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The Practice of Additive Manufacturing for Estimation of Average Absorbed Dose in Clinical Proton Beams

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Abstract

There is a necessary requirement to provide precise dosimetry measurements for radiotherapy and radiobiological studies in the proton beams. The most common practice nowadays to obtain the dose distribution is the use of ionization chambers. However, for many needs, it is also required to estimate an average absorbed dose in the target, while the targets themselves might have complex geometries and large volumes. One of the recent successful method for such measurement is the chemical dosimetry using FBX solutions coupled with the additive manufacturing, which can ensure the accurate representation of complex target geometries. In this study, we chose an optimal chemically neutral material for 3D printing that is not reacting with any of FBX compounds, manufactured the sealed waterproof target models with complex geometry and performed preliminary measurements of the average absorbed dose in a number of volumes representing the different shapes of the targets. The obtained results strongly confirm the possibility of the use of the presented technology for practical dosimetry of proton beams.

Keywords: chemical dosimetry, additive manufacturing, proton beams

1. Introduction

The proton beam therapy is one of the promising methods for treating oncological diseases [1]. Due to unique physics properties, that is Bragg peak for massively charged particles, it is possible to shape a conformal dose distribution maximizing the absorbed dose inside the target volume, while at the same time minimizing the irradiation at the critical organs and adjacent healthy tissues. This feature of the proton therapy allows one to irradiate the tumors located near the viable organs or tissues with the difference in radiosensitivity [2], reirradiation of tumors [3] or perform multiple irradiation regimes [2].

The essential thing to ensure the advantages listed above is to perform correct dosimetry measurements. At the time according to IAEA recommendations formulated at TRS-398 protocol [4], the suggested dosimetry tools are flat and cylindrical ionization chambers and water phantoms. Recently the promising techniques arising to use the anthropomorphic phantoms of human head [5] and radiochromic films [6, 7]. However, for practical needs, it is usually necessary to estimate the average absorbed dose in a volume of interest, but the possibility to perform such measurements with ionization chambers is limited due to the complexity of clinically treated volumes and shapes coupled with the extent of ionization chamber effective volume. Moreover, despite that the anthropomorphic phantoms might be used to estimate the volumetric dose distribution, their geometry, as well as allocation of ionization chambers, are restrained by the manufacturer. Also, the cost of both radiochromic films and phantoms is high, which definitely limits its everyday application.

The aim of the study is developing a method of rapid average absorbed dose estimation in the irradiated volume using additive manufacturing and chemical dosimetry.

2. Material and methods

The dosimetric studies using chemical dosimetry methods performed at the scanning proton pencil beam “Prometheus” (ZAO PROTOM, Protvino, Russia). The proton therapeutic facility located at A. Tsyb MRRC, Obninsk, Russia. The proton energy range is 30-330 MeV with a relative uncertainty less than 0.15%. The accelerator contains fixed beam output and active scanning, the intensity of a beam is $1 \cdot 10^9\ s^{-1}$. The extraction system coupled with the rotating armchair for patient immobilization may produce up to the 36 directions [2, 8].

The complex target volume geometry has been reproduced using FDM 3D printing technique when the object is made by fusing the multiple layers of materials accordingly to the computer model description.

The average absorbed dose estimation has been performed using the highly-sensitive dosimetry FBX system, which is based on the liquid Fricke solution. The FBX solution has been prepared according to the method described in [9].

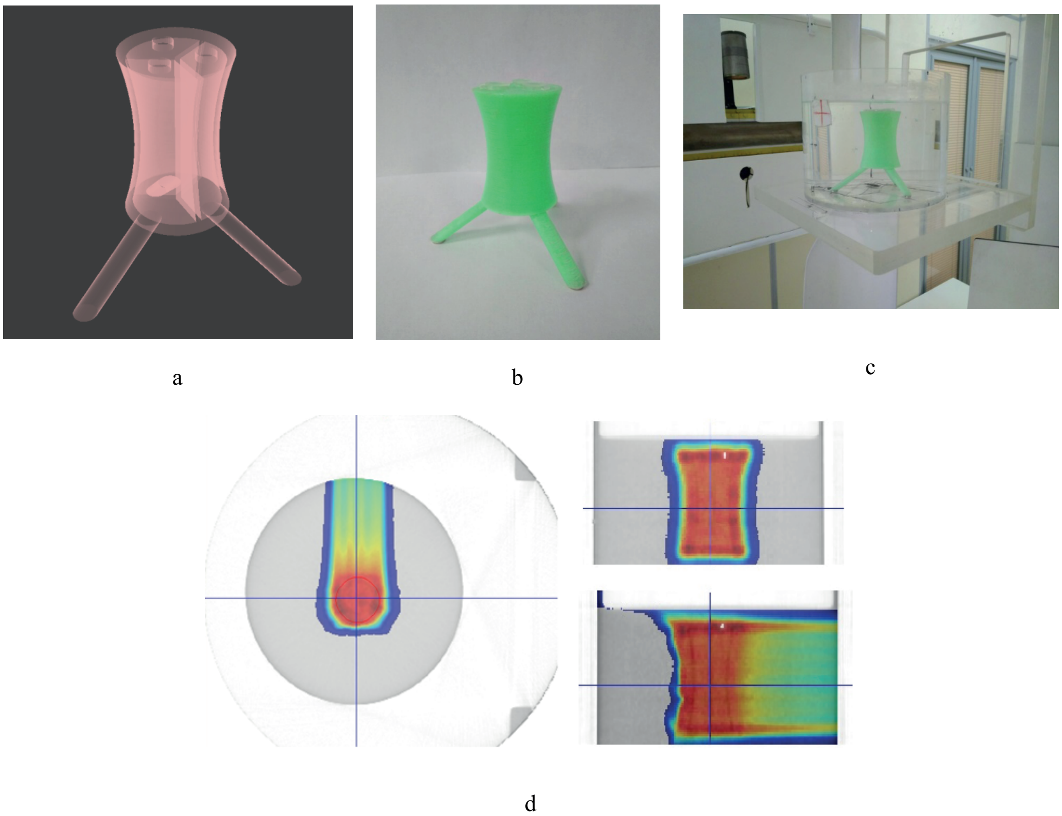


Figure 1: Implementation of the proposed methodology (a) a digital target model, (b) a printed model (c) a model filled with a dosimetric solution in an aqueous phantom, (d) an irradiation plan.

The overall description of the suggested technique is following. The 3D-CAD software Inventor (https://www.autodesk.ru/products/inventor/overview) used to perform a drawing of the model, the drawing further converted to an STL format describing the three-dimensional object model. The model in Fig. 1A contains 3 zones to place the FBX system. There is also possible to place the ionization chamber inside. Then the 3D model converted to g-code using Cura software (`https://ultimaker.com/en/products/ultimaker-cura-software`), and this g-code transmitted to the 3D printed. The 3D printer manufacturing the model accordingly to this g-code. In this work, the TotalZ Anyform 250-G3 printer has been used (`http://totalz.ru/printers/uni/anyform250G3`). The printed model has been additionally treated with methylene chloride to ensure the tightness properties. The cameras designated for FBX dosimetry additionally treated with Potassium dichromate and distilled water, as soon as even a little presence of impurity may affect the chemical yield of Fe^{3+} ions leading to the discrepancy is the FBX-based dose estimation.

After the whole chemical preparations, the model is placed inside the water phantom, and the computed tomography images of the objects obtained using the proton facility built-in tomography system. These images used in the radiation treatment planning software to create a treatment plan (see Fig. 1D). Upon the treatment completed, the cameras filled with the FBX solution and the model placed at the exact same place. On Fig. 1V the photo of the model taken right prior to the irradiation. After the necessary positioning corrections, the calculated plan delivered by the synchrotron management system. Finally, the dosimetry system extracted and analyzed to assess the dose distribution.

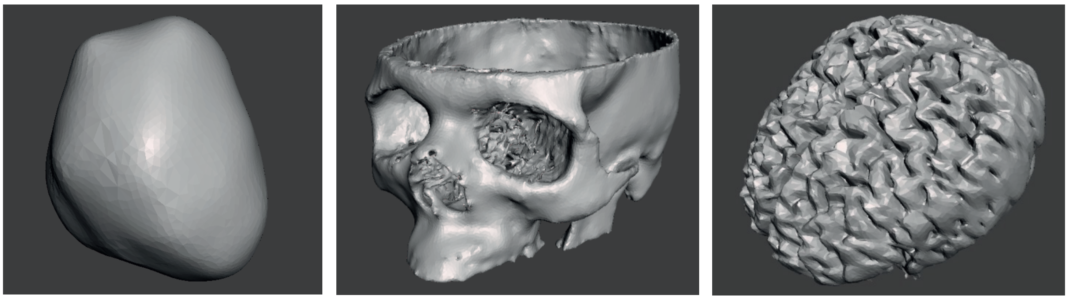
3. Results

The technology of 3D printing offers many advantages. Firstly, there are a wide variety of materials available for 3D printing, and it allows one to choose most suitable compounds according to necessary chemical and mechanical properties of plastics for a particular needs. Secondly, almost all the plastics used nowadays has a low toxicity, which means that the 3D printed might be installed in any room without additional preparations. Finally, it should be noted the low cost of materials for printing using FDM technology.

There are different types of thermoplastics used in additive manufacturing, e.g. polylactic acid, ABS-plastic, nylon, polyethylene etc. In this study, we have chosen polylactic acid as the neutral material that is not reacting with any of FBX compounds. During the printing, the material in wire shape goes through the printing head, also called “an extruder”, with the mechanical system. Inside the heating block of the extruder, the material is melted at the predefined temperature and pushed straightly through a nozzle, which has a specific diameter, onto the working surface. The extruder head can freely move along X, Y axis and deliver the layers of material onto the table, which is moving in a vertical direction. The results 3D object built layer-by-layer in this way according to the prescribed object model.

To manufacture the sealed waterproof model to put FBX solution, it was also necessary to achieve adhesion properties between the layers of fused plastics. This has been done by increasing the temperature, but not so high that it could damage the model.

The irradiation of FBX solution has been performed three times for each model. The value of the average absorbed dose determined based on the previously performed calibration of FBX dosimeter in proton beams [10]. The averaged on three trials value of the absorbed dose was 2.91 and 2.89 Gy respectively. It should also be noted, that the response curve of the relative optical density from the absorbed dose of protons in the range 1-5 Gy is linear [10]. During the current study, the chemical dosimetry



a b c

Figure 2: Models of anatomical structures (a) tumor, (b) skull, (c) brain.

also has been verified up to 10 Gy. The deviations of the measured points from the previously obtained calibration curve are within the statistical error, which also means that the linearity of the chemical dosimetry dose response might be even wider than previously assumed.

4. Discussion

At the time, the most used method to perform the treatment plan verification is the use of ionization chambers. In practice, the estimation of the average absorbed dose using this method takes a long time due to the necessity of sequential moving the chamber between multiple points inside the irradiation volume and repeating the irradiation plan. By using the suggested method, it is possible to create a model of therapeutic patient volumes, which filled with the chemical dosimeters. After a single irradiation of such a model the relevant estimation of the average absorbed dose could be obtained, which might significantly decrease the total time needed for the dosimetry studies. By creating the models of other anatomical structures and coupling them to the therapeutic volumes, it is also possible to assess the average dose that adjacent healthy tissues and critical organs receive during the therapy, that will ultimately lead to the improvement of the overall therapy quality. Such a models might be created using both CT and MRI diagnostic modalities with multiple software, e.g. 3D Slicer (https://www.slicer.org/). The Fig. 2a-c represents various anatomical structures obtained from CT and MRI images of the patient treated with proton therapy that are ready to use in 3D printing.

In addition, the suggested method can be used to create personalized phantoms of a human head. It may solve the problem of necessity of such a phantoms and impossibility of purchasing them due to the high initial cost of all the currently available phantoms at the market. Such a phantoms might be successfully used in clinical practice to verify the dose distribution and in radiobiological studies. Another option for the whole phantoms and representations of anatomical structures of humans and animals is a space industry, due to a rise of interest to the human traveling in near cosmic space. Such a phantoms might be effectively used to assess the dose distributions from the various charged particles existing in the cosmic waves and solar wind background, and the results of such studies might be effectively used to predict the physiological reactions of organisms and construct a cosmic ray shielding.

The development of complicated shapes to use in radiobiological studies for cell cultures is also possible [11].

There is also another question of deep concern regarding the training of medical physicists, especially assuming the rapidly growing the number of radiotherapy centers [12]. In practice, the 3D printing methods allowing one to develop non-trivial irradiation plans, which are personalized and requiring the non-homogeneous dose distribution inside the volume. Solving such tasks in real practice requires a deep knowledge and understanding which is necessary to perform a personalized treatment.

The 3D printing also might be used to manufacture the immobilizing devices, e.g. using the MRI or CY data it might be possible to print a personalized mask for proton therapy, or other equipment for various body parts.

5. Conclusion

The suggested technology of additive manufacturing technique using 3D printing method for accurate estimation of the average absorbed dose inside the irradiated volume and investigated for use in proton therapy, provides new opportunities for highly-precise radiotherapy. The concept developed in accordance with the technology implies and covers the practical need of designing the complex shapes following the treatment volume or the whole phantoms suitable for both clinical practice and radiobiological studies. Moreover, the suggested technology might be used for training purposes, as a part of educational courses for medical stuff specialized to solve unordinary tasks in the personalized medicine fields, which definitely require the highly qualified specialists. The design of the personalized phantoms using multiple densities might be an accurate and precise description of the patient's anatomy, which can be further used to develop a new schemes and therapy regimes, especially hypofractionation and radiosurgery.

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