Journal of Engineering and Applied Sciences 12 (Special Issue 10): 8978-8983, 2017
ISSN: 1816-949X

Theoretical Calculation of Positron-Nuclear Emulsion Image Resolution Using Geant4 Code

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Abstract: This study will focus on how closely micro tracks can be resolved in an image formed by the nuclear emulsion film traversed with a positron, this will be presented in a theoretical treatment using Geant4 code. Based on the simulation results, this application has been found very promising because of its accuracy and fast simulation to validate the measurements. This technique can improve and develop the tumor detectability in clinical oncology and the strategies for cells labeling.

Key words: PET, Fedra codes, image resolution, image reconstruction, nuclear emulsion detector, Monte Carlo simulation

INTRODUCTION

The essential objective in molecular imaging modalities is to gain images with optimized quality and exhaustive data of object to provide a detailed report about the measurement of radioactive tracers distribution *in vivo*. The image reconstruction and image resolution play a crucial role in appearance of these measurements. Whenever the determination and estimation of the kinetic parameters of particles which are produced in the collision event as accurately as possible a detailed clearness image is produced.

Positron Emission Tomography (PET) is a functional imaging modality creates images of metabolic processes in the body. In PET imaging the distance between beta emitter point and the Line of Response (LOR) is the task issue in the image reconstruction process (Rahmim *et al*., 2013). This distance has degraded the image resolution and this will have an effect on patient's treatment.

In this reserach, we propose an innovative technique rely on the nuclear emulsion technique for positron radiography. Human cells will be labeled with the positron emitting radiotracer to be loaded to the nuclear emulsion detector. The positrons tracks will be detected and their positions through the patient's body will be measured to produce the more sophisticated image with high precision reconstruction. For image reconstruction, the tracking measurements set in the tracking detector will be recognized into a series of measurements which are believed to originate from the same particle using the iterative correction method (LEP Design Report CERN-LEP 8-01, 1984). The particle positions will be estimated based on the least-squares methods (Allen *et al*., 1993). The images will be produced from the nuclear emulsion traversed with a positron, whenever the overlapping measurement between the two objects as precisely as possible an excellent image resolution is achieved. Fedra library codes (Framework for emulsion data reconstruction and analysis in the OPERA experiment) (Tioukov *at al*., 2006) and Allen method (Allen *et al*., 1993) are used as a theoretical treatment to investigate the image resolution.

Positron radiography with nuclear emulsion

Positron radiography: PET is a diagnostic tool used to create images of metabolic processes in the body in order to obtain a detailed report about the cancer location, spread and effects on the organs function (cancer's stage).

A radioactive material (radio tracer) is injected into patient's body in small quantity, it's carried by a familiar body molecules such as glucose. The cancer cells will absorb more radioactive material than the normal cells because of their abnormal nutrient consumption. PET detects these accumulations of radioactive material to perform a 3D image describing the function of tissues and organs in the body (Walker and Hawkesworth, 1987).

The positron resulted from the decay process of radioisotope will be interacted with the body's tissue. The

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multiple scattering will occur and the particle will lose its energy step by step with each scattering until be stopped.

The positrons are annihilated with the electrons already existing in the body resulting into two gamma photons (0.511 MeV each) at opposite direction. PET photon ring detector is located around the patient to detect the photon's position and energy. A large set of data will be collected from each event to be reconstructed with a specific algorithm (filtered back projection or Iterative reconstruction). These data should be sufficient to create the cross sectional image of concentration and distribution of the radiotracer in different planes to reflect the patient's state. The typical realizable image resolution in PET is around 5-10 mm (Wernick and Aarsvold, 2004; Spasic-Jokic, 2009). Thanks to high resolution and high sensitivity PET plays an important role in the diagnostic and treatment field. A large set of researches are addressed with this application (Rohren *et al*., 2004; Tai and Piccini, 2004; Bengel, 2006). In this reserach, we present the nuclear emulsion film detector for the positron radiography.

Nuclear emulsion technique: This technique is currently used in the field of autoradiography and for studying particles interactions (Baker, 1989; Lane, 2005; Kulangara, 1961). High sensitivity, density, stopping power and resolution allow it to record all the ionizing particles that are crossed it and to reconstruct tracks in 3D. The nuclear emulsion is composed of silver halide micro crystals interspersed in a gel. Each works as an independent microdetector with a band gap 2.6 eV (Meisel, 2010). A large raw of data according to the number of microcrystals will be reconstructed in a reasonable time. Even a smaller thickness of this emulsion (20~30 μm) can give 3D tracks with angular precision of the order of 10 mrad. All these points give the nuclear emulsion importance *in vivo* and *in vitro* applications (Naka *et al*., 2013).

When the nuclear emulsion is traversed by the ionizing radiation or by light latent image centers (sensitized sites) is produced, after chemical development, these sites become visible under an optical microscope as a dot (grains). The dots are aligned along the path of particles in a medium, this principle makes the nuclear emulsions 3D tracking detector used to detect charged particles usually with a sub-micrometric precision.

Typical structure of the nuclear emulsion sheet is composed of two sensitive emulsion layers separated with one plastic base layer when the ionizing particle crossed both sides, providing two sequences of aligned grains called the microtracks which will be detected by the human operators or by the automatic systems (Bozza and Nakano, 2012; Bozza *et al*., 2017).

This technique has gained increasing interest after many developments. Kimura *et al*. (2013) presented a development study for CERN experiment to use the nuclear emulsion in ordinary vacuum. High sensitive and high performance nuclear emulsion is gained in another development study of the nuclear emulsion technologies presented by Kunihiro for OPERA experiment (Morishima, 2015). For track position, the nuclear emulsion considers as the most accurate detector. The resolution of track detection depends upon the grain size and on the scanning system. The standard size of silver halide crystal is about 200 nm with a linear density 2.3 AgBr/μm, this type of crystal is suited for the particle physics uses. OPERA collaborators are presented a development study (Natsume *et al*., 2007) in order to gain high resolution nuclear emulsion which is enough to detect nuclear recoil tracks from Weakly Interactive Massive Particles (WIMP). The developed crystal is about 40 nm with a linear density 11 crystals/μm. Thanks to these developments, this technology has been introduced into many fields.

MATERIALS AND METHODS

Resolution modeling: When the radiation penetrates into an emulsion sheet the tracks will be performed in two emulsion layers from many points. The track points positions will be connected together forming a line. This line constructs the micro track in each emulsion layer. The micro tracks will be reconstructed using the tracks points positions (x, y, z) in each emulsion sheet which will be selected from the text file to be rolled within the track reconstruction code using the iterative correction method. Simple mathematical model is required to get a comprehension about the most complex molecular interactions. The most popular model is the Lennard-Jones potential (Morishima, 2015). It provides a fair description of the interaction between pairs of rare-gas atoms and also quasi-spherical molecules. The Kihara potential is another model considers for the spherocylinders. This model relies on Lennard-Jones potential. It describes the sperocylinders as a sphere consists of a set of points that are within a distance R from a line segment of length L. A sphere of radius R can be drawn around every point on this line segment. The sphere contains all points that are within a distance R. Thus, spherocylinders can be considered as the volume that is swept out by a sphere of radius R that is moved along a line segment of Length L. The spherocylinders will be overlapped and to test this overlapping the shortest distance between two line segments that form the essence of the spherocylinders should be computed. In this reserach, we determine the shortest distance between two line-segments in 3D after oriented the micro tracks position parameters of two adjacent emulsion layers as two finite line-segments i and j in space to be involved in a topological calculation from Fedra library. In this calculation, we need to use the information below for the two segments:

- x1 = seg1.X
- x2 = seg2.X
- y1 = seg1.Y
- y2 = seg2.Y
- z1 = seg1.Z
- z2 = seg2.ID
- ax1 = seg1.ID
- ax2 = seg2.TX
- ay1 = seg1.TY
- ay2 = seg2.TY

where, float TX referes to tan(theta_x); theta_x is the angle between the segment vector and Z axis, float TY referes to tan(theta_y); theta_y is the angle between the segment vector and Z axis and int ID referes to segment ID.

The shortest distance between two line-segments in 3D and the track point position parameters will be employed to calculate the distance of closest approach squared as shown in Fig. 1.

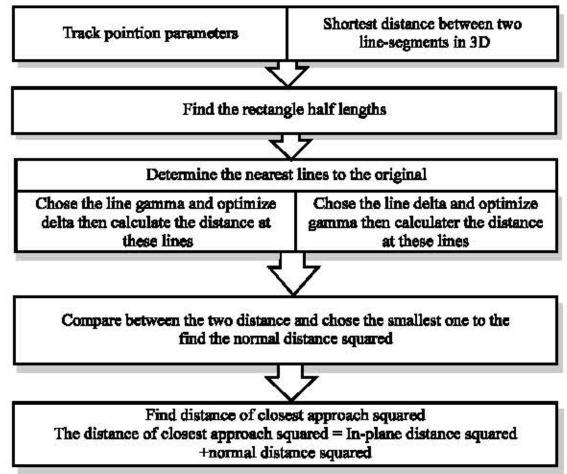

Fig. 1: Steps diagram illustrating the calculation of distance of closest approach squared. Gamma and delta are the lines parameters reckoned from the intersection

Simulation study: Geant4 is a platformfor thesimulationof the passage ofparticles throughmatter which the user must excute it by himself (Anonymous, 2004). To construct a program using the Geant4 code we need to implement the three mandatory classes depending on the Object Oriented Programming (OOP) concept to cover the most features of the simulation process: G4V user detector construction class is used to design the nuclear emulsion detector. This detector consists of two emulsion layers, each 100×120 mm×50 μm made from Silver Halide material and one plastic layer 100×120 mm×200 μm made from Plastic_SC_Vinyltoluene material. The positron source and physics processes were coded in Physics List class. For positron particle, multiple scattering, ionisation, bremsstrahlung and annihilation processes are defined with a valid energy range from 250 eV up to 1 GeV.

G4V user primary generation action is used to set the positron particle travelling along the z-axis with energy selected of 1 MeV. This source is positioned at the center of two detectors in a Cartesian coordinate system with an isotropic momentum direction using G4Uniform Rand() function. The control of simulation at the different stages of each event is made by the event action class. The algorithm for generating computing efficiency was implemented in the run action class and the interesting processes were registered in the stepping action class.

Event, run and stepping are Geant4 optional classes. This program allows two detectors to record the track's point position and energy according to a special request which is implemented in the stepping action class. These data will be stored in the text file to be selected at the end of each annihilation event according to a special code which is implemented in the root file to be involved in a theoretical treatment (tracks reconstruction and image resolution calculation).

The hardware platform used to run the Geant4 Version 9.5 Code is a Linux (Scientific Linux CERN 5) Personal Workstation with 2.1 GB RAM. The statistical computation plots and the fit functions are solved using the root software (object-oriented data analysis framework Version 5.27/06).

RESULTS AND DISCUSSION

We calculate the shortest distance between two line-segments in 3D (p1p2) and the distance of closest

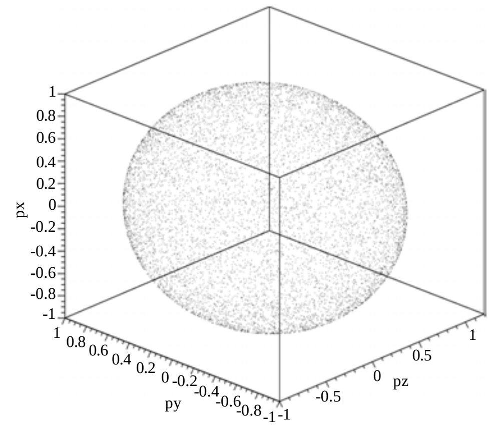

Fig. 2: The isotropic momentum direction of positron particle with energy 1 MeV simulated at the nuclear emulsion

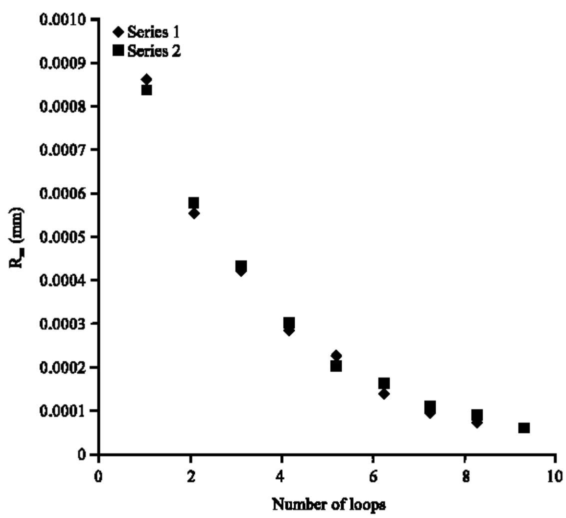

Fig. 3: R_{ms} (p1p2) plot with error bar for two positron sources. Series 1 the results of one source located at 0.002, 0, 0 mm and series 2 the results of one source located at-0.002, 0, 0 mm, the correlation coefficient is 0.997

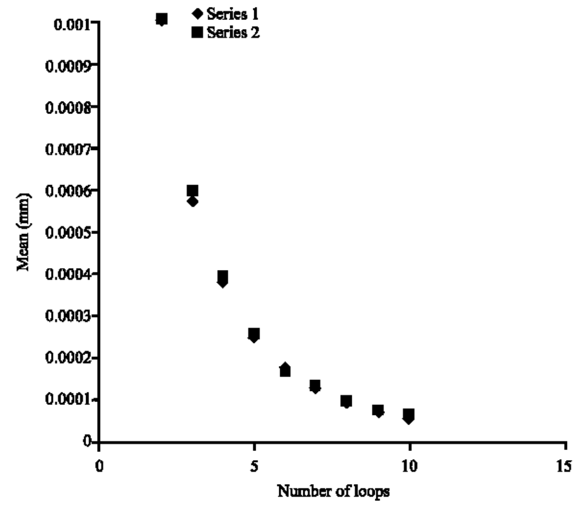

Fig. 4: Mean (p1p2) plot with error bar of two positron sources. Series 1 the results of one source located at 0.002, 0, 0 mm and series 2 the results of one source located at-0.002, 0, 0 mm, the correlation coefficient is 0.999

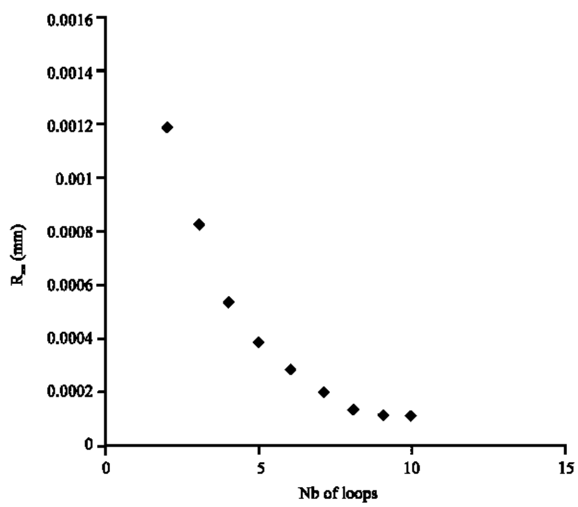

Fig. 5: The calculation results of the shortest distance between two line-segments in 3D for two positron sources were set together at sheet thickness 10 μm

approach squared (rcl sq) for the microtracks formed from the nuclear emulsion traversed with a positron. The calculation results are presented using different loops, distances and errors studies.

Figure 2 shows the positron source is simulated at the nuclear emulsion sheet as we explaind in the simulation part.

In Fig. 3 and 4, we presented a compareson between two studies. The first study, we simulate one positron source at (0.002, 0, 0) mm at the nuclear emulsion sheet and we calculated p1p2. Then, we made the second study at (-0.002, 0, 0) mm and we made the compareson between two studies using the errors bar. In Fig. 5, we simulated two positron sources (0.002, 0, 0 and -0.002, 0, 0) mm together at the nuclear emulsion sheet and we calculated p1p2 using different loops (2-10). Then by the using of Allen method, we calculated rc1sq and presented the result using loop 2 at Fig. 6.

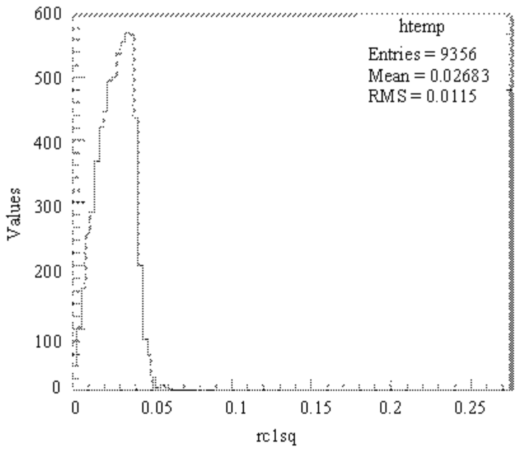

Fig. 6: The distance of closest approach squared (rc1sq) using two positron source

CONCLUSION

In this reserach, the simulation program is adapted for the positron-nuclear emulsion image reconstruction and image resolution calculation and this application has been found very promising because of its accuracy and fast simulation to validate the measurements. The application of Monte Carlo in this reserach emphasizes the adoption of these calculations on the simulation program and the treatment methods used.

This technique provides a limit of resolution ~0.001 mm for the shortest distance between two line-segments in 3D and for the distance of closest approach squared is ~0.01 mm, positive results allow us to announce. This technique can develop the strategies for PET molecular imaging of tumor metabolism, cell proliferation and hypoxia and for the improvement of tumor detectability in clinical oncology. This technique is required for accurate radiation therapy treatment planning. This technique can make a great challanges in proton radiotherapy. This technique can improve the strategies for cells labeling.

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