https://doi.org/10.7742/jksr.2021.15.6.849 "J. Korean Soc. Radiol., Vol. 15, No. 6, November 2021"

Development of the Radiological Range of Positron Emitting Radionuclides

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Received: November 03, 2021. Revised: November 26, 2021. Accepted: November 30, 2021

ABSTRACT

PET images used in medical diagnoses are created using positron emitting radionuclides. The radiation used for imaging is generated at 0.511 MeV by p-annihilation. The CSDA range is the distance the particle radiation flew physically, and it is different from the range shown in PET images. This study proposes a novel method that uses radiological criteria to measure this range. The experiment was conducted by applying the MCNP6 simulation to positron emitting nuclides ^{18}F, ^{11}C, ^{13}N, and ^{15}O. Radiological criteria were based on the location of the p-annihilation event, which is also the image signal. Results showed the radiological range of positrons to be 2.3, 3.9, 5.0, and 7.9 mm for ^{18}F, ^{11}C, ^{13}N, and ^{15}O, respectively. The higher the positron energy, the larger its difference from the CSDA range. Positron emitting nuclide is being developed and studied as a nuclide for dosimetry or radiotherapy. Further research needs to be conducted into various positron ranges.

Keywords: Positron, Ranges, PET

I. INTRODUCTION

Positron emission tomography (PET) is a medical imaging technique based on the use of positron emitting radioisotopes; it equips healthcare providers with a precise image of anatomical function[1] and represents a significant advance in cancer imaging, with great potential for optimizing radiation therapy (RT) treatment planning[2]. However, PET images are known to have lower resolution than medical images obtained from other methods. In light of this aspect, the range of positrons is a key factor in determining the blurring (and, subsequently, the clarity and resolution) of these images. It is typically measured using the continuous slow down approximation (CSDA) method, to which a single range of energies — represented in the form of its lower and upper limits, denoted by (min, max) — is applied[3]. However, this range refers only to the distance travelled by the positrons and does not account for the location of the p-annihilation event — a signal constituting the PET image. This study is aimed at bridging that gap by proposing a method to determine radiological range based on the location of the p-annihilation event, using the continuous energy of positrons.

II. MATERIAL AND METHODS

1. Source

The radiation sources used in this study were the positron emitting radionuclides of ^{18}F, ^{11}C, ^{13}N, and ^{15}O; Information on each of them is presented in Table 1[4].

Positron information for each source was obtained from the MIRDcell v2.0[5] program provided by the Committee on Medical Internal Radiation Dose (MIRD). The kinetic energy spectra of positrons for

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the above nuclides are obtained as shown in Figure 1.

Table 1. Classification of nuclides

		^{18}F	^{11}C	^{13}N	^{15}O
mean	Energy(keV)	252	390	488	730
	Range(mm)	0.66	1.26	1.73	2.96
Max	Energy(keV)	635	970	1190	1720
	Range(mm)	2.63	4.46	5.57	9.13

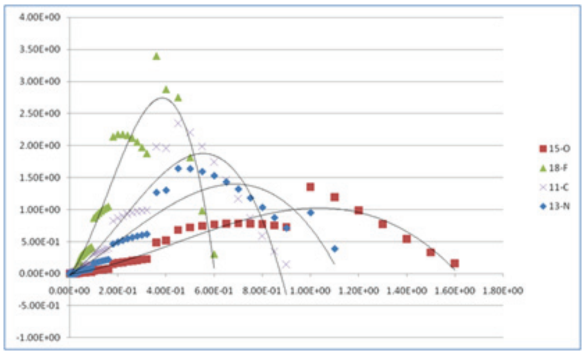

Fig. 1. Kinetic-energy spectra of positrons from ^{18}F, ^{11}C, ^{13}N and ^{15}O nuclides (normalized to have equal area under the curves).

2. Determination of Radiological Range

The radiological range of positrons was estimated based on the location where the 1.022 MeV of p-annihilation energy required for PET imaging was generated.

3. Method

In this study, the Monte Carlo N-Particle Transport Code (MCNP6, U.S.A.), which is a variant of the Monte Carlo simulation, was used. With regard to the geometry, a spherical structure composed of water with an atomic number similar to that of the human body's soft tissue was fabricated, after which the source was placed in the center of this structure. In order to ensure the stability of this arrangement, radiological range was measured with the mean and maximum energies used previously and then compared with the conventional CSDA range. The variation of radiological range with the size of the spherical structure was then studied.

The CSDA range, based on the continuous energy of the positron, is the length that the positron physical Range. and it was estimated as the range by simulating the energy reduction rate according to the distance. The size at a p-annihilation energy of 1.022 MeV in the log of the output was determined to be the range of the positrons. This was further comparatively analyzed with the corresponding CSDA ranges.

III. RESULT

The results of radiological range measurement using the energy of positron emitting radionuclides are presented in Table 2, and when Compared with the CSDA Range, the radiological range was high. The results of comparing it with the CSDA range by using continuous energy as a source are outlined in Table 3. and the radiological range was higher than the CSDA range, and the difference between the two values was larger as the energy of the emitted radiation increased.

Table 2. Mean and maximum values for radiological ranges for the emitted positrons (unti: mm)

Radiological Range	^{18}F	^{11}C	^{13}N	^{15}O
mean	0.8	1.6	2.1	3.6
max	3.0	5.0	6.1	9.3

Table 3. Continuous energy for radiological ranges for the emitted positrons (unti: mm)

	^{18}F	^{11}C	^{13}N	^{15}O
CSDA range	1.8	2.7	3.5	5.0
Radiological range	2.3	3.9	5.0	7.9

IV. DISCUSSION

The coulomb forces that result in the collisional energy loss of light charged particles exist regardless of the nature of charge on the particle (i.e., negative or positive). Positrons, at or near the end of their range, combine with electrons, leading to their mutual annihilation. The combined rest-mass energy is converted into two 0.511 MeV photons traveling in opposite directions. These photons are very penetrative in nature, lead to energy deposition far from the original positron track[6]. As a result, positrons annihilate each other at a distance from their emission points[7]. This causes a blurring of the source distribution and a consequent loss in spatial resolution[9–11]. To improve this, it is important to survey the distance effect from positron emission to annihilation. This effect is known as the “positron range ”, which is the key indicator of blurring in PET imaging[1]. In particular, many of the PET radioisotopes suitable for immunoPET and theranostic applications emit positrons with long ranges[8]. Future works can explore mechanisms to recover the loss in resolution associated with long positron ranges. The increasing use of these long-positron-range radioisotopes necessitates methods for resolution recovery[8]. In addition, the long positron range of some of these radioisotopes can not only blur their primary distribution but also generate image artifacts. Positrons can exit the target organs and travel through the air, annihilating at a point where there is no tracer uptake, generating “ghost” uptake[8]. Therefore, in this study, we propose a method to accurately measure the range of positrons. First, in order to validate the reliability of the geometry fabricated for range measurement, radiological ranges were measured using the mean and maximum energies and have been presented in Table 3. When the ranges measured using mean energy was compared with the conventional CSDA range in Table 1[6], the error between the two sets of data was 0.14, 0.33, 0.37, and 0.64 mm for ^{18}F, ^{11}C, ^{13}N, and ^{15}O, respectively—all of which were less than 1 mm. Similarly, ranges measured from the maximum energy, when compared with CSDA values. yielded errors of 0.38, 0.54, 0.53, and 0.17 mm for the same order of radionuclides; all of these errors, too, were less than 1 mm. Such low error values are a strong indicator of the reliability of the geometry fabricated in this study. Second, the results of the CSDA and radiological range measurements using continuous energy as a source are presented in Table4. The error between these two sets of values was 0.5, 1.2, 1.5, and 2.9 mm for ^{18}F, ^{11}C, ^{13}N, and ^{15}O, respectively. This shows that the wider the energy spectrum distribution, the larger the difference in the results obtained by the two range-measurement methods. In range measurements using single energy sources, the CSDA and radiological ranges were similar because the positron’s energy was completely converted to manifest its annihilation. However, when measuring them using continuous-energy sources, only positrons with an energy of 0.511 MeV or higher are involved in the radiological range, while CSDA measurements span the entire energy range. For light charged particles such as positrons, forward-scattering is dominant at high energies; at lower energies, however, backscattering also occurs freely, resulting in a radiological range larger than the CSDA range in which low energies are also involved. In the case of radiological measurements in which only those energies that exceed 0.511 MeV are involved in range determination, the range obtained is somewhat smaller than the corresponding CSDA value obtained using the maximum energy. As can be inferred from above, various ranges can be measured based on positron energy and the method of measurement. It can also be concluded from these results that the radiological range estimated using continuous-energy sources would be most appropriate for use in PET imaging. The development of novel PET tracers is actively underway, and positron-emitting radionuclides have various applications including RT treatment planning, immunoPET, and dosimetry using in-beam PET imaging in carbon therapy. Further research needs to be conducted into various positron ranges.

V. CONCLUSION

In this study, radiological range was measured based on p-annihilation with the continuous energy of positrons as a source. Differences were not only observed between the measured radiological range and the conventional CSDA range, but were also more pronounced at high positron energies. Since the CSDA range is an indicator of the distance travelled by the positron while using up all its kinetic energy, radiological range can serve as a more accurate measure to apply to imaging techniques. Moving forward, in line with the development of various positron-emitting radionuclides, several exhaustive studies on their ranges are required. In this study, a radiological range has been proposed as an alternative to the conventional CSDA range.

Acknowledgement

This work was supported by the Dongnam Institute of Radiological Medical Sciences(DIRAMS) grant funded by the Korea government (MSIT)(No.50605-2021)

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양전자 방출 핵종의 방사선학적 비정에 대한 제안

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요 약

양전자 방출 핵종은 진단영상인 PET영상 만드는데 이용된다. 이때 양전자의 비정은 영상의 해상도를 결정하는 인자이며, 본 연구에서는 방사선학적 기준을 통하여 새로운 비정 측정 방법을 제시하고자 한다. 실험은 MCNP6로 진행하였으며, 대표적인 양전자 방출 핵종인 ^{18}F, ^{11}C, ^{13}N, 및 ^{15}O를 대상으로 하였다. 방사선학적 기준은 영상을 만드는 신호인 소멸 복사선의 발생위치를 기준으로 하였다. 실험결과 양전자의방사선학적 비정은 2.3 mm(^{18}F), 3.9 mm(^{11}C), 5.0 mm(^{13}N), 7.9 mm(^{15}O)로 나타났으며, 양전자의 발생에너지가 높을수록 기존의 비정인 CSDA range와의 차이가 크게 나타났다. CSDA range는 현재 가장 많이 이용 되는 비정 측정방법으로 전자가 물리적으로 날아간 거리를 뜻하는 물리적 비정이므로, 방사성동위원소를 인체에 투여하는 핵의학의 경우 방사선학 기준을 적용한 방사선학적 비정을 적용하여야 한다.

중심단어: 양전자, 비정 PET

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