厚生労働科学研究費補助金（医療技術実用化総合研究事業）

分担研究報告書

陽子線高線量率ラインスキャニングの革新的技術の研究臨床試験に向けた研究

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研究要旨：ラインスキャン陽子線治療が期待される臨床疾患として、小児腫瘍がある。その他にも、粒子線治療が有用であるが費用対効果の面でどの程度の期待があるのかを、文献的に考察した。また、日本独自の研究テーマとして培われてきた、肝がんに関する陽子線治療の多施設共同前向き研究の可能性に関して検討を行った。

A．研究目的

陽子線治療や炭素線治療のコストパフォーマンスの検討を文献学的に行い、粒子線治療の有用性に関する国際的評価を探る。さらに、日本独自の肝癌の治療に関する多施設臨床研究の原案に結びつける。

B．研究方法

陽子線治療の費用対効果に関する過去の論文を網羅的に検索・抄訳し、高度先進医療制度から健保採用への申請資料とする。

C．研究結果

陽子線治療に関しては、スエーデンからの研究成果が最も詳細であった。重粒子線治療に関しては、日本からの報告が詳細であった。

①がんの陽子線治療：臨床的利点の可能性と費用対効果（Proton Therapy of Cancer：Potential clinical advantages and cost-effectiveness）.

リンドクヴィスト、カロリンスカ研究所

Lundkvist J, et al. Karolinska Institutet, Stockholm.

Acta Oncologica 2005; 44：850 -861.;

【要旨】

陽子線治療は、通常の放射線治療に比較して、多くのがん患者に対して臨床的に優位性を提供するかもしれない。しかし、陽子線治療施設の建設費用が高いために、陽子線治療費が通常放射線治療よりも高い。したがって、医学的な効果が、高額な費用に見合うかどうかは、重要である。我々は、４種の癌；左乳癌、前立腺癌、頭頸部癌、小児髄芽腫に関して、費用対効果分析を行った。マルコフ・コーホートシミュレーションモデルをそれぞれの癌種に対して作り、放射線治療を実施された患者の生活をシミュレーションした。コストと「生活の質に関して調整した生存年数(QALYs: 質調整生存年)を主計測項目とした。結果として、陽子線治療は、適切なリスクグループを選ぶことで、費用に見合う効果が得られることが示された。上記４種のがんに関して、陽子線治療で得られる１QALYあたりの平均費用(cost-effectiveness ratio)は、約10130ユーロであった。仮に、得られるQALYが55000ユーロだとすると、一陽子線治療施設で治療すると仮定した925名の４種のがん患者の治療によって、年間に2.08千万ユーロ（QALYの総価値　－　総費用）の総利益が得られる。

よって、このことは、陽子線治療装置への投資は、費用対効果が良いことを示唆している。しかし、データ不足やそれによる仮定の不確実さがあるので、この結果は注意して解釈されなければならない。

②小児髄芽腫の陽子線治療の費用対効果(Cost-effectiveness of proton radiation in the treatment of childhood medulloblstoma), Lundkvist J, et al. Karolinska Institutet, Stockholm. Cancer 103; 793-801, 2005

[要旨]背景：放射線治療は髄芽腫治療で重要な位置を占めているが、多くの患者が晩期障害のリスクを伴っている。陽子線治療は、従来の放射線よりも有害事象のリスクを減らせる可能性がある一方、コストが高くなる。この研究は、小児の髄芽腫の治療における陽子線治療と従来のX線治療の費用対効果の比較することを目的とした。

方法：マルコフシミュレーションモデルを使って放射線治療の結果を評価した。５歳の髄芽腫の患児を経過観察した。患児は、聴力低下、知能低下、甲状腺機能低下、成長ホルモン低下、骨粗鬆症、心臓病、二次がんなど多様な合併症のリスクがある。患者は、死亡のリスクもあり、通常の死、腫瘍再発による死、治療関連心臓疾患による死、治療関連二次がんによる死、他の治療関連死のリスクグループに分類された。モデル内のパラメーター決定のために文献がレビューされた。

結果：モデルとなった症例に関する解析では、陽子線治療は、23600ユーロの費用削減になり、患者あたりQALY(Quality-adjusted life-years,QOL 質調整生存年)が 0.68 延長することがわかった。解析は、IQ 低下と成長ホルモン低下の減少が、費用削減に一番大きく貢献し、費用対効果にとって重要であることが示された。

結果：陽子線治療は、小児髄芽腫の治療において、適切な患者選択をすることによって、従来の放射線治療に比べて、費用対効果が優れ、費用削減効果もあることが示された。しかし、長期生存の研究は少なく、放射線治療の長期成績に関するさらなる情報収集が必要である。

③直腸癌再発に対する炭素イオン放射線治療の費用対効果(Cost-effectiveness of carbon ion radiation therapy for local recurrent rectal cancer)

モバラキ、大野、山田、櫻井、中野. 群馬大学、放医研 Mobaraki A, Ohno T, Yamada S, Sakurai H, Nakano T. Gunma University & NIRS. Cancer Science 101: 1834 – 1839, 2010.

[要旨] 診断、再発治療、経過観察、患者移動、補完療法、合併症、入院に関して個々の患者２５名について検討。患者は、直腸の腺癌の原発部の再発に対して根治的手術のみを行い摘出不能の骨盤再発を起こしている。治療は炭素線治療あるいは、３次元原体照射＋化学療法＋温熱療法の比較を行った。２年生存率は、炭素線で８５％、化学放射線治療で５５％であった。平均的な費用は、炭素線治療で４８０万３９４６円、従来治療法で４６１万１１００円であった。炭素線の incremental cost-effectiveness ratio (ICER)を調べると、１％の生存率増加を期待するのに６４２８円の増加であった。必要入院期間は炭素線で３７日、化学放射線治療で６６日であった。炭素線治療は、費用対効果の優れた治療方法であると結論された。

D. 考察

いずれも、情報源の確かさには十分な注意が

必要である。小児髄芽腫に関しては、陽子線治療はコスト削減に繋がるため、十分に保健適応として良い治療であるということが示されている。頭頸部腫瘍、前立腺癌に関しては、治療上の効果がありそうであるが、明らかにコストは上昇することが示されている。これらを考慮して、臨床試験の枠組みを考える必要がある。

６ｃｍを超えるような大きな肝臓癌に関する陽子線治療の費用対効果は優れていることが示唆されている。これは、X線治療では十分な線量分布を得ることが難しいからであり、実際にそのような大きな腫瘍に対する陽子線治療の優れた研究結果も我が国から発表されつつある。

以上より、我が国として、肝癌に対するX線を用いた体幹部定位放射線治療と陽子線治療の前向き臨床試験を行うことが理にかなっていることが示された。

E. 結論

陽子線治療は、髄芽腫に対しては費用削減になる可能性が高く、国際的にも標準治療になりつつあり、多くの国が健保採用としている。しかし、症例数が少なく、これだけで粒子線治療施設を維持することは困難である。頭頸部腫瘍や前立腺癌では効果が優れていても費用は高まる方法にあり、費用対効果をどこまで許容するかは、国全体の考え方で決定するべきであるが、米国ではMEDICAREが承認している。我が国では現在は高度先進医療として患者本人と各医療機関に委ねられている。炭素線治療は、骨盤前面の直腸再発に関しては効果が優れているが費用は高まる。日本独自の肝癌の治療に関する多施設臨床研究のプロトコール作成の意義があることが示された。

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G. 知的財産権の出願・登録状況
（予定を含む）

1. 特許取得
なし。

2. 実用新案登録
なし。

3. その他

研究成果の刊行に関する一覧表

雑誌

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書籍

著者氏名	論文タイトル名	書籍全体の編集者名	書　籍　名	出版社名	出版地	出版年	ページ

研究成果の刊行物・別刷

Progress in NUCLEAR SCIENCE and TECHNOLOGY, Vol. 2, pp.912-917 (2011)

ARTICLE

The PTSim and TOPAS Projects, Bringing Geant4 to the Particle Therapy Clinic

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Though the Geant4 Simulation Toolkit has been widely accepted in the particle therapy community, with research and clinical use at most of the major centers currently involved in this innovative approach to cancer treatment, the high level of Geant4 expertise required for these applications has proven a serious barrier for users. The PTSim collaboration in Japan and the TOPAS collaboration in the United States wrap and extend the Geant4 toolkit to meet the needs of this critical community. PTSim has provided a common platform to model three Japanese proton and ion therapy facilities plus three more in other countries, allowing users who are not Geant4 experts to accurately and efficiently run Geant4 simulations for any of these pre-built configurations. Building on a rich history of proton therapy applications at MGH (site of the world's first proton therapy system), NCC Korea, and elsewhere, the TOPAS project aims to take flexibility further, allowing any particle therapy clinician or researcher to Geant4-simulate their own real or envisioned facility still without requiring a Geant4 expert. We describe these projects, how their designs bridge the gap between flexibility and ease of use, what key missing software components they have contributed and how the two projects may evolve together.

KEYWORDS: particle therapy, ion therapy, carbon therapy, proton therapy, Monte Carlo, simulation, Geant4

I. Introduction

Geant4[1, 2)] is a software toolkit to simulate the interaction of particles in matter. It has been widely used in various fields from high energy physics (HEP) to nuclear physics to space and medicine. A key area for Geant4 in medical physics has been particle therapy, radiation therapy performed with protons or heavy ions.

Particle therapy promises improved treatment and reduced side effects for many cancers compared with other therapeutic options such as x-ray or surgery. Thirty-five particle therapy centers are currently in operation world wide, with at least twenty-five more currently in planning or construction.[3)] Monte Carlo simulation can be helpful in design of such treatment facilities and in the comparison of treatment plans. Such Geant4 simulations have been carried out at many institutions with good agreement to measurement.[4, 5)]

While Geant4 has been heavily used in medical physics research, applications on the clinical side are limited by issues of computation speed and, more importantly, the level of Geant4 expertise required to perform these simulations. Key differences between the needs of clinical medical physics and those of Geant4's original user base, high energy physics, result in needs not met by the already rich toolkit of Geant4.

In parallel with improvements to accuracy and speed within Geant4 itself, groups of Geant4 developers and medical physicists have formed focused projects to address the specific needs of this community for reliability, repeatability, geometry, accuracy, speed, functionality and ease of use.

This paper describes two such efforts, one in Japan, PTSim (Particle Therapy Simulation),[6)] and another in the United States, TOPAS (TOol for PArticle Simulation). Both projects are designed along principles of Object-Oriented technology, are implemented like Geant4 in the language C++ and have committed to make their software freely available. The goal is that all users of particle therapy facilities, researchers and clinicians, should be able to exploit Monte Carlo simulation with improved reliability, repeatability and ease of use.

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Table 1 Institutions Sampled for PTSim Use Cases

Institution	Location	Particle
National Institute of Radiological Science (NIRS)	Chiba, Japan	carbon
National Cancer Center East Hospital (NCC-East)	Kashiwa, Japan	proton
Hyogo Ion Beam Medical Center(HIBMC)	Hyogo, Japan	proton and carbon
University of California San Francisco (UCSF)	San Francisco, USA	proton (UC Davis)
German Cancer Research Center(DKFZ)	Heidelberg, Germany	carbon (GSI)
CATANA at INFN Catania	Catania, Italy	proton
Proton Medical Research Center at U. of Tsukuba	Tsukuba, Japan	proton

II. PTSim Overview

PTSim has been developed in the project, "Development of simulation framework for advanced radio therapy", funded by the Japan Science and Technology Agency (JST) in the program of Core Research for Evolutional Research and Technology(CREST), October 2003 to March 2010. This joint project among Geant4 developers, physicists and medical physicists produced a software suite for simulating particle therapy with a special focus on carbon therapy. Efforts on further development of PTSim are still under way to include more functionality and improve the performance.

The design of PTSim was based on use-cases sampled from medical physicists at the treatment facilities shown in **Table 1**. PTSim includes a class library for geometry description, material definition, optimized physics process setting (PhysicsList in the Geant4 context), scorers, event level parallel processing and the main program.

III. TOPAS Overview

Building on a rich history of Geant4 proton therapy applications at Massachusetts General Hospital (MGH, site of the worlds first proton therapy system), the National Cancer Center Korea (NCC),[7] and elsewhere, the US National Institutes of Health-funded TOPAS project aims to take flexibility further. With TOPAS, any particle therapy clinician or researcher will be able to Geant4-simulate their own real or envisioned facility (modify an existing design, create a whole new one) still without requiring a Geant4 expert. TOPAS adds advanced I/O facilities for "phase space files", extends handling for patient scan data, phantoms and dosimetry devices, and provides a comprehensive "sequence management" system to handle the many time-dependent aspects of a particle-therapy setup (parts that physically move during treatment, such as modulator wheels or range shifters, fields that vary during treatment, such as for scanned beam treatments, or other time-varying quantities, such as beam current that is modulated during treatment). Like PTSim, TOPAS assures relevance to its user domain by teaming Geant4 developers and medical physicists in a single close collaboration.

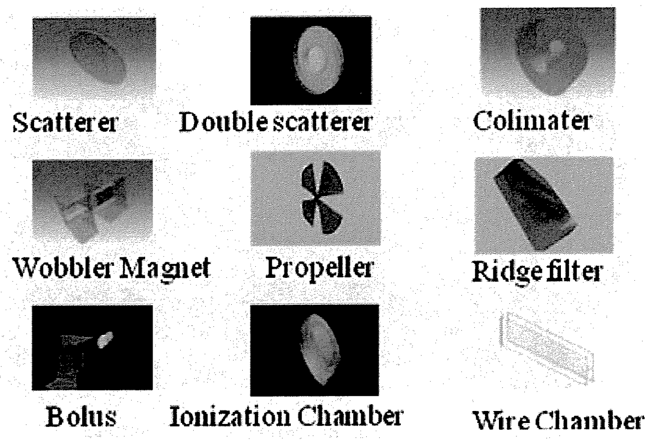

Fig. 1 Example PTSim beam line components

IV. Geometry

Both PTSim and TOPAS take the point of view that the medical physics user should not need to be an expert in Geant4 geometry description. While the geometry capabilities of Geant4 are significant, they can be confusing for new users. PTSim and TOPAS provide easier ways to describe geometry (while still allowing the user to use the full Geant4 C++). The PTSim user can access a library of already created beamline components and can adjust them from macro commands. The TOPAS user has similar capabilities configurable from control files.

PTSim and TOPAS are developed with the understanding that most users will not need to re-implement the geometry descriptions of a complete treatment facility. Rather, they will take an implementation from a previous user and then apply slight changes of their own. We therefore provide easy ways to share implementations between users.

In medical physics applications, we cannot rely on constructive solid geometry for all of the geometry as done in HEP. Geometry from DICOM files (Digital Imaging and Communications in Medicine, from the National Electrical Manufacturers Association[8]) and CAD (Computer Aided Design) play significant roles described below.

1. Beam Line Geometry

Through a study of many potential users, PTSim identified that many of sampled facilities have common components in their beam lines. PTSim provides abstract classes for these common components such that users can implement their own specific components by inheriting from these abstract classes. The most difficult to implement but most important components in a beam line are lateral beam spreading systems and range modulators. The base classes

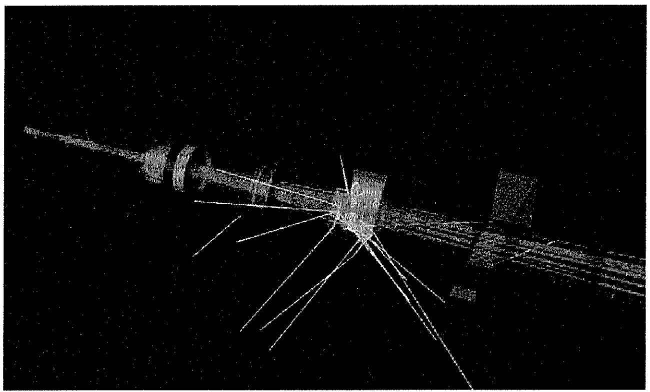

Fig. 2 Example beam line with simulated particles

for Wobbler magnets, scatterers, Ridge filters, propeller blades, beam scanning magnet and so on are provided within PTSim to make the implementation of such components easier (see **Fig. 1**).

After the individual components have been implemented, their positions and angles relative to the beam line are adjusted. **Figure 2** shows a PTSim example of a beam line with simulated particles.

The TOPAS project encapsulates component designs from earlier Geant4 implementations of the MGH and KNCC proton therapy beamlines. Future improvements to TOPAS will include the ability to import components from CAD. Such capabilities, originally developed for the Geant4 space user community are now being used for import of beam line components.[9)]

2. Patient Geometry

Hospital information systems typically provide patient scan information, from CT or MRI, in DICOM format. The DICOM represents the patient image as a contiguous set of voxels formed into a box (of typical dimensions, 512 × 512 × 256 voxels, with each voxel on the order of a half mm on a side). A scalar for each voxel represents the scanned value in that voxel. Because the overall DICOM forms a box, it is common for the DICOM to include both the patient and some amount of air around the patient. PTSim and TOPAS both include code to import such information and to automatically convert DICOM density information (Hounsfield units) into material information (composition and density).[10,11)]

PTSim also includes the capability to process the additional information present in the Radio Therapy extensions (RT) of the DICOM-RT format. This provides additional information about treatment settings (beam and patient angles, etc.) for each patient but is typically specialized to only a specific institution (the format contains a large amount of user-defined information). Thus while DICOM is well established, usage of DICOM-RT is still limited. Among facilities sampled by PTSim, RT is used only by HIBMC and the PTSim DICOM-RT interface is therefore specialized for HIBMC.

3. Geometry Uncertainty

Accuracy of geometry models in medical applications can be limited by manufacturer tolerance and the proprietary confidential nature of some aspects of medical equipment design. Where fully accurate designs are unavailable, the user is forced to rely on simplified drawings and with limited observation of the relevant components. Such uncertainties must be handled by the addition of free parameters to the models.[12)]

4. Geometry Overlaps

Another unique aspect of geometry for medical physics applications is the potential for overlap between parts of the treatment apparatus and parts of the patient geometry. Recall that the patient is represented in the DICOM format as a box, including some of the air around the patient. Because most particle therapy treatments bring the final parts of the beam delivery system very close to the patient, some parts of that beam delivery system may overlap some of the air parts of the DICOM. This can be dealt with by trimming back these air regions, but a more common solution is to mediate the calculation through a phase space file. In this technique, the output of the beam delivery simulation is recorded at a surface (generally a plane just after the beam delivery system), and this list of stored particles is then replayed from that plane through the patient.

5. Motion

Particle therapy involves many moving and otherwise time-dependent parts. A key component of many particle therapy systems, the range modulator wheel, moves throughout the treatment to change the depth penetration of the particles in the patient. Beam current may also be modulated during the treatment. Other treatment head components may move in or out of field during treatment to change scatter or collimation. The entire treatment gantry and/or patient couch may move to adjust the beam angle. Scanned beam therapy includes time-dependent magnetic fields to steer the beam.[13,14)] Finally, the patient is always moving, simply through breathing and gradual shifting of organs.[15)] PTSim accommodates much of this and TOPAS goes further to a comprehensive "sequence management" system.

6. Output Geometry

Visualization of patient geometry presents its own challenges to Geant4. While Geant4 already contained a wide variety of visualization drivers for investigation and presentation of the most complex constructive solid geometry,[16)] there were no tools to adequately represent the volumetric information of DICOM input or patient dose output.

To address this issue, PTSim developed a novel DICOM and volume data visualization system called gMocren.[17,18)] The gMocren system can represent DICOM outputs from multi vendor CTs and overlay additional Geant4 data such as treatment head geometry, particle trajectories and calculated dose in an integrated, highly interactive visualization.

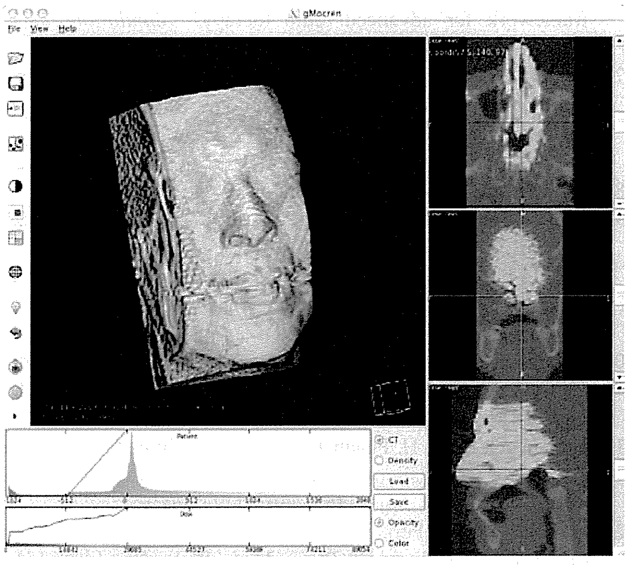

Fig. 3 gMocren image of dose overlaid on DICOM image

Figure 3 shows a Geant4 dose distribution simulation overlaid on a DICOM image. The gMocren client has been made freely available to all Geant4 users, with a corresponding volume data interface built into the Geant4 visualization system.

V. Accuracy and Validation

Accuracy requirements for particle therapy are on the order of a few percent. If Monte Carlo is much less accurate than that, users will instead opt for faster parameterized methods. Validation of simulation results against measurements has been done for protons and carbon ions. After improving Geant4 electromagnetic and hadron physics (in concert with the larger Geant4 community), PTSim reproduces dose profiles of therapeutic carbon and proton beams measured in water phantoms within the required accuracy in radiotherapy.19-21) TOPAS collaborators from MGH have achieved similar results.22)

VI. Calculation Time Requirements

Monte Carlo is inherently calculation-time intensive. A typical head and neck dose calculation at MGH requires 240 hours of running on a standard 2 GHz PC (run overnight as 20 jobs of 12 hours each). While simulation production in HEP may involve thousands of processors running continuously for many months, usage patterns for clinical medical physics follow more of a burst pattern. Running for 15 minutes on a thousand processors is more useful than a thousand minutes on 15 processors. PTSim includes a parallel execution option using MPI (Message Passing Interface)23) and also SAGA (Simple API for Grid Applications).24) TOPAS will include similar kinds of tools to simplify management of large numbers of parallel jobs suitable for cluster, grid and cloud solutions.

VII. Usability

Because it is an extremely general purpose toolkit, and because its original user community, HEP, involves large collaborations that can spend significant personnel resources on simulation development, Geant4 emphasizes flexibility. It is the role of applications such as PTSim and TOPAS to wrap Geant4 into something easier to use for a particular user community. In clinical medical physics, usability means reliability, and repeatability as much as ease of use.

1. Reliability

PTSim and TOPAS give the user pre-built sets of particle therapy beamline components, already validated against experimental data. They incorporate proven solutions for patient data import and validated sets of physics options. TOPAS will go on to add principles from Integrated Safety Management, in particular the use of Engineering versus Administrative Controls. The former means that the user will be specifically locked out from certain unreliable practices. For example, if any key setting is changed by the user in the middle of a run (something one may want to do for test purposes only), the code will automatically tag this run as "test only" and will refuse to send output to the standard output area.

2. Repeatability

TOPAS will incorporate the concept of Data Provenance, which tags a given result with all of the information that explains how that result was obtained. This accommodates the natural working method of the medical physicist, to change just one variable at a time, rerun the simulation and compare the results.

3. Ease of Use

Geant4's great flexibility is known to come with a steep learning curve. Domain-specific applications such as PTSim and TOPAS can help, providing examples of applications that are already close to the user's final requirements.

Among the features PTSim has contributed back to the Geant4 distribution to make Geant4 easier to use is a simplified scoring system. Geant4's original users were content to each develop their own sensitive detectors (detector development was a core Geant4 use case). Medical users on the other hand may simply wish to score standard quantities (dose, energy, etc.) in a simple surface or volume. The new scoring system now included in all Geant4 distributions allows the user to define scoring surfaces and volumes from C++ code or even from simple commands.

Both PTSim and TOPAS provide example applications that are already close to the user's final requirements. PTSim provides the user a library of pre-built particle therapy beamline components. TOPAS also includes such components, and adds an easy way for the user to modify such components through control files. The TOPAS architecture allows users to modify existing components or model new ones and then easily share these models with collaborators.

TOPAS has added an easy to use phase space input/output module so that the set of particles passing through a given surface can be easily written out to a standard, IAEA-compliant, file format and then later read back in as new primary particles.

In medical physics, there are times when one wishes to calculate dose as if the body were just water, and other times where one wishes to calculate dose as if the body were its full set of complex materials. TOPAS will calculate dose in both ways. This feature is particularly important for particle therapy, given the heavy dependence of proton and carbon dose on material.[25,26] TOPAS will extend its patient-import code to also handle various forms of computational phantoms[27] and various common dosimetry devices.

VIII. Conclusion

The concepts employed in PTSIM and TOPAS have proven practical for proton beam simulations in radiotherapy. PTSim has been used at many treatment facilities including NIRS, NCC-East, HIBMC and etc. TOPAS has been used to model the IBA and STAR beamlines at MGH's Francis H Burr Proton Center, the proton therapy eye treatment line operated by UCSF at UC Davis, and will be opening to selected alpha testers in the fall of 2011. Because PTSim will soon be moving to the Apache software license[28] with liberal terms similar to those already in the TOPAS project plan, the two teams anticipate strong sharing of components in the near future.

Acknowledgments

The authors would like to thank members of the Geant4 collaboration, especially, Makoto Asai, Dennis Wright and Tatsumi Koi of the SLAC National Accelerator Laboratory and Vladimir Ivanchenko of the EMSU Lomonosov Moscow State University for their great help in the development of our software. We also thank Prof. Oliver Jäckel of DKFZ and Prof. Takeji Sakae of Univ. of Tsukuba for the valuable discussion on the PTSim design. PTSim was supported by the Japan Science and Technology Agency in the program of Core Research for Evolutional Research and Technology. TOPAS is supported by the US National Institutes of Health under contract number 1R01CA140735-01.

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Development of activity pencil beam algorithm using measured distribution data of positron emitter nuclei generated by proton irradiation of targets containing ^{12}C, ^{16}O, and ^{40}Ca nuclei in preparation of clinical application

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(Received 1 April 2011; revised 10 August 2011; accepted for publication 31 August 2011; published 27 September 2011)

Purpose: The purpose of this study is to develop a new calculation algorithm that is satisfactory in terms of the requirements for both accuracy and calculation time for a simulation of imaging of the proton-irradiated volume in a patient body in clinical proton therapy.
Methods: The activity pencil beam algorithm (APB algorithm), which is a new technique to apply the pencil beam algorithm generally used for proton dose calculations in proton therapy to the calculation of activity distributions, was developed as a calculation algorithm of the activity distributions formed by positron emitter nuclei generated from target nuclear fragment reactions. In the APB algorithm, activity distributions are calculated using an activity pencil beam kernel. In addition, the activity pencil beam kernel is constructed using measured activity distributions in the depth direction and calculations in the lateral direction. ^{12}C, ^{16}O, and ^{40}Ca nuclei were determined as the major target nuclei that constitute a human body that are of relevance for calculation of activity distributions. In this study, "virtual positron emitter nuclei" was defined as the integral yield of various positron emitter nuclei generated from each target nucleus by target nuclear fragment reactions with irradiated proton beam. Compounds, namely, polyethylene, water (including some gelatin) and calcium oxide, which contain plenty of the target nuclei, were irradiated using a proton beam. In addition, depth activity distributions of virtual positron emitter nuclei generated in each compound from target nuclear fragment reactions were measured using a beam ON-LINE PET system mounted a rotating gantry port (BOLPs-RGp). The measured activity distributions depend on depth or, in other words, energy. The irradiated proton beam energies were 138, 179, and 223 MeV, and measurement time was about 5 h until the measured activity reached the background level. Furthermore, the activity pencil beam data were made using the activity pencil beam kernel, which was composed of the measured depth data and the lateral data including multiple Coulomb scattering approximated by the Gaussian function, and were used for calculating activity distributions.
Results: The data of measured depth activity distributions for every target nucleus by proton beam energy were obtained using BOLPs-RGp. The form of the depth activity distribution was verified, and the data were made in consideration of the time-dependent change of the form. Time dependence of an activity distribution form could be represented by two half-lives. Gaussian form of the lateral distribution of the activity pencil beam kernel was decided by the effect of multiple Coulomb scattering. Thus, the data of activity pencil beam involving time dependence could be obtained in this study.
Conclusions: The simulation of imaging of the proton-irradiated volume in a patient body using target nuclear fragment reactions was feasible with the developed APB algorithm taking time dependence into account. With the use of the APB algorithm, it was suggested that a system of simulation of activity distributions that has levels of both accuracy and calculation time appropriate for clinical use can be constructed. © *2011 American Association of Physicists in Medicine.*
[DOI: 10.1118/1.3641829]

Key words: proton therapy, proton beam monitoring, simulation of activity distribution, activity pencil beam algorithm, beam ON-LINE PET system, target nuclear fragment reaction

I. INTRODUCTION

The Beam ON-LINE PET system mounted on a rotating gantry port (BOLPs-RGp) was previously developed, and proton therapy has been performed for all patients with measurement using BOLPs-RGp at the National Cancer Center, Kashiwa, since October, 2007.[1] This system measures annihilation gamma rays generated from the irradiated volume in