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NUMERICAL SIMULATION OF RADIOTHERAPY BEAM INTERACTION WITH SOFT TISSUES AND PLA PLASTIC FOR 3D PRINTING OF DOSIMETRIC PHANTOMS

I.A. Miloichikova[1,2], A.A. Bulavskaya[1], D.A. Polomoshnova[1], V.O. Saburov[3], S.G. Stuchebrov[1]

[1]National Research Tomsk Polytechnic University
30, Lenin Ave., Tomsk, 634050, Russia
[2]Cancer Research Institute, Tomsk National Research Medical Center, Russian Academy of Sciences
5, Kooperativny St., Tomsk, 634009, Russia
[3]A. Tsyb Medical Radiological Research Centre – branch of the National Medical Research Radiological Centre of the Ministry of Health of Russia
10, Marshala Zhukova St., Obninsk, 249031, Russia

Abstract

Introduction. In the development of new methods of radiotherapy, studies of the biological effects of sparsely (photons, electrons) and densely (protons, ions) ionizing radiation are relevant. Reproducibility is a challenge in preclinical studies. Dosimetric phantoms of laboratory animals are an effective tool for dose assessment, facilitating standardization of tests conducted under different conditions. Existing phantoms often fail to address radiobiological issues like placing of biological samples or dosimetry detectors. A method for manufacturing dosimetric phantoms must be developed to accurately manufacturing products and modify their design in accordance with the task. **Aim.** This study develops a numerical model to simulate the interaction of photon, electron and proton therapeutic beams with 3D-printed PLA plastic samples and to determine the optimal 3D printing parameters for imitating soft tissues. **Material and Methods.** Fused filament fabrication proposed as effective means of creating such devices, given that the majority of polymers exhibit properties closely aligned with those of biological tissues, are employed in the manufacture of standard phantoms. A major advantage of 3D printing is the ability to make items with different specifications. Numerical simulation was employed to investigate the interaction of PLA plastic with an ionizing radiation used in radiotherapy. **Results.** The calculated depth dose distributions of different types of radiation in soft tissues and PLA plastic of varying densities were obtained. It was demonstrated that for adipose imitation using photons and electrons, it is necessary to utilise PLA plastic 3D-printed samples with a density of 0.91 g/cm³ (fill factor of 75 %); for muscle – 1.06 g/cm³ (fill factor of 88 %). For proton and carbon ion, the density of PLA plastic samples for adipose imitation was determined to be 0.97 g/cm³ (fill factor of 80 %); for muscle – 1.11 g/cm³ (fill factor of 93 %). **Conclusion.** The study demonstrates that the interaction of PLA plastic with rarely and densely ionizing radiation may be differed. This is a crucial consideration when planning experiments using solid-state dosimetric phantoms.

Key words: dosimetric phantom, preclinical studies, numerical simulation, Monte Carlo method, percentage depth dose distribution, 3D printing technologies, PLA plastic.

Милойчикова Ирина Алексеевна, miloichikova@gmail.com

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ВЗАИМОДЕЙСТВИЯ РАДИОТЕРАПЕВТИЧЕСКОГО ИЗЛУЧЕНИЯ С МЯГКИМИ ТКАНЯМИ И ПЛА ПЛАСТИКОМ ДЛЯ ТРЕХМЕРНОЙ ПЕЧАТИ ДОЗИМЕТРИЧЕСКИХ ФАНТОМОВ

И.А. Милойчикова[1,2], А.А. Булавская[1], Д.А. Поломошнова[1], В.О. Сабуров[3], С.Г. Стучебров[1]

[1]ФГАОУ ВО «Национальный исследовательский Томский политехнический университет»
Россия, 634050, г. Томск, пр. Ленина, 30
[2]Научно-исследовательский институт онкологии, Томский национальный исследовательский медицинский центр Российской академии наук
Россия, 634009, г. Томск, пер. Кооперативный, 5
[3]Медицинский радиологический научный центр им. А.Ф. Цыба – филиал ФГБУ «Национальный медицинский исследовательский центр радиологии» Минздрава России
Россия, 249031, г. Обнинск, ул. Маршала Жукова, 10

Аннотация

Введение. При создании новых методик лучевой терапии интерес вызывают исследования биологических эффектов при воздействии редкоионизирующих (фотоны, электроны) и плотноионизирующих (протоны, ионы) излучений. При доклинических исследованиях важным является вопрос воспроизводимости экспериментальных результатов, полученных на разных системах с различным типом ионизирующего излучения. При оценке дозы эффективным инструментом становятся дозиметрические фантомы лабораторных животных, позволяющие стандартизировать испытания в разных условиях. Существующие фантомы зачастую не отвечают необходимым требованиям для решения специфических радиобиологических задач, например, при размещении внутри фантома биологических образцов или элементов дозиметрических систем. Таким образом, существует необходимость разработки метода изготовления дозиметрических фантомов, позволяющего точно воспроизводить изделия и модифицировать их конструкцию в соответствии с решаемой задачей. **Цель исследования –** провести численное моделирование характера взаимодействия изделий из ПЛА пластика, изготовленных методом послойной печати, с фотонным, электронным и протонным терапевтическими пучками, а также определить параметры трехмерной печати для имитации мягких тканей. **Материал и методы.** Для создания таких устройств предложено использовать технологии послойной печати пластиком, так как большинство полимеров близко по свойствам к биологическим тканям и применяется для изготовления стандартных фантомов. Важной особенностью трехмерной печати является возможность создания объектов с разными настройками, от которых зависят свойства изготавливаемых изделий. Методы численного моделирования использованы для исследования особенностей взаимодействия ПЛА пластика с различными видами ионизирующего излучения, применяемыми в радиотерапии. **Результаты.** Получены расчетные глубинные распределения разных видов излучения в мягких тканях и ПЛА пластике различной плотности. Показано, что для пучков фотонов и электронов при имитации жировой ткани необходимо использовать ПЛА пластик с плотностью 0,91 г/см^3, что соответствует коэффициенту заполнения при печати – 75 %, для мышечной ткани – ПЛА пластик с плотностью 1,06 г/см^3 (коэффициент заполнения – 88 %); для пучков протонов и ионов углерода: для жировой ткани – ПЛА пластик с плотностью 0,97 г/см^3 (коэффициент заполнения – 80 %), для мышечной ткани – ПЛА пластик с плотностью 1,11 г/см^3 (коэффициент заполнения – 93 %). **Заключение.** Характер взаимодействия ПЛА пластика с редкоионизирующим и плотноионизирующим излучением может отличаться, что крайне важно учитывать при планировании доклинических экспериментальных исследований с применением твердотельных дозиметрических фантомов.

Ключевые слова: дозиметрический фантом, доклинические исследования, численное моделирование, метод Монте-Карло, процентная глубинная доза, технологии трехмерной печати, ПЛА пластик.

Introduction

In the contemporary medical community, the issue of oncological diseases continues to be a significant concern [1]. It is established that approximately half of all cancer patients undergo radiotherapy at some stage of their treatment [2]. The development of new therapeutic approaches relies heavily on the results of preclinical studies.

The objective of large-scale multicentre preclinical studies is to enhance the efficacy of radiotherapy for malignant neoplasms. Of particular interest are studies of the biological effects of protons and ions, methods for increasing the conformity of irradiation with electron and photon irradiation, and a combination of photons and densely ionizing radiation in one course [3, 4]. In the context of preclinical studies, the question of reproducibility of experimental results obtained on different systems and with different types of ionizing radiation, specifically the assessment of the radiation dose, is a significant consideration [5]. To address these challenges, dosimetric phantoms offer a valuable solution. Their design enables the placement of a cell culture in the area of interest or the simulate of a laboratory animal's anatomy, with the option of incorporating ionizing radiation detectors [6]. However, existing standard phantoms frequently fail to satisfy the requisite criteria for addressing specific radiobiological issues. Consequently, there is a pressing need to devise a methodology for the fabrication of tissue-equivalent phantoms that are suitable for the experimental validation of radiation dose in preclinical studies.

Three-dimensional printing technology has the potential to revolutionize the field of radiation medicine by enhancing precision, effectiveness, and personalization, ultimately improving patient outcomes and the quality of care provided [7, 8]. The creation of bespoke treatment plans entails the generation of 3D-printed anatomical models derived from imaging data, thereby enabling oncologists to visualize tumors and adapt therapies to the specific anatomy of each individual [9]. The fused filament fabrication method has been demonstrated to be an effective approach for the creation of dosimetry phantoms [10]. This method is distinguished by its relatively low cost in comparison to other fabrication techniques, its capacity to create models derived from tomographic three-dimensional data sets, its high degree of accuracy in reproducing complex phantom geometries, and its versatility in simulating a wide range of tissue properties through the use of diverse materials [11].

One of the most commonly used materials for the creation of objects via 3D printing methods is PLA plastic (polylactide) [12]. PLA is derived from renewable resources, such as cornstarch, which renders it more biocompatible than some petroleum-based plastics [13]. Due to its relatively low atomic number, PLA is an appropriate material for simulating soft tissue in radiotherapy [14]. The capacity to modify the settings for manufacturing products using the fused deposition method permits the fabrication of objects with varying physical density by altering the fill factor during printing [15]. A solid-state dosimetric phantom for preclinical studies, produced using the fused filament fabrication method, should replicate the characteristics of biological tissues with a specified degree of accuracy in regard to their interaction with sparsely (photons and electrons) and densely (protons and ions) ionizing radiation.

In order to develop new dosimetric phantoms, it is necessary to evaluate the possibility of using PLA plastic for their production, which will be carried out using the fused filament fabrication method. Numerical simulation methods may be employed for this purpose. Monte Carlo method is widely used to calculate the dose distribution of radiotherapy [16]. This method is integral to advancing medical technology and improving patient care through their applications in radiotherapy, medical imaging, drug delivery, and epidemiology [17, 18].

The objective of this study is to develop a numerical model to simulate the interaction between PLA plastic objects manufactured by fused filament fabrication and various types of ionizing radiation used in radiotherapy. Additionally, the study aims to determine the optimal 3D printing parameters of the PLA plastic samples for imitating soft tissues.

Material and Methods

Software for numerical simulation

A numerical simulation is conducted utilising the Geant4 toolkit (version 10.2p02) [19], which processes the parameters of the beam and the nature of particle interaction with a range of materials. The Geant4 toolkit is based on the Monte Carlo method, which relies on random sampling to obtain numerical results. This method is particularly useful for complex systems where deterministic methods may be insufficient. It is used to simulate the radiation transport in monitoring systems, beam-shaping devices, dosimetry phantoms, and biological tissues [18, 20]. In this work, the QBBC Physics List was applied, which is the most widely used in medical physics simulation [21, 22].

Materials under study

In the context of preclinical testing, products that imitate soft tissues are of particular practical interest [23, 24]. In the presented research, the most common biological tissues, namely adipose and muscle, were selected for analysis. In order to create numerical models of biological tissues, the chemical composition and physical density were determined on the basis of data sourced from the literature [25].

In this study, PLA plastic was selected as the material for investigation in the context of three-dimensional printing. PLA plastic offers a number of advantages for 3D printing. PLA is relatively straightforward to print with, as it adheres well to the print bed and typically requires lower temperatures compared to other materials, thereby reducing the risk of warping. Furthermore, the production of odour is minimal during the printing process, and the resulting finish is smooth, which makes it the optimal choice for detailed models. Furthermore, PLA plastic is biodegradable under the appropriate conditions, which contributes to the broader objective of sustainable manufacturing practices [13, 14]. The parameters for modelling PLA plastic were determined based on a review of the literature [14].

The creation of the PLA plastic simulation model involved the utilisation of varying densities, given

Table/Таблица

Parameters of the investigated materials used for the numerical simulation [14, 25, 27]

Параметры исследуемых материалов, используемых для создания модели [14, 25, 27]

Parameter/Параметр	Natural PLA plastic/ Натуральный ПЛА пластик	Adipose/ Жировая ткань	Muscle/ Мышечная ткань
Content of elements (by weight)/ Элементный состав (по весу), %	C – 50.0; H – 5.6; O – 44.4	H – 11.1; C – 29.7; N – 0.9; O – 58.0; Na – 0.1; P – 0.1; S – 0.1	H – 10.4; C – 10.3; N – 2.4; O – 76.2; Na – 0.1; P – 0.1; S – 0.1; Cl – 0.2; K – 0.2
Density, g/cm^3/Плотность, г/см^3	0.85–1.18	0.91	1.06
Mean excitation energy, eV/ Средняя энергия возбуждения, эВ	77.9	70.2	74.7

Примечание: таблица составлена авторами.

Note: created by the authors.

that the density of the printed sample can be modified through alterations to the fill factor during the manufacturing by 3D printing. In order to ascertain the physical densities of printed products derived from PLA plastic, cubic objects with dimensions of 2×2×2 cm were produced on an Original Prusa i3 MK3s 3D printer utilising the fused filament fabrication method. The following 3D printing parameters were employed during the printing process: nozzle diameter, 0.4 mm; layer thickness, 0.3 mm; number of perimeters, 1; number of lower layers, 0; number of upper layers, 0; print speed, 60 mm/s; extruder temperature, 195 °C; table working surface temperature, 65 °C; fill factor, 70 % to 100 %. It was determined that a fill factor of at least 70 % was necessary to avoid the formation of excessive air voids within the product, which would be undesirable for the fabrication of phantoms [15]. Consequently, the range of sample densities that was printed from natural PLA plastic was established, spanning from 0.85 g/cm^3 to 1.18 g/cm^3 with the step of 0.01 g/cm^3. The relationship between the fill factor and sample densities was established.

Models of adipose and muscle tissues, as well as the PLA plastic, were created in accordance with the parameters that must be taken into account in numerical modelling using the Geant4 toolkit. These parameters include density, chemical composition, and average excitation energy during interaction with ionizing radiation. Based on the available data on the density and chemical composition of biological tissues and PLA plastic, the average excitation energy was determined using the international database [26].

The resulting values were then used to create models of all the studied materials, as presented in Table.

Simulated geometry

A numerical model was constructed for photons with an energy of 1.25 MeV (representative of the average energy of gamma radiation emitted by the Co-60 isotope), electrons with an energy of 6 MeV, protons with an energy of 150 MeV, and carbon ions with an energy of 300 MeV/nucleon. The selected types of ionizing radiation and beam energies align with the parameters typically employed in radiotherapy [27].

The geometry illustrated in Figure 1 was utilised as the basis for the ensuing numerical experiments. A flat square 10×10 cm beam with uniform distribution of particles over the source area (No. 1 in Fig. 1) was selected as the radiation source for photon and electron beams simulation. The source was located in a vacuum chamber at a distance of 1 mm from the surface of a phantom measuring 30×30×30 cm, constructed from the material under study (No. 2 in Fig. 1), in accordance with the standard irradiation parameters. In the case of proton and carbon ion beams simulation, a circular beam with a diameter of 1 cm was employed. The geometry of the calculation phantom was selected to align with that of a standard solid-state tissue-equivalent plate phantom. In the calculation, the phantom was divided into elementary sensitive

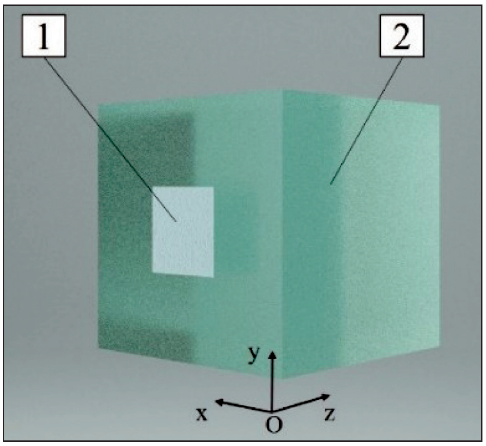

Fig. 1. The numerical simulation geometry. Notes: 1 – ionizing radiation source; 2 – investigated material; created by the authors
Рис. 1. Геометрия численного моделирования. Примечания: 1 – источник излучения; 2 – исследуемый материал; рисунок выполнен авторами

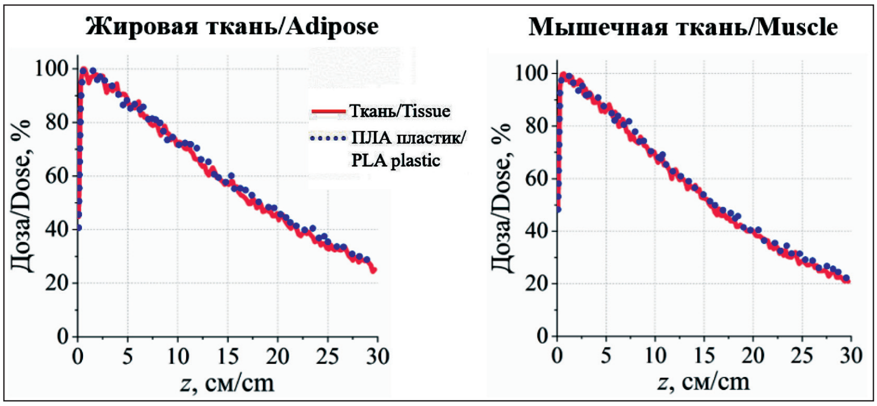

Fig. 2. The calculated percentage depth dose distributions of the 1.25 MeV photon beam in soft tissues and PLA plastic. Note: created by the authors
Рис. 2. Расчетные процентные глубинные дозовые распределения фотонного пучка с энергий 1,25 МэВ в мягких тканях и ПЛА пластике. Примечание: рисунок выполнен авторами

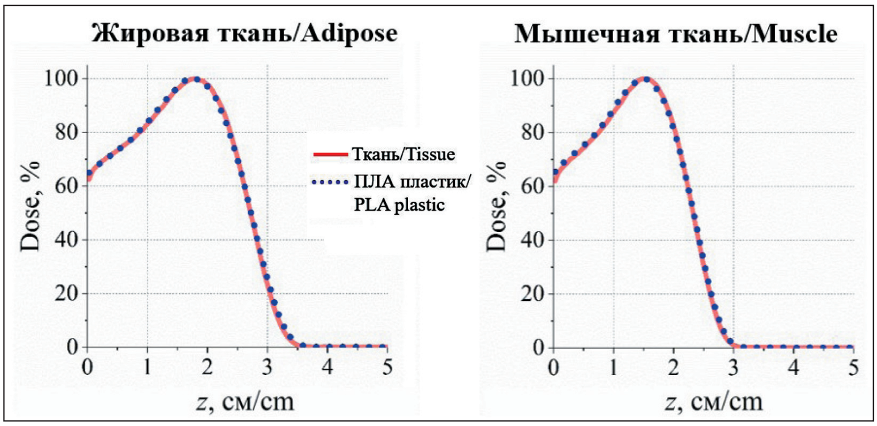

Fig. 3. The calculated percentage depth dose distributions of the 6.0 MeV electron beam in soft tissues and PLA plastic. Note: created by the authors
Рис. 3. Расчетные процентные глубинные дозовые распределения электронного пучка с энергий 6,0 МэВ в мягких тканях и ПЛА пластике. Примечание: рисунок выполнен авторами

volumes, or voxels, measuring 0.475×0.475×0.05 cm for photons and electrons, and 6.175×6.175×0.025 cm for protons and ions. The voxel sizes were selected in accordance with the sensitive volumes of ionization chambers employed in clinical dosimetry, with taking into account the type of radiation [28]. The percentage depth dose distributions (PDD) of radiation were determined for the central voxels along the Oz axis (Fig. 1). The calculated results were found to have a statistical error of 3 %.

Results

In the context of the research work, calculated depth dose distributions of sparsely (photons and electrons) and densely (protons and carbon ions) ionizing radiation in soft tissues (adipose and muscle) and PLA plastic of varying densities (0.85 to 1.18 g/cm³ with the step of 0.01 g/cm³) were obtained.

The physical properties of the plastic material that permit the imitation of biological tissues were determined by means of a comparison of the obtained percentage depth dose distributions.

In the case of photon radiation, the objective was to achieve a matching of the percentage depth dose distributions in terms of the absorbed dose at a depth of 10 cm in tissues and the studied plastics. The absorbed dose in tissues was found to be 72.1 % for adipose and 69.0 % for muscles. Figure 2 illustrates the outcomes of the numerical simulation of the percentage depth dose distribution of photons with energies of 1.25 MeV in biological tissues and PLA plastic. For each PDD curve a process of normalisation was carried out on the maximum dose value.

It was established that PLA plastic with a density of 0.91 g/cm³ is suitable for imitating adipose tissue in terms of its interaction with photon beam, while PLA plastic with a density of 1.06 g/cm³ is appropriate for imitating muscle (Fig. 2).

Similarly, the 6 MeV electron beam percentage depth dose distributions in PLA plastic and soft tissues were obtained (Fig. 3). The data obtained for the electron beam were analyzed by estimating the depth where the radiation dose is reduced by half, which was found to be 2.83 cm for adipose and 2.33 cm for muscle.

For electrons, the densities of PLA plastic for imitating adipose and muscle were found to be 0.91 and 1.06 g/cm³, respectively. This is similar to the result obtained for photon beam.

The principal benefit of radiotherapy utilising proton and light ion beams is the distinctive shape of the depth dose distribution, known as the Bragg curve [5]. The PDD for heavy charged particles at the entrance to the target is characterized by a plateau with a low dose and a distinct peak at the end of the particle track, known as the "Bragg peak". This is followed by a sharp decrease in dose to a minimum level. The depth of the Bragg peak position was selected as the reference characteristic for the analysis of the calculated data (Fig. 4). For a proton beam with an energy of 150 MeV, the depth of the Bragg peak in adipose tissue was 17.0 cm, and in muscle – 14.8 cm.

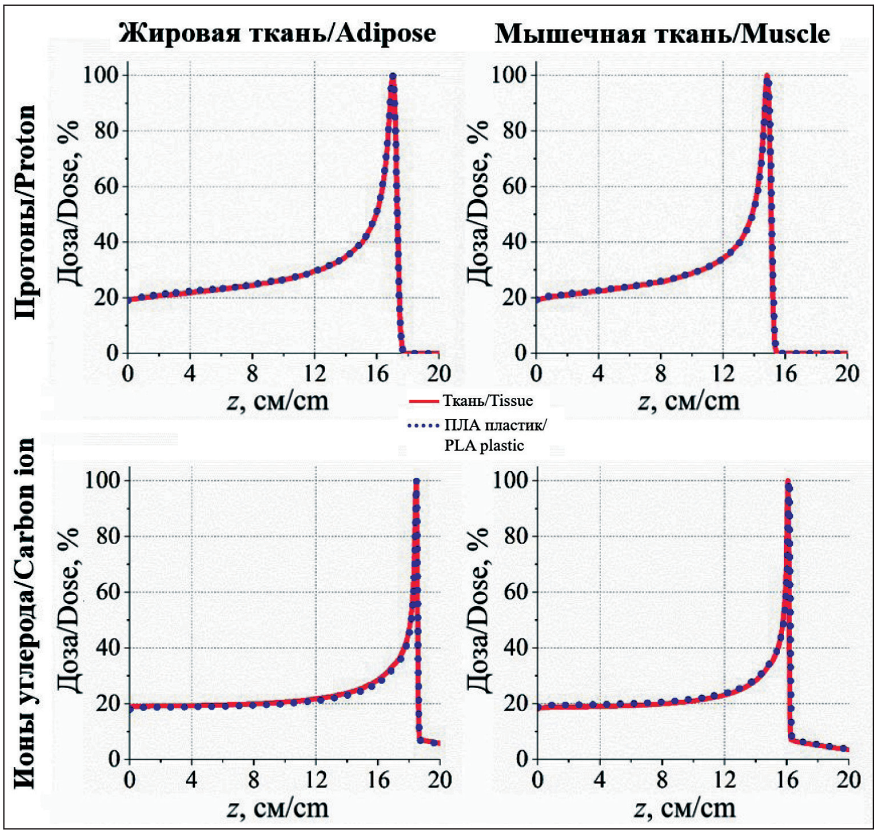

Fig. 4. The calculated percentage depth dose distributions of the 150 MeV proton beam and 300 MeV carbon ion beam in soft tissues and PLA plastic. Note: created by the authors
Рис. 4. Расчетные процентные глубинные дозовые распределения протонного пучка с энергий 150 МэВ и ионов углерода с энергией 300 МэВ в мягких тканях и ПЛА пластике. Примечание: рисунок выполнен авторами

For carbon ion with an energy of 300 MeV/nucleon, the depth of the Bragg peak in adipose tissue was found to be 18.5 cm, while in muscle – 16.1 cm.

It was established that PLA plastic with a density of 0.97 g/cm³ is suitable for imitating adipose in terms of the interaction of protons and carbon ions with tissue, while PLA with a density of 1.11 g/cm³ is appropriate for imitating muscle.

Discussion

The results of the numerical simulation indicated that the required densities of the PLA plastic objects could be used to imitate soft tissues. Based on these findings, the corresponding parameters for three-dimensional printing of samples using the fused filament fabrication method were established. Therefore, to manufacture phantoms for dosimetric studies on photon and electron beams, 3D printed samples PLA plastic with a density of 0.91 g/cm³ should be used to simulate adipose tissue, which corresponds to a fill factor of 75 % during 3D printing, and to simulate muscle – PLA plastic with a density of 1.06 g/cm³, which corresponds to a fill factor of 88 %.

In the case of proton and carbon ion beams, alternative values for the 3D-printed samples from PLA plastic density were determined for the purpose of tissue imitation. For adipose tissue, the PLA plastic with a density of 0.97 g/cm³ was identified, corresponding to a fill factor of 80 %. For muscle tissue, PLA plastic with a density of 1.11 g/cm³ was selected, corresponding to a fill factor of 93 %.

The data obtained demonstrate that when conducting dosimetric tests with different types of ionizing radiation, it is essential to consider the nature of the interaction between a specific type of radiation and the phantom material. The flexibility of 3D printing technology allows for the production of phantoms of the same shape and different densities, enabling the conduct of radiobiological tests on different beams of ionizing radiation.

Conclusion

The work included numerical simulation of the interaction between photons, electrons, protons and carbon ions with human soft tissues (adipose and muscle) and PLA plastic with varying mass densities. It was established that PLA plastic with densities equivalent to those of adipose or muscle tissue can be employed to simulate soft tissues when constructing a dosimetric phantom, provided that the radiation in question is rarely ionizing, such as photons or electrons. However, for densely ionizing radiation, it is necessary to use plastic printed samples with a higher density than that of biological tissues. Therefore, the samples 3D printed from PLA plastic with a density of 0.91 g/cm³ should be employed to imitate adipose tissue, which corresponds to a fill factor of 75 %, and to imitate muscle, PLA plastic with a density of 1.06 g/cm³ should be utilised, which corresponds to a fill factor of 88 %. For proton and carbon ion beams, the following densities of the PLA plastic samples should be used to imitate adipose and muscle tissues, respectively:

0.97 g/cm³ (fill factor– 80 %) and 1.11 g/cm³ (fill factor– 93 %).

The study demonstrates that the interaction of PLA plastic with rarely and densely ionizing radiation may differ in nature, which is a crucial consideration when planning preclinical experimental studies utilising solid-state phantoms that simulate biological tissues. The findings of the study indicate that 3D printing technologies can be effectively employed to address such issues.

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ABOUT THE AUTHORS

Irina A. Miloichikova, PhD, Medical Physicist, Senior Researcher, Radiotherapy Department, Cancer Research Institute, Tomsk National Research Medical Center, Russian Academy of Sciences; Associate Professor, Research Center of for International Nuclear Education and Career Support International Students, School of Nuclear Science and Engineering, National Research Tomsk Polytechnic University (Tomsk, Russia). Researcher ID (WOS): L-5300-2016. Author ID (Scopus): 56377790400. ORCID: 0000-0001-7741-2810.

Angelina A. Bulavskaya, PhD, Associate Professor, Research Center of for International Nuclear Education and Career Support International Students, School of Nuclear Science and Engineering, National Research Tomsk Polytechnic University (Tomsk, Russia). Researcher ID (WOS): F-8559-2017. Author ID (Scopus): 57191170007. ORCID: 0000-0002-7332-2540.

Daria A. Polomoshnova, master degree student, National Research Tomsk Polytechnic University (Tomsk, Russia). ORCID: 0009-0005-7243-0055.

Vjacheslav O. Saburov, Researcher, Acting Head of the Laboratory for the Development and Operation of Irradiation Equipment, Radiation Biophysics Department, A. Tsyb Medical Radiological Research Centre – branch of the National Medical Research Radiological Centre of the Ministry of Health of Russia (Obninsk, Russia). Researcher ID (WOS): AAH-5803-2020. Author ID (Scopus): 57205359311. ORCID: 0000-0002-6907-2753.
Sergei G. Stuchebrov, PhD, Associate Professor, Research School of High-Energy Physics, National Research Tomsk Polytechnic University (Tomsk, Russia). Researcher ID (WOS): C-7029-2015. Author ID (Scopus): 55247303500. ORCID: 0000-0003-3493-2319.

AUTHOR CONTRIBUTIONS

Irina A. Miloichikova: numerical simulation, interpretation of results, writing of the manuscript.
Angelina A. Bulavskaya: investigation of the 3D printed samples parameters, data analysis, writing of the manuscript.
Daria A. Polomoshnova: production of samples using 3D printing methods, writing of the manuscript.
Vyacheslav O. Saburov: scientific editing, writing of the manuscript.
Sergei G. Stuchebrov: study conception, data analysis, approval of the final version of the manuscript, general management of the project.
All authors approved the final version of the manuscript prior to publication and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work were appropriately investigated and resolved.

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СВЕДЕНИЯ ОБ АВТОРАХ

Милойчикова Ирина Алексеевна, кандидат физико-математических наук, медицинский физик, старший научный сотрудник отделения радиотерапии, Научно-исследовательский институт онкологии, Томский национальный исследовательский медицинский центр Российской академии наук; доцент Научно-образовательного центра международного ядерного образования и карьерного сопровождения иностранных студентов Инженерной школы ядерных технологий, ФГАОУ ВО «Национальный исследовательский Томский политехнический университет» (г. Томск, Россия). SPIN-код: 1191-8178. Researcher ID (WOS): L-5300-2016. Author ID (Scopus): 56377790400. ORCID: 0000-0001-7741-2810.
Булавская Ангелина Александровна, кандидат физико-математических наук, доцент Научно-образовательного центра международного ядерного образования и карьерного сопровождения иностранных студентов Инженерной школы ядерных технологий, ФГАОУ ВО «Национальный исследовательский Томский политехнический университет» (г. Томск, Россия). SPIN-код: 5167-0470. Researcher ID (WOS): F-8559-2017. Author ID (Scopus): 57191170007. ORCID: 0000-0002-7332-2540.
Поломошнова Дарья Анатольевна, магистрант, ФГАОУ ВО «Национальный исследовательский Томский политехнический университет» (г. Томск, Россия). ORCID: 0009-0005-7243-0055.
Сабуров Вячеслав Олегович, научный сотрудник, и.о. заведующего лабораторией разработки и эксплуатации облучающей техники отдела радиационной биофизики, Медицинский радиологический научный центр им. А.Ф. Цыба – филиал ФГБУ «Национальный медицинский исследовательский центр радиологии» Минздрава России (г. Обнинск, Россия). SPIN-код: 7212-1328. Researcher ID (WOS): AAH-5803-2020. Author ID (Scopus): 57205359311. ORCID: 0000-0002-6907-2753.
Стучебров Сергей Геннадьевич, кандидат физико-математических наук, доцент, доцент Исследовательской школы физики высокоэнергетических процессов, ФГАОУ ВО «Национальный исследовательский Томский политехнический университет» (г. Томск, Россия). SPIN-код: 2117-0033. Researcher ID (WOS): C-7029-2015. Author ID (Scopus): 55247303500. ORCID: 0000-0003-3493-2319.

ВКЛАД АВТОРОВ

Милойчикова Ирина Алексеевна: проведение численного моделирования, интерпретация результатов, написание статьи.
Булавская Ангелина Александровна: исследование свойств напечатанных образцов, анализ данных, написание статьи.
Поломошнова Дарья Анатольевна: изготовление образцов методами трехмерной печати, написание статьи.
Сабуров Вячеслав Олегович: научное редактирование, написание статьи.
Стучебров Сергей Геннадьевич: разработка концепции научной работы, анализ данных, утверждение окончательного варианта статьи, общее руководство проектом.
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