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Study of the effect of magnetic field in positron range using GATE simulation toolkit

G Soultanidis[1], **N Karakatsanis**[2], **G Nikiforidis**[1] **and G Loudos**[3]

[1] Department of Medical Physics, School of Medicine, University of Patras, Rion, Greece
[2] Biomedical Simulations and Imaging Applications Laboratory, School of Electrical and Computer Engineering, National Technical University of Athens, Greece
[3] Department of Medical Instruments Technology, Technological Educational Institute of Athens, Greece

E-mail: georgios.soultanidis@kcl.ac.uk

Abstract. In simultaneous PET-MR systems, the emitted positrons trajectory is influenced by the magnetic field. The aim of this study is to define that influence to the positron annihilation distribution. Monte Carlo methods have been applied, using GATE. Several isotopes were studied, in various types of materials and with different magnetic field strengths. The results showed variations in the positron range between different components and especially between the lung and water. Measurements of the 1-D positron annihilation distance indicated a reduction of the mean positron annihilation distance for ^{82}Rb of ~25%, ^{68}Ga of 19% and ^{18}F of 3.5%, at 3 Tesla. When the magnetic field was increased to 9.5 Tesla, the reduction was significant for all isotopes, and mainly for ^{68}Ga and ^{82}Rb, with approximately 41% reduction of the mean positron annihilation distance in water. Finally, the positron annihilation distribution varies according to the alignment with the magnetic field lines. The results of this study could be used to improve positron annihilation correction algorithms for simultaneous PET-MR acquisition, by taking under consideration the non-isotropic distribution.

1. Introduction

In the family of hybrid medical imaging systems the newest addition is the PET-MR. Using optic fibers or solid-state detectors, PET can be combined with MRI. As an example, RatCAP is the first system with the use of solid-state detectors [1]. Also, in PANDA and PANDA II systems, the light is guided outside the magnetic field and detected by PMTs [2, 3]. Finally, a simultaneous PET-MR system was developed by Judenhofer *et al.* for simultaneous scans with a 7 Tesla MRI [4]. It is well known that the magnetic field affects the path of a positron and therefore the final positron range. In fact, Raylman *et al.* describes this phenomenon with the use of Monte Carlo simulations. By his study, it is obvious that the magnetic field affects positron range and especially the equal distribution of positrons [5]. The main reason for studying positron range is to model it, compress range effects and make isotopes with higher positron emission energy suitable for PET imaging. Especially in small animal imaging, positron effect can be a strong limiting factor in overall resolution for isotopes such as ^{68}Ga and ^{82}Rb and hamper their application.

Bai *et al*. performed a study in order to correct the range effect for inhomogeneous materials, where EGS4 has been used [6]. Few studies on positron range are reported; as a complementary of the previous studies we used GATE, aiming to define the mean positron range for different materials and magnetic field amplitude, in order to present not only the 3-D positron range, but also the 1-D, along the axes lying parallel and perpendicularly to the magnetic field.

2. Materials and methods

In this study, the GATE (V 5.0.0_p01) simulation toolkit has been used [7]. GATE, as it is based on the Geant4 simulation toolkit, can simulate a vast background of physical processes. Preliminary studies of magnetic field effects have been carried out [8]. In GATE, the magnetic field can be adjusted in the three dimensional space. The influence of magnetic field upon each particle and the recalculation of its trajectory can be described by the Lorentz equation:

$$\vec{F}_{Lor} = q\vec{V}\times\vec{B} \tag{1}$$

where q is the charge of the particle, B is the strength of the magnetic field and V is the velocity of the charged particle.

The materials used for this study were water, lung and ribs as defined in GATE. The isotopes selected for this study are: ^{18}F, ^{11}C, ^{15}O, ^{68}Ga and ^{82}Rb. Finally, the magnetic field strengths for this study are: 0, 1.5, 3 and 9.5 Tesla, selected in order to cover a wide range of clinical and experimental MR systems. The magnetic field was coordinated along the z-axis of the PET scanner.

The experiment geometry contained a single point source in the middle of a sphere with a radius of 40 mm. For each simulation ~ $20\mathrm{x}10^6$ positron annihilations were measured. The software used for data acquisition and analysis was ROOT.

Data acquired in this study were the mean positron range in the 3-D plane and 1-D plane. The mean distance of positron travel is a (x, y, z) vector from the origin point to the annihilation point in the 3-D plane. The 1-D plane is the travel distance in a single dimension. The dimensions selected to be presented, are the x and z plane, perpendicular and parallel to the magnetic field, respectively.

3. Results

Table 1 presents the mean 3-D positron range while table 2 and table 3 give more specifically the mean 1-D range of positron at x and z planes, respectively.

Table 1. Mean 3-D Positron range (mm).

	Water				Lung				Rib Bone			
B_0	0 T	1.5 T	3 T	9.5 T	0 T	1.5 T	3 T	9.5 T	0 T	1.5 T	3 T	9.5 T
^{18}F	0.56	0.56	0.54	0.43	2.23	1.88	1.49	1.20	0.33	0.33	0.33	0.29
^{11}C	1.05	1.03	0.96	0.67	3.98	3.03	2.43	2.06	0.56	0.56	0.55	0.46
^{15}O	2.44	2.31	2.00	1.41	9.26	6.20	5.28	4.53	1.29	1.28	1.22	0.90
^{68}Ga	2.62	2.47	2.12	1.50	9.94	6.58	5.64	4.84	1.39	1.37	1.30	0.95
^{82}Rb	5.21	4.77	3.90	2.88	19.80	12.07	10.76	9.61	2.78	2.70	2.48	1.74

Table 2. Mean 1-D Positron range at x plane (mm).

	Water				Lung				Rib Bone			
B_0	0 T	1.5 T	3 T	9.5 T	0 T	1.5 T	3 T	9.5 T	0 T	1.5 T	3 T	9.5 T
^{18}F	0.27	0.27	0.26	0.16	0.73	0.65	0.46	0.19	0.16	0.16	0.16	0.13
^{11}C	0.44	0.43	0.40	0.21	1.21	0.96	0.61	0.25	0.26	0.26	0.25	0.19
^{15}O	0.90	0.86	0.73	0.32	2.66	1.68	0.99	0.34	0.53	0.52	0.50	0.31
^{68}Ga	0.93	0.89	0.76	0.33	2.74	1.75	1.03	0.35	0.56	0.55	0.52	0.32
^{82}Rb	1.87	1.68	1.27	0.50	6.07	2.79	1.60	0.48	1.05	1.02	0.93	0.48

Table 3. Mean 1-D Positron range at z plane (mm).

	Water				Lung				Rib Bone			
B_0	0 T	1.5 T	3 T	9.5 T	0 T	1.5 T	3 T	9.5 T	0 T	1.5 T	3 T	9.5 T
^{18}F	0.27	0.27	0.28	0.30	0.72	0.80	0.91	1.02	0.16	0.16	0.16	0.16
^{11}C	0.43	0.44	0.45	0.51	1.20	1.42	1.55	1.71	0.26	0.26	0.26	0.27
^{15}O	0.89	0.89	0.92	0.98	2.69	3.26	3.33	3.88	0.52	0.53	0.54	0.59
^{68}Ga	0.92	0.95	1.02	1.13	2.77	3.37	3.61	4.10	0.55	0.56	0.57	0.63
^{82}Rb	1.89	1.96	2.08	2.13	6.15	7.36	7.24	8.00	1.04	1.06	1.09	1.18

4. Discussion

In this study GATE was used to simulate the influence of the magnetic field to the positron range. The results were accurate, reliable and in agreement with the literature, where the mean positron range of fluorine in water at 0 Tesla is similar [6]. Yet, the literature is poor for other isotopes and their mean positron range. As it was expected by equation (1), isotopes with higher positron energy have the most spectacular reduction of mean 3-D positron range. The reduction of mean 3-D positron range is less for the broadly used fluorine but gives better statistics to other potential isotopes.

The variation of mean positron range between materials is enormous, especially in the case of the lungs. The big mean positron range indicates that, even if the reduction is big, for some isotopes a correction algorithm is necessary.

The mean 1-D positron range reveals another aspect of the influence of magnetic field. The mean 1-D positron range might be reduced in the x plane but the range in the z plane is increasing. This result brings new evidence about the need for re-evaluation of the existing positron range correction algorithms, in order to be adapted to PET applications inside magnetic fields.

To conclude, this study points out that GATE has the capability to model the presence of magnetic field and produce reliable results on positron range. The impact of the magnetic field on the spatial resolution can be modeled. Finally the data of anisotropic distribution of annihilation might be used as an input for improved positron range correction algorithms in PET-MR applications.

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