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Transverse profile forming for high energy electron beams using 3D-printed plastic samples

A A Bulavskaya[1], Yu M Cherepennikov[2], A A Grigorieva[1], B M Gavrikov[3], A A Loginova[4], I A Miloichikova[2,5], N E Toropkov[6,7] and S G Stuchebrov[1]

[1] Research School of High-Energy Physics, Tomsk Polytechnic University, Tomsk, Russia
[2] School of Nuclear Science & Engineering, Tomsk Polytechnic University, Tomsk, Russia
[3] Moscow City Oncology Hospital №62, Moscow, Russia
[4] Radiotherapy Department Dmitry Rogachev National Research Center of Pediatric Hematology, Oncology and Immunology, Moscow, Russia
[5] Cancer Research Institute of Tomsk NRMC RAS, Tomsk, Russia
[6] Institute of Strength Physics and Materials Science of Siberian Branch of Russian Academy of Sciences, Tomsk, Russia
[7] School of Advanced Manufacturing Technologies, Tomsk Polytechnic University, Tomsk, Russia
E-mail: bulavskaya@tpu.ru

Abstract. The work presents application of previously proposed approach for transverse profile forming of high energy electron beams with plastic samples made using 3D printing technology. The collimator made of PLA (polylactide) plastic is designed and produced in a frame of this work. The results of transverse profile forming for 6 MeV electron beam of clinical linear accelerator Elekta Synergy using designed collimator is presented. Obtained results comparison with data from XiO dosimetry planning system shows good agreement of calculated and experimentally formed by plastic collimator electron beam dose fields.

1. Introduction

The wide range of applications where electron beams are used causes the presence of many different requirements for the form of their profiles [1, 2], that provides necessity to develop new approaches to their modification [3]. One of these approaches is to use new materials for the forming samples creation. In the framework of this study, it is proposed to form a transverse profile of high-energy electron beams with plastic samples made using 3D printing technology.

The use of rapid prototyping methods in medical physics is gaining more and more attention among researchers, since their advantages allow increasing the efficiency of patient treatment [4]. Additive technologies have found various applications in medicine. For example, 3D printing is used for surgical planning, where medical imaging data is used to make patient-specific phantoms [5]. Preliminary training with these phantoms lets surgeons to minimize risk in real procedure [4, 5]. Besides, samples made using additive methods is used for tutorial purposes [5], for structural implants production [6–8], and for tissue scaffolds [9]. Recent studies with clinical phantoms is dedicated to 3D printing technology application for boluses production, which provides percentage depth dose shifting in external beam radiation therapy sessions with photon and electron beam and in contact X-ray brachytherapy with gamma rays [10, 11].

Currently, metal is the most widely used material for manufacturing of samples for electron beam transverse profile forming [12–14], Difficult process of metal collimator manufacturing limits using of such devices since for working with metal specially trained and high qualified staff is necessary as well as specially equipped room, that is hard to provide in medical center [14]. An alternative approach is to use polymer samples produced with 3D printing technology [15,16]. This approach provides shorter manufacturing time of forming samples that is important because several oncology diseases are characterized by very high progression dynamics and high response to therapy. Besides, this approach has relatively low cost of equipment and consumables. The latter causes commercial prospects of the developed method [4].

To investigated prospects of the proposed approach to transverse profile forming for high energy electron beams using 3D printed plastic samples we produce plastic collimator allowing forming electron beam of linear accelerator [14].

2. Materials and methods

2.1. Radiation source.

As a source of radiation we use electron linear accelerator Elekta Synergy (Elekta Instrument AB, Stockholm, Sweden) [17]. This accelerator is designed for radiation therapy sessions and provides necessary parameters of the radiation field, particularly the uniformity of dose distribution. The test of proposed method to transverse profile forming for high energy electron beams is carried out with 6 MeV beam energy.

2.2. Production of plastic collimator.

The collimator made of PLA plastic by 3D printing was specially designed for this method [18, 15]. PLA plastic produced by Bestfilament (Bestfilament, Tomsk, Russian Federation) is chosen due to high availability and high strength of printed samples [18]. The shape of the collimation hole corresponds the data calculated with dose planning system XiO (Elekta Instrument AB, Stockholm, Sweden) [19]. The thickness of the plastic sample is chosen accordingly to the previous investigations [20] and equals 8 cm. This thickness is enough for total absorption of electron beam with energies up to 12 MeV.

To print plastic collimator with hole corresponding to coordinates calculated in XiO planning system, it's 3D model is designed using Autodesk Inventor software (Autodesk Inc., San Rafael, California, United States) in STL format (Figure 1), which can be used for sample printing by rapid prototyping systems [21, 15].

Figure 1. Three-dimensional model of plastic collimator.

The forming sample is produced with printer Prusa Mk2 (Prusa Research S.R.O., Prvniho Pluku, Praha) with modified printhead using fused deposition modeling approach [22]. The collimator was printed with 100% filling of sample volume by the material. Figure 2 shows process of plastic collimator production.

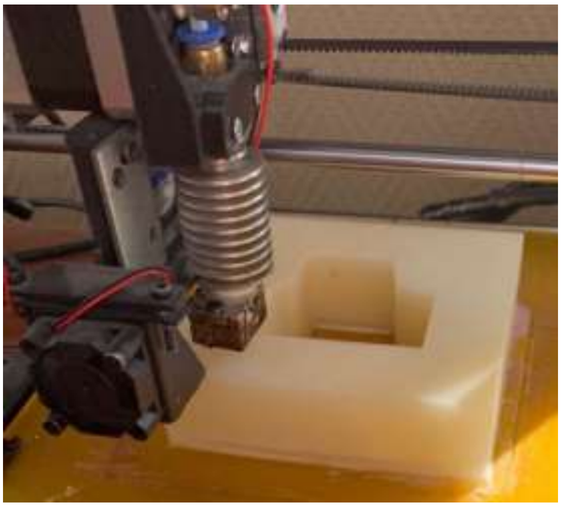

Figure 2. Production of plastic collimator using fused deposition method.

2.3. Experimental scheme.
In the experiment, conventional rectangular applicator of electron linear accelerator Elekta Synergy (10×10 cm^2 sized radiation field) is supplemented with a previously described custom plastic collimator [17]. Figure 3 demonstrates experimental scheme.

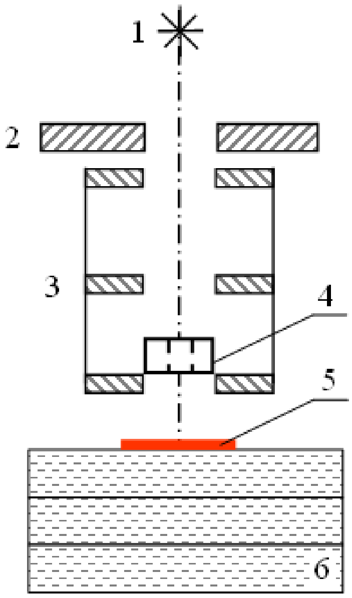

Figure 3. Experimental scheme: 1 – electron source; 2 – primary collimator; 3 – metal applicator; 4 – collimator; 5 – dosimetry film; 6 – tissue equivalent phantom.

To estimate dose field of formed electron beam we use pre-calibrated dosimetry film Gafchromic EBT3 (Ashland Inc., Covington, Kentucky, United States) [23], fixed to the surface of the solid tissue equivalent phantom SP34 (IBA, Louvain-La-Neuve, Belgium) [24]. The source-to-surface distance equals 100 cm, collimator front edge to the surface distance – 6.3 cm. Dosimetry film is fixed perpendicularly to the beam propagation.

3. Results and discussions
Experimental investigation of the applicability 3D printed plastic collimator produced by fused deposition method is performed in according with the experimental scheme shown in Figure 3.

The plan of irradiation is specially calculated in a frame of this work using dose planning system XiO. Electron beam with complex shape with 6 MeV energy falls on solid tissue equivalent phantom SP34 perpendicularly. Irradiation is normalized on the dose at a 1.1 cm depth of phantom. Results of calculation are 3D dose distribution in a phantom volume. Dose distribution on the phantom surface is a two-dimensional matrix contained dose value with resolution corresponding to the size of the voxel chosen for calculation. In the work this size equals 2 mm^3.

Experimental dose distributions of the high energy electron beam is observed by the dosimetry film Gafchromic EBT3 (Figure 4). Color flatbed scanner Epson Perfection V750 Pro (Seiko Epson Corporation, Suwa, Nagano, Japan) [25] is used to digitalize dosimetry film measurements.

Figure 4. Radiation field of the high-energy electron beam formed by 3D printed collimator.

Digitalized data observed with dosimetry films is processed with ad-hoc program code in MATLAB package (MathWorks Inc., Natick, Massachusetts, United States) [26]. The dose uncertainty is about 5% [27–29].

To compare calculated and experimental data the dose distributions from dose planning system XiO is overplayed with results observed with dosimetry film. Figure 5 shows comparison of the calculated in planning system and experimentally observed electron beam radiation field.

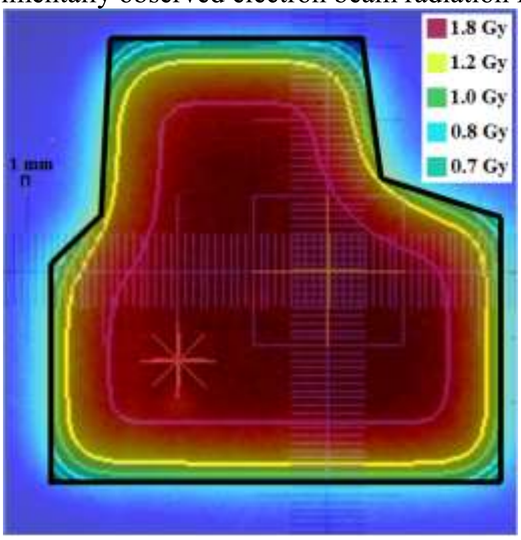

Figure 5. Comparison results of calculated in dose planning system XiO and formed by the 3D printed PLA plastic collimator electron beam radiation fields.

Figure 5 Demonstrates both quantitative matching of the calculated and experimental electron beam radiation field dose distribution, and quality matching of field shapes and collimation hole.

As it seen, the dose beyond the collimator hole is not higher than 0.1 Gy that proves effective absorption of the electron beam in the material of collimator.

The latter proves that samples made of PLA plastic using fused deposition modeling allows collimation of the high energy electron beam.

4. Conclusion

The work demonstrates, that samples made of PLA plastic using fused deposition modeling maintain both mechanical and absorption properties, after absorbing of radiation dose up to 1.5 kGy, that proves prospects of this material using for production of samples forming depth dose distribution of electron beams.

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