half maximum of the distal edge ($\Delta W_{50\%}$). The error on the determination of $\Delta W_{50\%}$ of the two methods with variable statistical conditions is also reported in Figure 2. For spots of 2×10^8 and 10^9 primary protons, the error is 1.5 mm and 0.5 mm, respectively. MLEM and SFR give comparable results. In the case of the PMMA and "ZEBRA" phantoms irradiation presented in this study, even if the shapes of the activated profiles loose reliability for 10^8 the information on the $\Delta W_{50\%}$ is preserved with an error of ~2.5 mm.

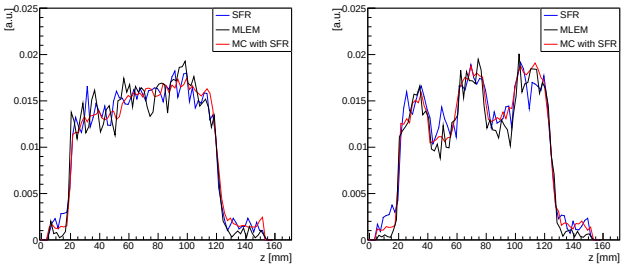

Figure 1: Reconstructed longitudinal profiles (beam axis). Data (10^9 primary protons) are reconstructed with MLEM (black line) and SFR (blue line) methods. The MC FLUKA prediction (red line) is reconstructed with the SFR method. PMMA (left) and" ZEBRA" (right) phantoms.

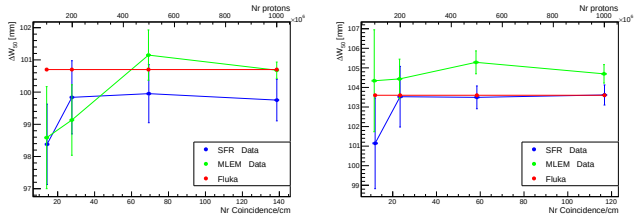

Figure 2: The $\Delta W_{50\%}$ reconstruction capability of the two methods with variable statistical conditions; PMMA (left) and "ZEBRA" (right) phantoms.

6. Conclusions

A new reconstruction method for PET data was developed and gives comparable results in terms of $\Delta W_{50\%}$ with respect to MLEM and FLUKA predictions. Having two different procedure to evaluate the activity range allow us to be more confident on the results. For monitoring purposes a localized geometrical information is advisable and is achievable using pencil beams. To have an error on the determination of $\Delta W_{50\%}$ lower than 1.5 mm we found that a number of protons greater than 2×10^8 is necessary both for homogeneous and heterogeneous phantoms. This number is comparable with the number of protons delivered for each cm^2 in the distal energy layer of a treatment plan of 1 Gy. In view of safety margin reduction and dose escalation, this approach opens up the possibility to image guidance procedures with selected pencil beams.

References

[1] G. Battistoni et al;. The FLUKA code: Description and benchmarking. *AIP Conf. Proc.*, 896:31–49, 2007. [,31(2007)].

[2] E. Fabbiani et al.;. Proton therapy treatment monitoring with in-beam pet: Investigating space and time activity distributions. *NIMA*, 861:71, 2017.

[3] L. A. Shepp and Y. Vardi;. Maximum likelihood reconstruction for emission tomography. *IEEE Transactions on Medical Imaging*, 1(2):113–122, Oct 1982.

[4] N. Camarlinghi et al.;. An in-beam pet system for monitoring ion-beam therapy: test on phantoms using clinical 62 mev protons. *JINST*, 9(04):C04005, 2014.

[5] S. Muraro et al;. Proton therapy treatment monitoring with the dopet system: activity range, positron emitters evaluation and comparison with monte carlo predictions. *JINST*, 12(12):C12026, 2017.