様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

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研究課題名（和文）Reconstruction of dose distributions using PET images in heavy ion therapy

研究課題名（英文）Reconstruction of dose distributions using PET images in heavy ion therapy

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研究者番号：１０５５４７３５

交付決定額（研究期間全体）：（直接経費）　　3,200,000円

研究成果の概要（和文）：粒子線治療の検証をすることは望ましく、そのために、粒子線治療における陽電子放射断層撮影（PET）画像からの線量分布を予測する方法を開発し、11Cと15Oビームに対するその方法の妥当性を実証した。炭素線治療施設で、両方のイオンビームに対して同じ条件下でポリメチルメタクリレート（PMMA）ファントムの深度線量とPET画像を測定した。本研究では、単一エネルギービームを使用して、様々なエネルギービームによるPET画像を再現し、深度線量を計算しました。予測された線量プロファイルは測定と良く一致し、Braggピークの80%の位置も11Cおよび15Oビームの両方に対して0.2mm以内で予測された。

研究成果の学術的意義や社会的意義
Treatment verification is highly desirable in ion therapy to cover tumors with maximum dose and to spare normal tissues or organs at risk near the tumors. We developed a method to predict dose distribution from positron emission tomography (PET) images in ion therapy for treatment verification.

研究成果の概要（英文）：It is desirable to verify the treatment during ion therapy. For this purpose, we developed a method for predicting the dose distributions from positron emission tomography (PET) images in ion therapy and demonstrated the validity of the method for 11C and 15O ion beams. The depth doses and PET images were measured in polymethyl methacrylate (PMMA) phantoms for both ion beams under the same conditions in the carbon therapy facility of the Heavy Ion Medical Accelerator in Chiba (HIMAC). The mono-energetic beams were used to reproduce the measured PET activity of the poly-energetic beams and then the depth doses were calculated using the proposed method. The predicted dose profiles were in overall good agreement with the measured ones and the distal fall-off positions at 80% of the Bragg peaks were also predicted within 0.2 mm for both 11C and 15O ion beams.

研究分野：放射線科学関連

キーワード：Dose reconstruction　PET image　heavy ion therapy

様　式　C－１９、F－１９－１、Z－１９（共通）

１．研究開始当初の背景

Monitoring the stopping position of primary ions in a tumor is desirable for effective tumor treatment by ensuring correct tumor coverage and preventing overdose exposure to normal tissues in ion therapy. Positron emission tomography (PET) has been applied to image positron emitters produced through fragmentation reactions [Acta. Oncol., 42, pp 123-136, 2003], but a patient-dependent difference between the PET peak position and the dose peak position prevents straightforward understanding of PET images [Nucl. Instrum. Methods A, 525, pp 284-288, 2004]. Using a radioactive ion (RI) beam, such as ^{11}C or ^{15}O, is recognized as an ideal method for range verification [Phys. Med. Biol., 49, pp 3179-3195, 2004] since it allows direct visualization of the ion beam stopping position by PET. We have shown the feasibility of this idea through an in-beam PET study for both ^{11}C and ^{15}O ion beams using OpenPET systems [Phys Med Biol., 64, pp 145014, 2019].

Since dose is the main quantity of interest in ion therapy, dose assessment itself would support treatment verification even better. A deconvolution technique has been suggested to predict dose distributions from produced positron-emitter distributions using PET images in carbon ion therapy [Phys. Med. Biol.,64, pp 025011, 2019]. Another method has also been developed for the dose reconstruction of ^{12}C ion beams with the spread-out Bragg peak (SOBP) [Phys. Med. Biol., 65, pp 235052, 2020]. Both methods needed a library of dose distributions and activity distributions of positron-emitters for various mono-energetic beams which were obtained using Monte Carlo simulation (Geant4 toolbox).

２．研究の目的

Since it is desirable to have information on dose distribution in order to be able to verify the treatment during ion therapy, we focused on developing an algorithm or method to estimate dose distribution from PET images for stable and radioactive ion beams.

３．研究の方法

A library of dose data and PET data for ^{11}C and ^{12}C ion beams with energies of 170, 210, 290 and 350 MeV/u for a PMMA phantom was made using Monte Carlo simulation (PHITS code). The algorithm for converting PET data to dose distribution was constructed and optimized. A ridge filter for ^{11}C and ^{12}C ion beams (350 MeV) with 2-3 centimeters of SOBP was designed and tested experimentally in the carbon therapy facility of the Heavy Ion Medical Accelerator in Chiba (HIMAC).

The algorithm for converting PET data to dose distribution and its optimization was applied for ^{11}C and ^{15}O ion beams. The depth dose was measured for both ion beams with mono-energetic and poly-energetic conditions in the HIMAC. The PET images were obtained for an irradiated polymethyl methacrylate (PMMA) phantom with both beams under the same conditions using a prototype PET system. For dose prediction, first a library of depth dose and PET profiles was created for several mono-energetic ion beams using the measured dose and PET images for the mono-energetic ion beams. The depth dose and PET activity profiles for each energy were estimated from the measured data using a simple power law, known as the range-energy relationship. The PET activity profiles of the poly-energetic beams were represented by a weighted summation of the PET activity depth profile of the mono-energetic beams with different energies. The optimized weights, which were obtained after applying the best fit between generated and measured PET data, were used for dose prediction. The conformity between the predicted and measured doses was quantified by comparing the positions in the distal falloff of the Bragg curves at 80% of their peaks.

４．研究成果

The depth doses and the yield of positron emitters in a PMMA phantom irradiated by ^{11}C ion beams of 170, 210, 290 and 350 MeV/u were obtained using the Monte Carlo method-based code, PHITS. The one-dimensional PET distribution was obtained from the yield of positron emitters and a deconvolution approach, which was proposed by Hofmann et al [Phys. Med. Biol.,64, pp 025011, 2019], was applied to the data to predict the depth dose profile. Deviations of the predicted Bragg peak positions to the ideal ones from simulations were 0.5 mm for mono-energetic irradiation; however, optimization of approach was required to reproduce the build-up, peak and tail of depth dose profiles with minimum deviations and good agreement. Figure 1 compares the simulated and predicted dose profiles in depth of a PMMA irradiated with ^{11}C ion beams of 290 MeV/u.

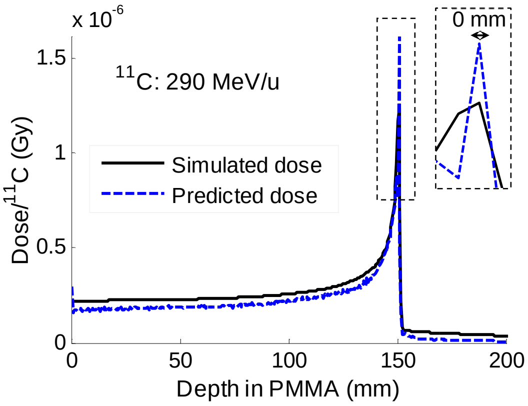

Figure 1. Comparison of simulated and predicted depth dose profiles in an irradiated PMMA phantom with a ^{11}C ion beam of 290 MeV/u.

The depth dose profiles were predicted from the measured PET images in the HIMAC using the proposed method for ^{11}C and ^{15}O ion beams. The predicted and measured doses for the poly-energetic ^{11}C ion beam are compared in Figure 2. The depth doses were predicted with overall good agreement and the distal fall-off position at 80% of the Bragg peak matched the measured one within 0.2 mm. Nevertheless, the mean percentage error between predicted and measured dose profiles in the three regions, i.e., build-up, peak, and tail, was less than 6.4% with a maximum percentage error of 12% for both ion beams.

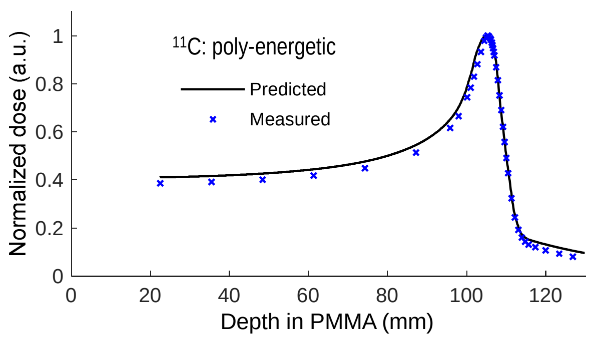

Figure 2. Comparison of predicted and measured depth dose in a PMMA phantom for a poly-energetic ^{11}C ion beam.

５．主な発表論文等

〔雑誌論文〕　計1件（うち査読付論文　1件／うち国際共著　1件／うちオープンアクセス　0件）

１．著者名 Akram Mohammadi, Naoko Inadama, Fumihiko Nishikido, Taiga Yamaya	４．巻 66
２．論文標題 Development of dual-ended depth-of-interaction detectors using laser-induced crystals for small animal PET systems	５．発行年 2021年
３．雑誌名 Physics in Medicine & Biology	６．最初と最後の頁 175029-1-13
掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/1361-6560/ac18fc	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計1件（うち招待講演　0件／うち国際学会　1件）

１．発表者名 Akram Mohammadi
２．発表標題 PET-based range verification of 11C ion beam with SOBP
３．学会等名 2022 IEEE NSS MIC RTSD (2022 IEEE Nuclear Science Symposium, Medical Imaging Conference and Room Temperature Semiconductor Detector Conference)（国際学会）
４．発表年 2022年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関